ON FLEXIBILITY

Graphite drawing by Mark West (1995)

"It may be noted that although reinforced concrete has been used for over a hundred years and with increasing interest during the last decades, few of its properties and potentialities have been fully exploited so far. Apart from the unconquerable inertia of our own minds, which do not seem to be able to adopt freely any new ideas, the main cause of this delay is a trivial technicality: the need to prepare wooden forms."

-- Pier Luigi Nervi
(extract from Structures, F.W. Dodge, USA , 1956, p95)

1. Control

Concrete has next to no opinion about its shape; a wet, heavy, gloppy, material, it will take any shape you give it, so long as you can hold it still for a few hours. Its plasticity suggests that it might take an extraordinary variety of forms -- so how did such an amorphous material end up as so many rectangular solids and cylinders?

The origins of the right angle, and its ubiquity in the realm of human affairs, holds a deep and complex story. The following little story only touches the surface, but it will do:
Nearly all industrial building materials are produced through some form of simple mill – saw mill, rolling mill, extrusion, etc. These are all single-axis mills, whether powered by wind, water, animal, or engine*. Whatever passes through such a mill will have a uniform section along its length. This is the instrumental origin of all the straight, flat, sticks and sheets that constitute our building materials. Obvious exceptions include things that are carved or cast. But if you are casting into a mould made of sheets and sticks, then the casting will likely be both flat, straight, and built with 90 degree joints. A rectangular box, after all, is the easiest thing to make from flat, uniform-section, stock.

Developed in parallel with single-axis production mills, are engineering calculation techniques that rely on the analysis of (flat) sectional areas.

* The exception in traditional milling is the lathe, which operates on 2-axes. (Multi-axis, robotic, milling is dealt with later in this chapter).

The slide rule, which developed alongside structural theory and its calculation methods, is an analog computer that can multiply (or divide) only two numbers at a time, and as such was particularly suited to calculating the area of rectangles and uniform-section volumes. This combined and coherent kit is indigenous, so to speak, to the similarly evolved Cartesian X-Y-Z coordinate system. Nearly all our traditional tools, from the table saw, to the drafting machine, to the crosshairs of the cursor in your computer, are saturated with this self-same orthography*. This is a powerfully coherent material culture indeed, and when reinforced concrete architecture makes its appearance (let's say, from the late 19th Century) it is little wonder that the shape of its moulds fell right in line. Although the potential for concrete to take other kinds of forms is latent, and many have dreamed of and sought such liberation, the cultural current of the right angle remains, very strong indeed.

Today, concrete is an old material, and as such, habit has largely taken command of imagination. Conventional industrial methods of construction and design in concrete take place in a highly evolved traditional system where prismatic forms are a foregone conclusion. In this context, the making and detailing of concrete formworks is rarely the concern of designers. When construction takes concrete's plasticity into account at all, it is likely to be thought of as a merely utilitarian quality that allows for its transport and placement into its (rigid, prismatic) moulds.

But the game is entirely changed when moulds are made flexible; the plasticity of concrete reappears to us as something extraordinary in a construction material (which it is). In a flexible mould, concrete is rediscovered as a wet, sensual, and responsive material. Its relationship to its mould is no longer passive, but an active one in which concrete's plasticity and weight play a particular and crucial role in determining its final shape. Concrete's *activity* in this new relationship constitute an empowerment of plasticity in construction and design.

The arrival of flexibility and plasticity into construction alters form in a fundamental way. The biologist Ste-

* Orthography is used here as another word for "orthographic projection", though its other meaning of "correct writing" could also apply.

Fig. 1. A permeable mould skin under pressure bleeding mix water. [see Chapter 8 Column Moulds Fig.16]

ven Vogel observes that there are fundamental differences between Natural and human-made forms: Living structures are generally small, wet, and flexible, while human-made structures are generally large, dry and brittle[1]. Fabric-formed concrete, however, presents a strange and temporary exception to this rule. When formed in a flexible mould, concrete begins life as a wet and flexible system, behaving precisely as a natural, biological, structure might. As such, it assumes geometries that are often deeply reminiscent of those found in living things. Over a short period of time, however, this wet flexibility turns dry and brittle, making it useful to us as any other a human-made structure.

