



Bodies in Formation

THE MATERIAL EVOLUTION OF FLEXIBLE FORMWORKS

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ABSTRACT

Borne from the complex negotiation between liquid mass and tensile constraint, flexible formwork castings are resonant with material energy. Hard as stone, yet visually supple and fluid, the pre-cast architectural assemblies produced using flexible formwork techniques suggest integrative design strategies that acknowledge the intricate associations between form, fabrication, and material behavior. This tripartite synthesis between geometry, making, and performance has emerged as one of the central themes of contemporary architecture and engineering. Borrowing ideas of morphology from biology and physics, 20th century architectural innovators such as Antoni Gaudi and Frei Otto built a legacy of material practice that incorporated methods of making with material and geometric logics. The emergent effects (and affects) produced through these highly integrative practices serve as the basis of much of the research and design at Matsys. Building on the flexible formwork research of Miguel Fisac in the 1970s, the P_Wall series by Matsys explores the use of digital tools in the generation and fabrication of these bodies in formation.

1 Diagrams of Force

Biomimicry, the study of natural processes for design inspiration, has been a popular topic in the last decade of contemporary architectural design. However, one of the most overshadowed concepts fundamental to biomimicry is the importance of physics in our understanding of the natural world, both organic and non-organic. That is, underlying every process of formation, from the geologic to the biologic, is a complex network of physical principles that guide the organization of material systems. Although we often hear of the importance of genetic information determining the morphogenesis of life forms, these genetic processes must still play by the rules of the physical world. Put another way, the software (code) still has to run on the hardware (physical reality).

In the early 20th century D'Arcy Thompson, the noted scholar of mathematics and zoology, attempted to communicate this concept in his book *On Growth and Form*. Although a proponent of evolutionary theory, Thompson was uneasy with the "black box" approach that many then (and now) use to explain complex living systems. Thompson felt that although evolution certainly contributed greatly to the morphology of forms, the physical environment was a more fundamental factor (Thompson 2000). Philip Ball, a contemporary science writer summarizes this issue:

D'Arcy Thompson brought to the fore the issue of exactly how such forms come about through the action of physical forces. It just wasn't a question of ensuring that evolutionary biology obeys physical and chemical laws; he felt that these laws play a direct, causative role in determining the shape and form of biology. Thus he insisted that there were many forms in the natural world that one could, and indeed should, explain not by arguing that evolution has shaped the material that way, but as a direct consequence of the conditions of growth or the forces in the environment (Ball 2009), 12).

Thompson developed this thesis through countless examples demonstrating how simple physical principles such as surface tension, gravity, and pressure inform the organization of matter both organic and non-organic (**Figure 1**). He argued, "the form, then, of any portion of matter, whether it be living or dead, and the changes of form which are apparent in its movements and in its growth, may in all cases alike be described as due to the action of force. In short, the form of an object is a diagram of forces" (Thompson 2000, 11). Although some of Thompson's specific theories proved wrong over time, his fundamental concept of the importance of force in the development of form provided the conceptual and technical framework for the great material practitioners of 20th century architecture.

2 Practice, Practice, Practice

The research and work of these material practices runs both in parallel and counter to the mainstream Modern movement. Although working at the same time and with similar materials, these architects, engineers, and fabricators resisted the prevalent Fordist principles in favor of the development of non-standard production techniques that sought a higher integration between form, fabrication, and material performance. Unsatisfied with the Modernist tendencies towards mass-production and abstract formalism, these practitioners experimented rigorously with new material systems and, like Thompson, looked for relationships between form and force that could be used productively in the design and construction of new architectures.

The members of this group of 20th century material practitioners span the geographic and material spectrum. In contrast to the emerging "professional" architect, these practitioners were inveterate experimenters who constantly engaged in the development of new technical, formal, and constructive techniques.