Before being filled with wet concrete, a slack fabric mould is largely indiffernt to its shape -- its form in space remains flacid and variable. But when these two more or less amorphous materials are combined, they hold each other in a mutual embrace, producing an energized system of burden and restraint. A system of resistance ia crated where the materials themselves actively seek the shape of their own stability in the gravitational field. The bias towards the right angle and the necessity of a uniform-section disappear. The cast's final geometry is neither generic nor rigidly imposed. Instead, it is arrived at in a kinetic and highly particular way.

When form so clearly arises from *an event*, relations between designer, builder, and the material world are energized in a way that presents new prospects, both professional and intellectual. In such a flexible system, the materials in play can no longer be considered inert or passive. Instead they are alive to action as they engage in a kind of formal self-invention in real time. This aliveness is a direct result of the system's mechanical flexibility, which challenges the designer/builder to think of matter as a participant in determining form*.

Ursula Franklin, the Canadian scientist and observer of technology and culture, reminds us that Technology is a not a collection of gadgets or tools, but rather "a way of doing something". Franklin contrasts two different ways-of-doing that she identifies

* As anyone who wrestles with matter will know, this kind of reciprocity is always present, although we tend to become inured to this fact. A palpably flexible and resistant response on the part of a material is a reminder of matter's innate vitality.

Fig. 2. Storefront For Art And Architecture facade installation (New York, NY (1992) (with Aryaya Asgadom).

Fig. 3. Storefront For Art And Architecture facade installation (New York, NY (1992) (with Aryaya Asgadom).

as "prescriptive" or "holistic" technologies.

Prescriptive technologies seek to control the outcome of work by prescribing a step-by-step sequence of actions [think of tax forms, or military drills, or industrial "best practices"]. Prescriptive production works hard to be independent of context, believing that all the essential parameters of production can be controlled (input and output) and that whatever is outside the production realm is external and irrelevant. Holistic technologies, on the other hand, require attention to, and reciprocal engagement with, a particular context. Engaged with a complex surrounding context, Holistic production requires situational judgments and adjustments. Farming is a good example of this[2].

The act of construction, by its very nature, requires a combination of prescriptive and holistic methods. The contract documents produced by an architect, for example, are a form of prescriptive direction, but these are always an incomplete fiction of an ideal. The act of construction is, by its nature, filled with adjustments, change orders, and countless micro-improvisations. Everyone actually knows that, one way or another, the final construction will never exactly follow the original, prescribed, design. In terms of prescriptive control, the result falls short of what was intended. From a "holistic" perspective, adjustments will be made, and solutions will be found as inevitable contingencies unfold.

As a noun, the word "Mould" implies fixity; as a verb it implies action and change. Flexible moulds remain un-fixed until the very end of their action. That action is not one of strictly commandeering matter and events, but rather of finding an *accommodation*, within rigidly set limits. Boundaries are set and openings are sought, through which the material world is invited to offer solutions on its own terms.

Much is said these days about "working with Nature", yet our industrialized methods tend towards increasing levels of control and efficiency. Our methods of prescriptive production seek to commandeer the material world in order to assure predictable or "optimal" results. Yet, attentive, responsive, collaborations with the world-at-large would seem to be a prerequisite for anyone seeking to work “with Nature”. Holism and flexibility would be our allies, yet they are regarded with justifiable suspicion in an industrialized building culture and economy.

In this context, building with a flexible mould may be understood not merely as a technical enterprise, but also as a theater of freedom, restriction, control, and accommodation -- i.e. a ‘little world’ in which larger themes or actions are played out with some precision. As such, this practice is a precise functional analog for broader questions of “holism” in design and construction, and for how we engage with the physical world in general. The practitioner of such a flexible technology is called upon to be personally attentive and selectively yielding in ways that rigid materials and methods do not require. The designer/builder is brought face-to-face with this central and essential question: what actually needs to be controlled and what does not?