Bridging the divide between architect, engineer, and fabricator due to their intensive research and experimentation, many of these practitioners have become associated with particular material systems and techniques: Gaudi (masonry arches), Otto (pneumatics, cable nets, gridshells), Dieste (brick shells), Fisac (pre-cast concrete beams and skins), Isler and Candela (thin-shell concrete), Torroja and Nervi (folded concrete shells), etc. (**Figure 2**). A central methodology to all of these practices was

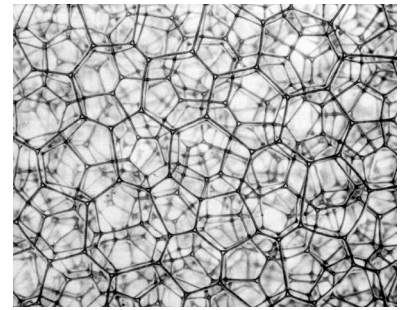


Fig. 1



Fig. 2

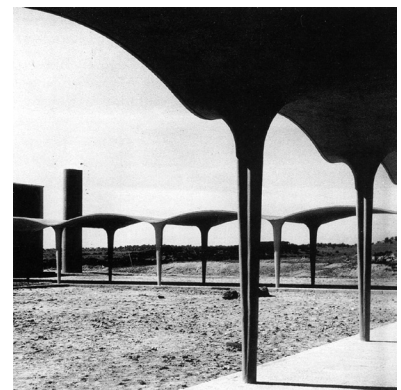


Fig. 3

Figure 1. D'Arcy Thompson based his research on studying the emergence of order in simple, non-organic materials systems such as soap bubbles. He would then extrapolate how the principles governing these systems can be seen in more complex systems such as bees' honeycombs, cells, and tissues. Frei Otto extended this research to the architectural scale at his Institute for Lightweight Structures. (Photo Credit: The Institute for Lightweight Structures)

Figure 2. The Mannheim Multihalle - Mannheim Germany. 1969 - Designed by Carlfried Mutschel and Partners' with Atelier Warmbronn, Frei Otto, Ewald Bubner, and Ove Arup and Partners (Photo by author)

Figure 3. The Teacher Training Center, Madrid, Spain (1954-1957) by Miguel Fisac (Photo Credit: The Miguel Fisac Foundation)

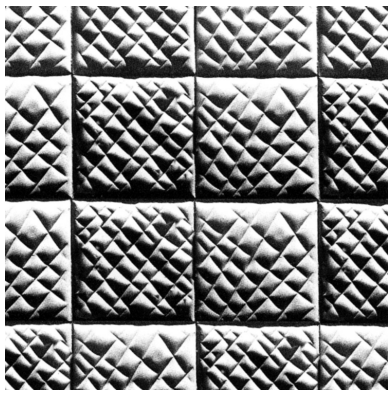


Fig. 4



Fig. 5

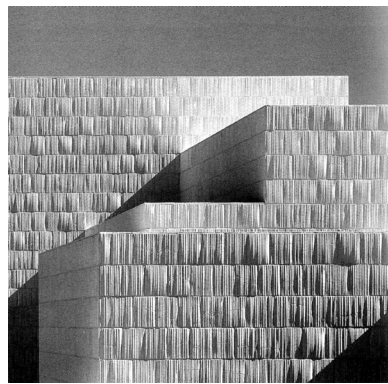


Fig. 6



Fig. 7

the use of form-finding: an experimental process that uses the self-organization of material under force to discover stable forms. The most famous example is Gaudi's use of hanging chains to find optimum curves for his stone and brick arches. However, Frei Otto and others have developed dozens of techniques that allow designers to quickly test systems of great formal and material complexity. Although often these techniques are used to prototype structures at a smaller scale, the fact remains that these forms emerge not from abstract ideas, but from the interplay of "top-down" constraints put in place by the designer and the "bottom-up" negotiation between material and force. That is, there is a synthesis between code (the design parameters) and force in the material system and this synthesis could be called the craft of material practice.

3 Risky Business

Usually far outside the model of the straight-laced professional architect, the members of this group were experimental craftsmen at heart. Walking the line between architect, engineer, and fabricator, they resisted the de-skilling of labor through mass-production strategies and instead developed their work through intensive material and technological experimentation. Like all experimental research, the work was risky and often pushed the limits of material performance and craft. Through intensive experimentation, these designers extracted knowledge about new technologies, materials, and processes and converted this knowledge beyond raw engineering and into works of fine craftsmanship and architecture.