With a flexible mould, control is accomplished by choosing the specific materials in play, providing specific restraint conditions, and establishing the fabric’s pre-tensioning (if any). Wherever the mould is rigidly constrained, the fabric and concrete are forced to comply with the shape(s) they are given. These rigid boundary conditions are described by drawings and specifications in the usual prescriptive manner. But those parts of the mould that remain flexible will not take their final form until energized by the wet concrete. The complex set of actions and reactions that result can be predicted in some cases, while in other situations and set-ups the materials may have an infinite number of solution sets to choose from, making prediction of the final shape less than clear. So, for example, the shape taken by a structurally taut membrane can be calculated (or digitally modeled) as it will have a single, static, solution. The buckles of a loose, crumpled, sheet of fabric, on the other hand, can have innumerable possible solutions, as in the buckles seen in Fig. 4 [see Chapter 11 Non-Pressurized Moulds: Wrinkled sheets Pg. ##:].

One of the first questions that might be asked about fabric-cast construction is whether multiple casts from the same mould can be reliably dupli-

Fig. 4. Thin-shell wall Panel [see Chapter 11 Non-Pressurized Moulds, Figs. 48-51]

Fig. 5 Pre-cast Vaults and branching columns illustrating multiple identical casts from a flexible mould, made by CAST “Team Gravity”: Leif Friggstad; Aynslee Hurdal; Michael Johnson; Kyle Martens (2007). [See Chapter 12 Truss and Branching Forms, Figs. 3 -- 6]

cated. The answer turns not only on issues of flexibility/rigidity and control, but also on the issue of construction tolerance. Certainly the products from a flexible mould are repeatable -- the crucial question is: within what tolerance? The construction tolerances that are accepted in conventional reinforced concrete construction can vary considerable from job to job and place to place. Generally speaking, yes, if the dimensions and boundary conditions of the mould remain the same, repeated casts from the same flexible mould are dimensionally predictable and repeatable, within normally accepted construction tolerances. There are, however, some special circumstances to consider.

For example, a small-diameter cylindrical column, cast in a fabric mould, is highly predictable and repeatable. At most, the appearance or location of slight wrinkles may vary between subsequent casts, but this is a minor detail of "ornament", not of structural dimensions or serviceability. A larger diameter column, however, may produce a slightly greater diameter at the bottom than at the top as the fabric strains under higher hydraulic pressures. In this case, what variation is acceptable between top and bottom diameters? Where tolerances are tight, strains can be controlled by increasing the stiffness (structurally speaking) of the fabric, or by slowing down the pour rate (to reduce pressure levels). But where tolerances are more generous, minor variations in diameter may not be an issue at all. Another example of flexibility and construction tolerance is raised in the discussion of spray foam-backed rigidified fabric moulds in Chapter 11 Non-Pressurized Moulds pg. ##.

While on this topic, it bears mentioning that the ability for a single mould to provide *variations* in the form and dimension of subsequent casts, holds sculptural, architectural, and logistical value. See, for example Chapter 11 Non-Pressurized Moulds Fig. 7, or the Text Box on pg. ## (Casa Dent).

At the extreme end of geometric and dimensional control, we have CNC (computer numeric control) robotic tools, which like flexible moulds, are not tied to the geometric imitations of uniform-section, prismatic volumes. CNC techniques for making large, complex-curvature moulds for architectural-scale constructions, currently include multi-axis 3-D milling of rigid polystyrene blocks and computer-controlled, piston-actuated, flexible formwork sheets (ex rubber sheets). Technologies for 3-D printing of building components in concrete are also being developed.

The simplicity of flat sheet fabric formworks stands in stark contrast to the relative complexity of CNC robotic production. But these contrasting approaches to design and construction are not strictly at odds with each other. Both approaches are available, and neither need displace the other, and may well allow for synthetic combinations with each other. The choice of when to use one method of mould-making over the other turns on their different strengths and weaknesses, outlined below as follows:

Despite the relative ease of drawing complex geometries in the virtual design-space of a computer, actually constructing such designs involves a host of material complexities and limitations. The dream of somehow "printing" a digital building design is a strong one, holding as it does the promise of an almost unlimited freedom of form-making. Increasingly high levels of technical complexity and control have been placed in service of this dream. CAD/CAM design and production is a highly industrialized and capital-intensive mode of construction that reduces the involvement of human labor in construction.

Software for designing Fabric-formed structures is not readily available (yet), so for the time being its integration into the fully digitized design-space of architecture lags behind CAD/CAM methods. The extraordinary simplicity and economy-of-means found in fabric formworks, however, makes it universally available to both high and low-capital building economies. But not just any curved shape can be built using a flexible sheet mould; while they easily provides complex, structurally intelligent, and beautifully curved forms, these are limited to the class of shapes produced by tension membranes. Fabric formwork accepts the geometric constraints imposed by its material and technical simplicity. Matter's resistance is taken as a virtue, rather than as a difficulty to be (heroically) overcome. A flexible practice, if we may call it such, also requires a special kind of attentiveness and cunning -- prime virtues in all building cultures, but perhaps particularly crucial in this instance.

Currently, a rigid mould holds the great advantage of giving an ordinary builder (unfamiliar with flexible moulds) the confidence to set a price for its use -- and without this confidence, nothing much gets built. (Methods for rigidifying flexible fabric moulds are explored in Chapter 11 Non-Pressurized Moulds.) But rigidity carries its own price: Rigid moulds need to be, essentially, zero-deflection constructions. Achieving this high level of stiffness requires significant depth and commensurately higher levels of material volumes for the mould's construction. This price of rigidity can be gauged by comparing the muscularity of conventional panelized wall formworks with those of a fabric wall mould, as shown in Chapter 9 Wall Moulds, Fig. 7. In column or wall formworks, a fabric mould will use hundreds of times less material than a rigid, rectangular, zero-deflection box. [See also the 9m (30 ft.) tall columns in Chapter 6 Connections Fig. 35, and the Text Box on pg. ##.]

Fig. 6. Thin-shell facade panel plaster model

2. A New Language of Form

The visual appearance and affect of fabric-formed concrete is strikingly different from that of conventional concrete architecture. Its “organic”, “biological”, or “sensual” nature contrasts sharply with the “hard” machine aesthetic of industrial modernism. To have access to a new formal language for architecture is not insignificant. In this case we are invited to think differently not only about form, but about *how* we build and what difference that might make.

As discussed at the beginning of this essay, the form-language of machine modernism can be (instrumentally) traced to the uniform-section sticks and sheets of industrialized building culture, founded in the co-evolved methods of traditional drawing, structural calculation, and the actions of the single-axis mill. The machine paradigm is surely one of the most profound products of the modern world, and the extraordinary changes this brought to previous, and archaic, agrarian-based cultures and economies cannot be overstated. The story of how a machine-like language of architecture displaced earlier biological/vegetal forms surely mirrors more profound changes in culture and imagination, as well as our relationship to Nature in general.

The agrarian basis of pre-industrial architectures can be seen in nearly every archaic architectural language of form. Consider the fleshy curves and vegetal and animal adornments of ancient Greek and Roman architecture, or the succulent stone leafs of ancient Egyptian capitals, or the endless variations of carved foliage from lotus to acanthus, or combinations of animal and human bodies, adorning facades and entablatures of classical architectures throughout the world; or more abstractly, the organicism of gothic architecture with its bundled column stalks and the “flowering” of its ribbed vaults. All are products of agrarian cultures. While one can point to examples of non-machine, “organic”, 20th Century modernisms, overall, the image and power of the machine has been triumphant.

It is interesting that at this particular historical moment, when architectural design production has become fully digitalized, and when multi-axis robotic manufacturing technologies are making their entrance into industrialized construction economies, such a machine-saturated practice would be exploring ways of constructing curved, non-uniform-section forms and structures. It seems that a project of shaking off the geometric shackles imposed by “Industrialization 1.0” is well under way. Also interesting is the fact that this is happening at a time when ecology and “sustainability” hold a new and increasingly urgent place in our considerations and actions. It seems as if a desire for "biomimetic" architecture is arising simultaneously from ecological concerns (or nostalgia?) and from digital design/production culture. The re-discovery of flexible formworks (see Chapter 2 History of Fabric Formwork) arrives in this milieu.