It is this focus on the craft of architecture that most distinguishes these designers from others. Without risk, there is no innovation and these designers pursued a risky practice that relentlessly pushed the material, technological, and formal possibilities of architecture. The designer, thinker, and maker David Pye developed this concept of craft and risk in his seminal book *The Nature and Art of Workmanship*:

If I must ascribe a meaning to the word craftsmanship, I shall say as a first approximation that it means simply workmanship using any kind of technique or apparatus, in which the quality of the result is not predetermined, but depends on the judgment, dexterity and care which the

Figure 4. *Mupag Rehabilitation Center*, (1969-1973) by Miguel Fisac (Photo Credit: The Miguel Fisac Foundation)

Figure 5. *Centro Social de las Hermanas Hospitalarias, Madrid, Spain* (1985-1986) by Miguel Fisac (Photo Credit: The Miguel Fisac Foundation)

Figure 6. *Centro Cultural, Castilblanco de los Arroyos, Sevilla* (2000) by Miguel Fisac. (Photo Credit: The Miguel Fisac Foundation)

Figure 7. *First experiment with flexible formworks, Matsys*

maker exercises as he works. The essential idea is that the quality of the result is continually at risk during the process of making; and so I shall call this kind of workmanship 'The workmanship of risk': an uncouth phrase, but at least descriptive (Pye 1995, 20).

Unlike the dry rationality of the mainstream canon of Modernist work, the material practices of the 20th century crafted an architecture that was unsettling in its vitality. That is, the work was often not "crafted" in the sense that it was clean, resolved, and precise. Rather, the craft of their work lay in its acceptance of risk as an essential byproduct of innovation and life. Columns leaned and branched, walls folded and rolled into roofs, surfaces bore the marks of their making. Traditional notions of Form (or in Sanford Kwinter's term "the merely formulistic" (Kwinter 2004, 96)) were resisted in their work in favor of the emerging ideas of "formation", the inseparability of form, growth, and behavior in all systems (Kwinter 2004).

4 Grotesquely Sublime

The work of the Spanish architect Miguel Fisac exemplifies this trajectory of the 20th century material practice. Working in post-war Spain, Fisac hovered between architect, engineer, and fabricator and focused on the rigorous development of pre-cast concrete structural beams and façade systems. Known mostly for his long-span concrete roofs of the 1950s and 1960s, Fisac's later work in the 1970s and 1980s concentrated on the use of flexible formwork in pre-cast concrete façade modules. Fascinated by concrete's fluid nature, Fisac began using plastic sheeting and metal wire in his formwork. The flexibility of the plastic sheeting, constrained by the metal wire, allowed the finished panels to resonate with concrete's inherent fluid properties.

Fisac first began thinking about these ideas early in his career during the Teacher Training Center (**Figure 3**) project in Madrid in the 1950's:

I then started to think about concrete – which I considered the best building material – and wanted to reflect its fluid condition in some way, set it apart from the remaining materials that arrive solid on the construction site. Stone is carved, Brick is pressed in a mold, but concrete is a material that is poured in a doughy state. With that in mind, I decided to make molds for the canopy with strings and plaster which, after some nine days, we removed leaving those soft contoured shapes. This was the beginning of a research that led me years later to the flexible formwork. (Fernández-Galiano 2003, 40).

It wasn't until the Mupag Rehabilitation Center project (1969-1973) that Fisac began fully exploring the use of flexible formwork (**Figure 4**).

After a decade making exposed concrete, I realized that something was not right, because the concrete took on the texture of the planks, as if it were wood; so I decided to give it an expression of its own, because if it is a material you pour on site when it is still soft, it should have a final appearance resembling that fluidity. While I was building Mupag, I asked the foreman to use a wooden mould and to tie up some wires like those you use to join the reinforcing bars; we put plastic on top of it and set the steel mesh between two concrete lifts of about 3cm; when we removed the formwork it looked great, a smooth and bright surface as if it were still soft. (Fernández-Galiano 2003, 100).

Not only did the use of the plastic sheet produce a quilted surface curvature that resonated with the concrete's fluid fabrication, but also the plastic sheeting formwork itself was inexpensive, easy to construct, and less wasteful than traditional wood formwork. Fisac continued to develop these techniques, however not everyone has appreciated the new forms that were expressed in the facades (**Figures 5, 6**). Kenneth Frampton, commenting on Fisac's entire body of work, barely noted Fisac's flexible formwork projects with the exception to call them "grotesquely textured 'plastic' surfaces" and to indicate they were a distraction from his larger focus on the structural capacity of concrete (Frampton 2003, 9). However, others, such as Mohsen Mostafavi, place Fisac's surface experiments in the context of the informal and its ability to talk to things in formation rather than the cold rationality of idealism. Mostafavi states, "Fisac's explorations with surface, linearity and curvature imbue his work with a sense