It is remarkable, from a sculptural point of view, that the energies at play in a flexible mould can be "read" so precisely in the final form. High levels of stress are cast as an energized field of tensed impressions. Areas of low stress appear almost palpably relaxed. One does not need formal structural knowledge to feel the differences in the energy created and held by a flexible mould. This knowledge seems innate to our own bodily existence and our own struggles with gravity – we know these forms and forces in our bodies, in our skin, in our clothing, and in the skins of other living things, both animal and vegetable. The degree to which these energies can be felt and innately understood from their final solidified forms is uncanny. It seems we know them intrinsically. This energy, once solidified, holds and conveys a tacit understanding between ourselves and force-in-matter, establishing an empathy with the world as we find it. These understandings are not so much represented by the final (cast) shapes, as embodied in them as a kind of 'fact', in the root meaning of that word: 'a thing done'.

Where form appears and solidifies of its own volition, so to speak, it has an aspect, and an affect, more akin to that given by Nature than by the artifices of architecture. A casting from a flexible mould is almost like a physical form of "automatic writing" – it is made by us, but seems to come not from us. In this sense, the products of fabric-formed concrete are outside of "design". One cannot say if these shapes are "old" or "new", "human" or "natural'. They simply are, in much the same way as tree bark is (which is to say, as tree bark *happens*). In this sense there is no Style (as in fashion) in these architectural forms. They cannot be tied to any historical period – not even the present. They are new and immediate, yet they are as old as weaving, as old as skin.

In this sense there is a strange *Time* in these forms – both perpetually immediate time (like a photograph's "stoppage" of a single instant) and extraor-

Fig. 7. The tensed and the relaxed -- immediately understood.

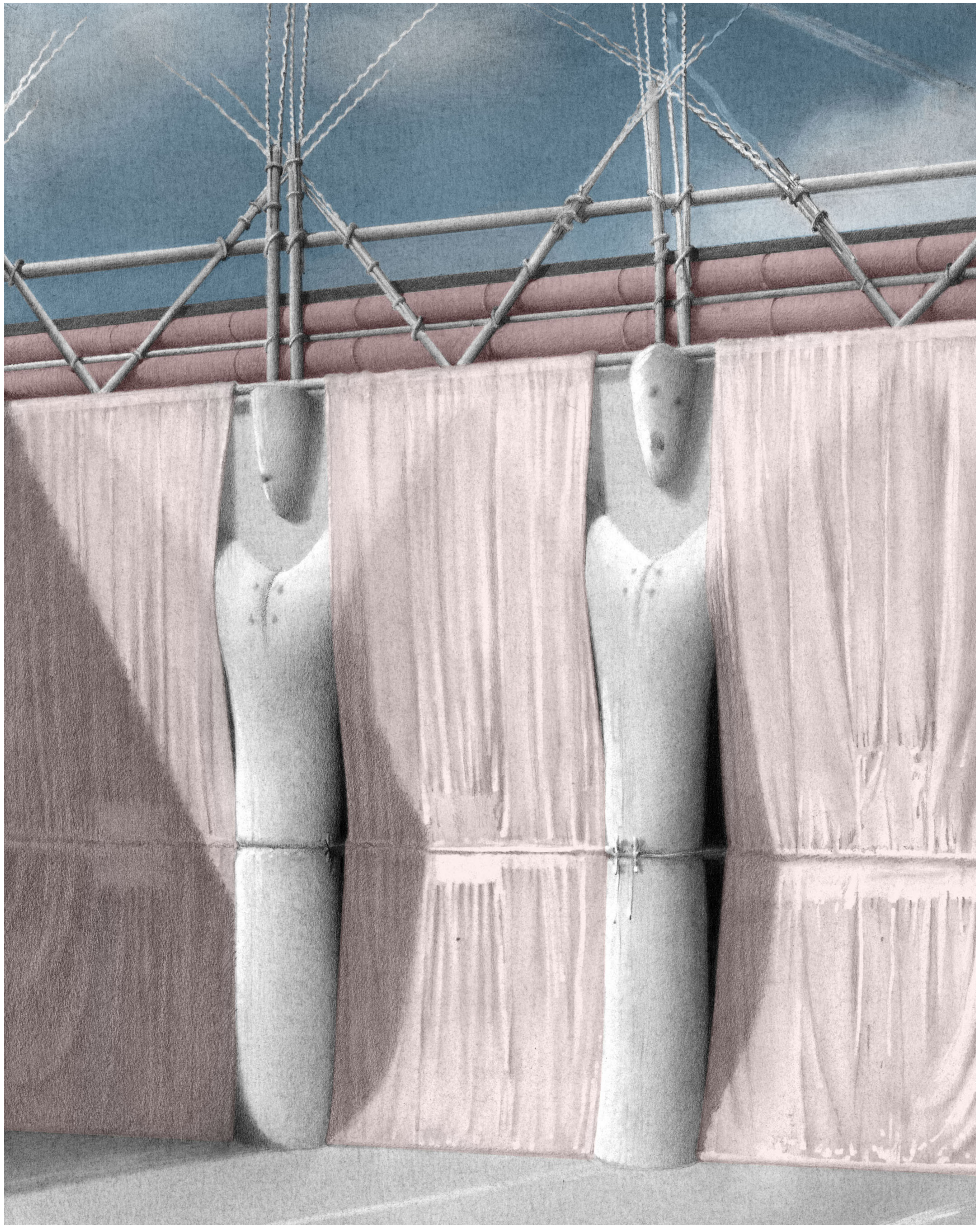

Fig. 8 Drawing by Mark West: Hotel Edward Hopper Courtyard (2011)

dinarily archaic time (as if it has always been this way). What we see is clearly a result as much as it is an object. The verb-like nature of these action-forms gives them a kind of held motion in the held-time of their becoming. It is this, perhaps, that also lends a narrative aspect to these energized, or vitalized, forms -- they are quite literally the end of an action story: something happened and it ended exactly like this. This narrative aspect is both explicit (as 'read" in the forms) and latent -- that is to say, this new language is waiting to be used in an architectural ensemble that can speak of time and occurrence as much as it does of function or spatial composition.

When forms of structural resistance are given, for example in a funicular compression vault made from a hanging fabric sheet, the action of the structure's becoming (i.e. the resistance inside the fabric of the hanging mould) is perpetually re-played in its inversion as a compression structure [see Chapter 3 Structural Intelligence of Flexible Materials]. In this case, the forces in the concrete are not merely sculptural allusions to a remote held-time or state, they are the actual shape of the concrete's resistance to its own self-weight. All this is a direct result of flexibility – the ability to yield spatially to an imposed force – and the resistance generated by flexible materials through their deflection (think of how the increasing resistance of a stretched spring perfectly imatches its increase in length).

What the possibilities are for deploying such an energized "language" of verb-like, time-saturated forms in architecture is a very open question. Alongside this question is the parallel technical question of what new processes are called for once flexibility is allowed into the realm of construction and design. This chapter raises the first question, while this book as a whole, attempts to answer the second.

One intriguing aspect of fabric-formed concrete is the organic production of ornamental details. These are the self-forming bulges, tension arcs, wrinkles, pull-buckles -- the stretch-marks so to speak -- that are offered up by the thin membrane of the mould. The same fabric formwork, held in a slightly different way, will produce slightly different formal or surface "events". A builder's decision about construction details directly determines the ornament-events to come, bringing the hand of the builder back into architecture in a surprising way. Just when the role of the builder's hand in the language of architecture seemed completely erased, reduced to a pre-industrial historical relic, it makes a surprising reappearance precisely because of the flexibility (sensitivity) of the formwork material. Without struggle or nostalgia, an opening for the voice of the builder in architectural ornamentation and form returns. This is something that can be ignored, embraced, or suppressed, but the opportunity is quite real.