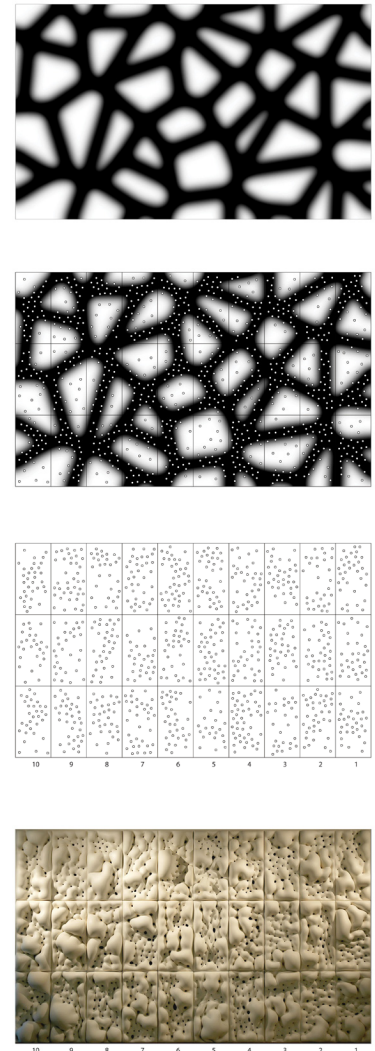


Fig. 8

Figure 8. Process diagram: (from top) An image was made that roughly sketched areas of high or low density of desired constraint - The image is then processed by a script to convert it into the desired number of constraint points located within the required minimum and maximum allowable tolerances - The pattern is then divided into 30 modules measuring 18" x 36" each - Each module is cast from using the specified point pattern and then assembled into the larger wall



Fig. 9



Fig. 10

Figure 9. Fabrication Sequence (from top): base constraint point template, lower support frame, upper fabric frame, cast panel in mold

Figure 10. Cast panel removed from mold

of the monstrous and the imperfect. ...Fisac rejects the ideality of pure and rational order." (Mostafavi 2003, 15). Like Gaudi and Otto, Fisac was not interested in purely rational structuralism, but in the ability of emergent material forces and new construction techniques to literally inform form. These forms, grotesque to some, offer a new approach to the aesthetics of architectural form. Impure, imperfect, and complex, the undulating facades of Fisac's pre-cast facades point to a certain resonance between form, growth, and behavior that is beyond the domain of the designer.

5 Informal Form: P_Wall 2006

Matsys was established in 2004 with the intent of building on the legacy of the material practices of the 20th century through the use of new digital fabrication and generative tools. At the time, I was infatuated with the control these new tools provided in the development of complex systems. However, the more I scripted the more I saw the need to return to first principles and rediscover the material resonances that most inspired me in the work of Gaudi, Otto, and others. More often than not, scripting in design is used to facilitate complex, but completely deterministic processes. After a particularly demanding project that involved a great deal of (deterministic) computational design and fabrication, I sought a research project that would engage my interests in informal forms and emergent processes. Inspired by Fisac's work, I began a three-month initial research phase to simply understand the techniques and processes of flexible formwork.

The first prototype was a complete failure, or so I thought at the time (**Figure 7**). Using a small wooden mold and an elastic fabric skin, my desire was to form a perfect funnel shape by pulling and constraining the fabric at the center. The result was anything but perfect. Covered in wrinkles, cracks, and blemishes, the cast form fell into the "monstrous" category, for which I was initially unprepared. After weeks of work, experimenting with various elastic fabrics, plaster mixes, and increasingly complex molds, I began to realize that I was less interested in achieving a pre-conceived "perfect" formal idea and the initially grotesque became not only acceptable, but also desirable. That is, through the process of inventing more and more complicated ways to attain an ideal form, I realized that the imperfect was more interesting as it emerged on its own through very simple constraints.