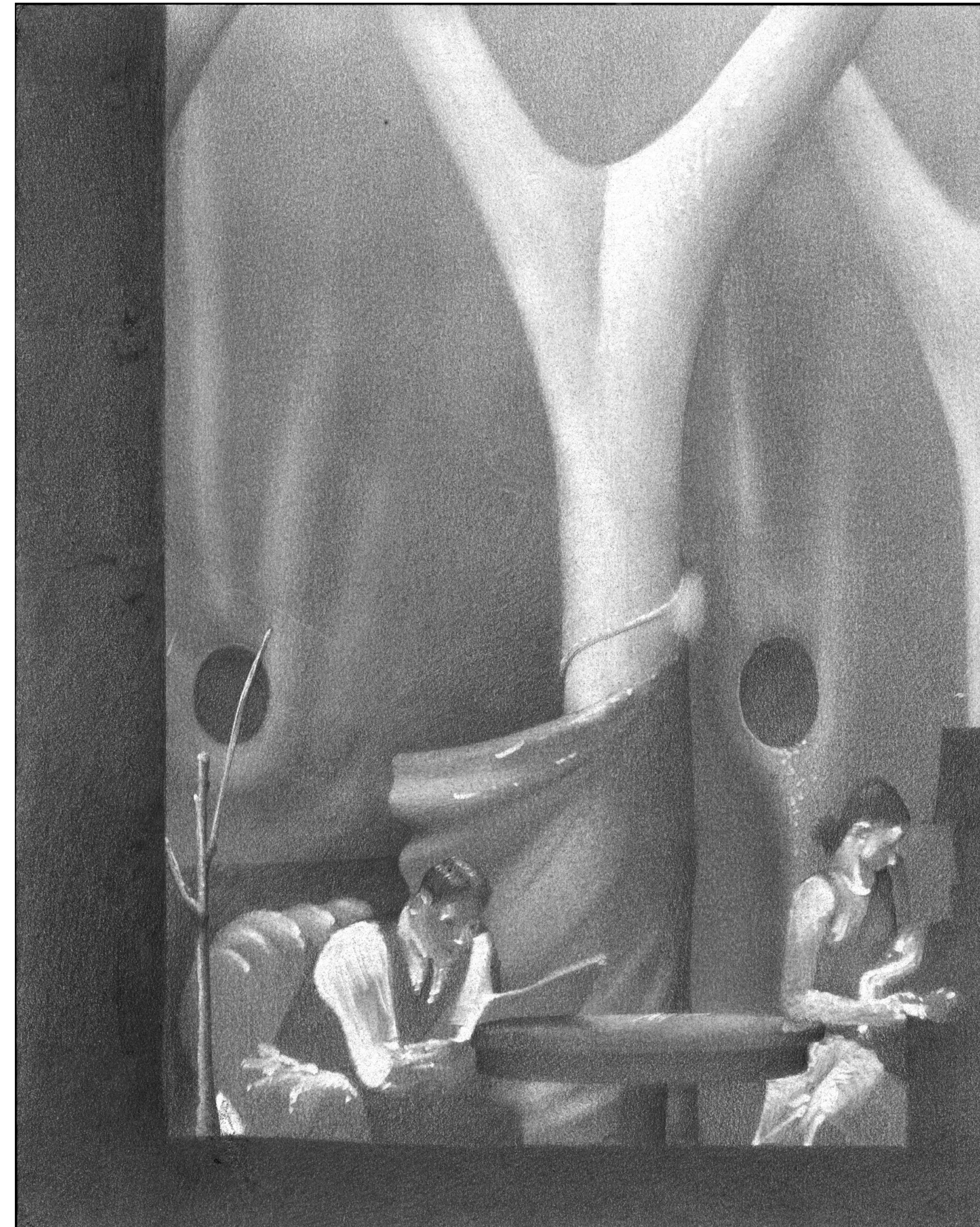

Fig. 9. Drawing by Mark West: Hotel Edward Hopper Lobby (2011)

The unexpected arrival of an organically ornamented architecture also introduces a level of scalar density that has been missing from architectural design since machine modernism eliminated applied ornament. Speaking very broadly, the common traditions of pre-modern, or pre-industrial, architectures were all based, to one degree or another, in the emulation of Nature. This is particularly evident in the realm of ornamentation, which leant architecture a scalar density not unlike that found in the natural world. So for example, as one approaches a Gothic church from a distance, one first sees only its profile, but as one gets closer, other forms within this larger shape begin to appear: the profile of the windows, buttresses, etc. Still closer, smaller figures appear in the carvings and eventually in the mouldings, stone patterns, etc. The unveiling of the next, and the next, and the next figural scale is seamless, right up until the grain of the stone appears to vision. This is much like the scalar density one experiences approaching a tree, or a mountain, or anything else in the more-than-human world. Machine modernism, by its loss of ornament, clears away these many seamless levels of figural scale. Fabric formwork, by its capacity for self-ornamentation, offers an opportunity for the reinvestment of scalar density in our constructions.

This project, taken broadly, was referred to in previous historical periods as the “imitation of nature”. More recently, the term “biomimicry” has been adopted to describe a closely related, and wide-ranging technical/cultural project. The word biomimicry is a bit misleading, as it focuses our attention on biology, while the world itself is made of innumerable non-biological natural structures: the forms/systems produced by erosion; the paths of rivers and their deltas; the self-formation of crystals, cyclones, clouds, sand dunes, are all non-biological emergent structures*.

A fabric-formed casting is, at least in part, an emergent thing, and in this respect can be understood as a non-biological natural event, or structure. A pressurized fabric mould can also bear an uncanny resemblance to biological bodies as well -- animal or vegetable. The biological resemblance is a coincidence, or rather a co-incidence, of physical mechanics. From the hydrostatic pressure inside individual cells to entire bodies inflated by blood pressure, living things are made with membranes under pressure (the wet, flexible, blobs and gobs of Life).

Overlaid on this co-incidence of pressurized membranes, is the world of textile folds and drapings. These textile-derived shapes have a deep human origin; we have covered our hides in textiles, from birth to death, since prehistory (it is a rare moment indeed, in life, when cloth is not somewhere touching your skin).

* Emergence describes a process whereby larger, more complex, patterns or entities (unexpectedly) emerge from simpler interactions between smaller and simpler parts or entities.

Fig 10. The builder’s construction detail swells into ornament.

These co-incidental geometric “voices”, the fluid-filled and the draped, are naturally found in fabric-formed concrete. Taken together, they speak to us effortlessly and at once of biological and non-biological Nature, and of humanity, both naked and clothed. Although thoroughly artificial industrial products, fabric-cast structures are not at all reminiscent of our machines. They remind us, instead, of nothing less than ourselves and of the more-than-human world[3] around us (and in us).

The aesthetic charge tapped by these biomimetic constructions is a deep and abiding source of pleasure and disturbance. What kind of architecture can be made from this? And what might it suggest about how we live in the world? Here is a surprise: the simplest technical change -- of swapping a rigid sheet for a flexible one -- suggests an intellectual and philosophical opening: the arrival, perhaps, of a more yielding and flexible way.

Notes:

1. Vogel, Steven. 1981. Life in Moving Fluids, The Physical Life of Flow. Princeton University Press, Princeton NJ, U.S.A.

2. Franklin, Ursula M. (1990) The Real World of Technology (Revised Edition). CBC Massey Lectures. CBC Enterprises. 1992 publication: House of Anansi Press, Toronto. pp 10-26. Franklin's original 1989 CBC Massey Lecture can be heard at: http://www.cbc.ca/radio/ideas/the-1989-cbc-massey-lectures-the-real-world-of-technology-1.2946845

3. I take the term "more-than-human world" from David Abram. It replaces the word "Nature" which, as a noun, tragically objectifies something that is emphatically not an object. To objectify something that is both saturating and enveloping, and at the same time so essential, is a terrible mistake, habitually made and reinforced by the use of this noun. [Abram, D. (1997) The Spell of The Sensuous. Vintage Books, New York.]