This idea was then developed into a proposal for a wall installation at the Banvard Gallery at The Ohio State University. The goal of the project was to use computation to develop a constraint system that would negotiate the complex material forces between the flexible formwork and the fluid plaster slurry. Through months of experimentation, it was determined that the point constraint spacing in the fabric formwork was critical to the formation of surfaces. The spacing of these constraints determined if the cast pieces failed through two ways. As the weight of the plaster slurry expands the elastic fabric, the ratio between the elasticity of the fabric and the weight of the slurry is critical. If the points are placed too close together, the fabric is over constrained and resists sagging. This lack of sufficient sagging results in very thin cross sections of the dried plaster forms which tend to be brittle and weak. On the other hand, if the spacing between points was too large, the fabric could become overloaded with the slurry weight causing the fabric to rip out of the constraint points. This would immediately lead to massive (and explosive) blowouts, ruining the fabric and wasting time and materials.

After a series of empirical tests to determine the appropriate minimum and maximum spacing of constraint points, a computational script was developed that would allow the user to create gradient fields that undulated between high and low densities of constraints (**Figure 8**). This script did not determine the overall form, but rather helped guide the fabrication to a position of acceptable risk. That is, the use of the scripted constraint points allowed me to gain a certain amount of generalized control over the areas of high and low density while still allowing the forms to self-organize at a more local level. I could not predict specific results but I could predict the larger pattern as well as know that the forms were emerging within tolerances that would not completely endanger the casting process.

The script used a very simple, “brute-force” algorithm to place the constraint points. Using a grayscale image as a guide, the script would sample the pixel luminance at random points and translate that value into an acceptable distance to the closest constraint point. The script would then compare this specified test distance with the actual distances between the test point and every other point already determined. If the point was within the acceptable minimum or maximum range, it was added to the list of constraint points. If there was already another point within the test distance, a new random point was tested elsewhere and the process would begin again until a specified total number of constraints were found. Although more sophisticated techniques could have been used (such as spring systems) that could have been faster or more efficient, the basic script performed well enough to locate roughly 1000 constraint points.

The final mold design consisted of three main components (**Figure 9**). The first component held the constraint points (vertical wooden dowels) in place according to the locations determined by the script. The lower wooden support frame was then positioned around and above this constraint template, locking it into place. Finally, an upper wooden frame with a taut elastic fabric was lowered into place on the lower frame. The dowels would push the fabric surface above the top surface of the upper support frame. Any fabric above the surrounding frame would be above the “waterline” of the plaster (like islands in the sea) and would appear as holes in the final cast surface. As the plaster was poured in the fabric expanded under its weight. The more plaster was poured in, the more the fabric would expand until the weight of the plaster reached equilibrium with the elastic tension in the fabric. That is, under a certain threshold based on the strength of the fabric, the surface would expand in proportion with the load of the plaster. Beyond that threshold, the fabric’s elasticity was surpassed and tears would occur in the fabric. Similar to blowing up a balloon or soap bubble, the surface expands until the material (or surface) tension is too great.

Appearing inflated and soft, the hard plaster wall resonated with the energy present in its making (**Figures 10-12**). As adjacent areas of the fabric surface expanded under the weight of the fabric, they slowly began to form creases, wrinkles, and folds in the surface. The complex forces at play informed even the constraint points: although fixed from below, the dowels often began to lean towards the larger loads in the surface, attempting to find equilibrium. Although the wall surface appears complex, the process simply relied on the self-organization of the two materials (plaster and fabric) to find a balance with each other based on a limited amount of design parameters.

6 From Object to Field: P_Wall 2009

In 2009 the San Francisco Museum of Modern Art commissioned a new version of the wall for inclusion in their permanent collection and for exhibition in *Sensate: Bodies and Design*. This new work was dramatically larger than the original wall. At 45 feet long and 12 feet high, the new wall was four times the size of the 2006 wall. This new opportunity allowed me to look back at the work of 2006 and rethink several areas of the design.

The dramatic difference in gallery dimensions greatly informed the design of the new wall. At 45 feet long, the new wall had moved further from the scale of an object on a wall to actually becoming the wall itself. Unlike the 2006 wall, the new wall was sited to take up the entire length and height of the gallery wall, essentially transforming the intentionally nondescript traditional gallery wall into an undulating contemporary body alive with irregularities, informalities, and energy. This scale shift led me to think about the wall more as a field than object. The shifts in constraint density in the original wall were related to the module size; each module contained both high and lower densities. The larger size of the wall at SFMoMA required a shift in scale from the singular module to the aggregation of multiple modules. Using the same constraint point script but with a source image with more gradual shifts between light and dark pixels (which translate into low and high densities of constraints), the overall depth of the wall could be controlled gradually between deep (white) and shallow (black). Arrayed on the wall, the slightly differing average depths of each module created large areas of the wall that either protruded or recessed from the gallery visitor, a series of undulating coves and overhangs (**Figure 13**).



Fig. 11



Fig. 12



Fig. 13

Figure 11. *P_Wall* (2006), Front view

Figure 12. *P_Wall* (2006), Oblique view

Figure 13. *P_Wall* (2006), Detail view



Fig. 15



Fig. 16

Fig. 17

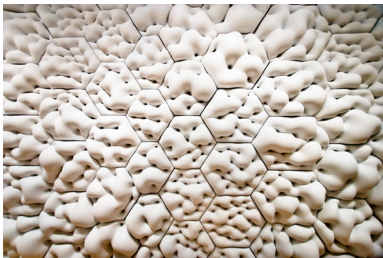


Fig. 18

Figure 14. *P_Wall* (2009), Elevation drawing

Figure 15. *P_Wall* (2006), Oblique view. The horizontal edges of the modules break up the continuity of the surface when viewed from the side

Figure 16. *P_Wall* (2009), Oblique view. The hexagonal pattern of the modules creates a more continuous landscape surface when viewed from the side

Figure 17. *P_Wall* (2009), Front view

Figure 18. *P_Wall* (2009), Front view

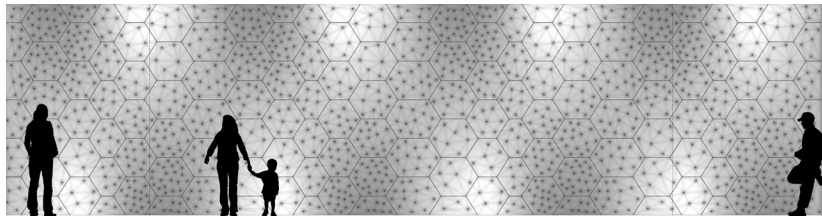


Fig. 14

Although much longer and higher, the gallery space at SFMoMA was much shallower than the Banvard Gallery at The Ohio State University. The SFMoMA gallery was only 8' deep compared to the 30' depth at OSU. Where the main view of the wall at OSU was frontal, it was oblique at SFMoMA. This difference in orientation between the viewer and the wall led to the second major change from the 2006 *P_Wall*. As one moves from the frontal view to the oblique view, the gaps between the modules become less noticeable and the entire wall appears as one seamless landscape. However, in the 2006 wall, the use of the rectangular modules prevented the horizontal seams to disappear in the oblique view (Figure 14). By moving to a hexagonal module, there was always one module interrupting the alignment of the horizontal seams that allowed the individual models to almost disappear in primary direction of view. Furthermore, the use of 4 different hexagonal module sizes (S, M, L, and XL) disrupted the seams in the diagonal sightlines as well as break up the rhythm of the modules in the frontal view (Figures 15-17). Unable to quickly perceive the actual rhythm of the module sizes (a repeating octave from XL to S and back to XL), the viewer focuses on either the larger or smaller spatial effects (Figures 18-20).

On the technical side, the 2009 *P_Wall* made several material, fabrication, and assembly improvements on the 2006 wall design. Although simple and easy to make, the casting plaster used in 2006 was brittle. Not only were the panels heavy, but also they were delicate. By adding a higher density and strength plaster to the normal casting plaster as well as chopped fiberglass strands to the plaster, the plaster modules were much less prone to damage. In addition, perlite aggregate was added to the slurry that allowed the weight of each panel to be cut by almost half. The design of the molds was also improved to make their disassembly, cleaning, and reassembly each day much faster. As the wall was composed of 150 unique modules and 6 modules were cast every day, it was essential that it was fast and relatively easy to transition between separate pours. Finally, the hardware that allowed the modules to be hung on the wall was improved to make the wall's assembly on site more efficient.

7 Entropy and Life: *P_Wall* (Weathering)

In the context of a museum or gallery, the two walls have a different reading than Fisac's flexible formwork projects in the 1970's and 80's. Henry Urbach, curator of the Architecture and Design department at SFMoMA described the project as, "a radical reinvention of the gallery wall. Typically smooth, firm, regular and, by convention, 'neutral', the gallery wall has shed its secondary status to become a protagonist in the space it lines" (Urbach 2009). However, despite their "reinvention" of the traditional gallery wall, the projects still had to adhere to the restriction put on objects of art in museums or galleries. That is, despite the wall's sensuality, the museum viewer was not permitted to touch it and it remained a visual artifact out of the very tactile reach it evoked. This separation between object and user is not something architecture often confronts. Architecture is, almost by definition, a thing in constant physical contact with humans whereas Art often exists at a more formal, and mostly visual, level of interaction.

This issue became even more poignant when I began to reflect on the maintenance of the walls. During fabrication, I was constantly blowing dust, dirt, and even spiders from the crevices and holes of the panels. After installation, the museum preparators were on constant vigil, looking for handprints left by museum visitors snatching a touch when the security guard's back was turned. As a reaction to this situation, I wanted to create an alternate vision of the wall free of protection from both human contact and

natural weathering. The P_Wall (Weathering) project visualizes how I suspect the wall would age over several years outside (**Figure 21**). The P_Wall's surface encourages the deposition of soot, the growth of moss, the nesting of birds. Its surface is not optimized for cleaning and it would slowly accumulate an emergent community of organic and non-organic life. Although some have described this process as entropic, the tendency of a system to lose energy and deteriorate, it could also be described heading in the opposite direction: the wall's properties encourage the emergence of life (or higher levels of organization) across and through its surface.

8 Corporeal Parameters

Like many of the projects designed by the material practitioners of the 20th century, the P_Wall projects exhibit a corporeality that resonates with our own bodies and other organic forms. This resonance is not designed, but emerged from complex material forces wrestling with simple design parameters. It is this last fact that presents the most potential for the future of material practice. As computational design techniques such as scripting and parametric modeling are increasingly used within the architectural design discipline, it is useful to remind ourselves of the fundamental integration between form, growth, and behavior found in natural systems and how we, as designers, can strive to forge parallel relationships between geometry, fabrication, and performance in our synthetic systems. That is, we can leverage the power of parametric design technologies to do more than manage the complexity of differential geometries and rather use them along side in conjunction with simulation software to quickly explore the integral relationships between parameters and physical forces. Matsys is currently working on the next generation of the P_Wall series and is attempting to integrate parametric digital simulations of the physical forces involved in the fabrication process in order to better understand various design scenarios prior to fabrication. Through this process, it may be possible to shift some of the risk involved in fabrication process over to the digital simulation, making the craftsmanship of the parametric model even more essential to the overall success of the project.

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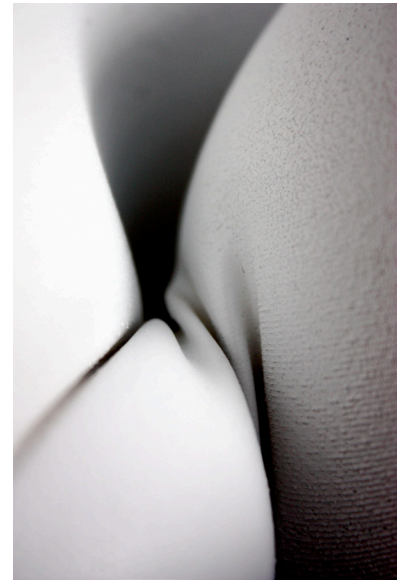


Fig. 19

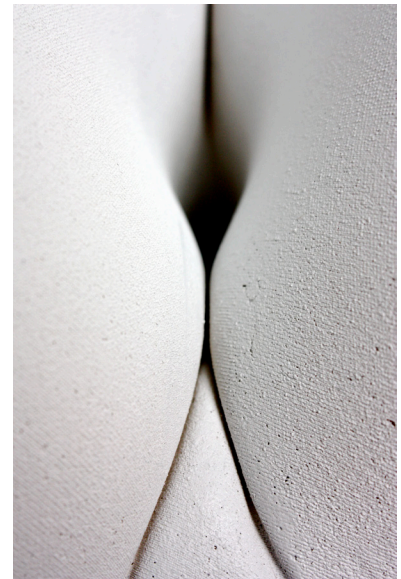


Fig. 20



Fig. 21

Figure 19. *P_Wall* (2009), Detail view

Figure 20. *P_Wall* (2009), Detail view

Figure 21. *P_Wall* (Weathering)