Skin Deep: Making Building Skins Breathe With Smart Thermobimetals

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> "The skin is the interface between an organism and its world...It is probably the most versatile of all organ systems, having mechano-sensory and skeletal functions as well, whose relative importance is different in different groups of animals. These functions can all be incorporated into our technology."
> - Julian Vincent in "Biomimetics of Skins"[1]

Fig. 1: Thermobimetal skin prior to installation.

INTRODUCTION

Despite the fact that thermal bimetals (TBM), or thermobimetals, have been around for decades, renewed interest in its responsive natures have brought it to the forefront of what some call *performative* architecture. A poster child for sustainable design, it has been used since the beginning of the industrial revolution and, more recently and commonly, in thermostats as a measurement and control system and in electrical controls as components in mechatronic systems. With today's digital technology and driving interest in sustainable design, this simple material can transcend its currently limited role as a mechanical device to a dynamic building surface material as well as expand the discourse of performance and bio-inspired systems in architecture. This article will present a case study project of ongoing TBM research that displays the qualities of performance and optimization in the discipline today.

The term *performative* has become the catchall phrase in architecture that reflects the current cultural interest of comprehensiveness and, as a result, is hard to define singularly or precisely. In his article for *Architecture Week*, Michael Crosbie points out that performative architecture is "a fresh new way of looking at architectural design that would be more inclusive than past approaches."[2] A symposium called "Performative Architecture: Instrumentality Plus?" at the University of Pennsylvania in Philadelphia in October 10-11, 2003 and in his correlating book called *Performative Architecture: Beyond Instrumentality*, Branko Kolarevic talked about performance in architecture as a "comprehensive approach to design," placing it above form-making as a design principle.[3] The term *performative* means choreography, or articulation of the performative. It is the shift of interest to things mutable and transient, not static and fixed. In some ways, it is a temporal condition where contexts and fields continually affect the equilibrium of the organism, or architecture. It can be applied to how a people occupy buildings, how parts of buildings go together in the balancing of systems, how generative rules or forms of algorithms influence

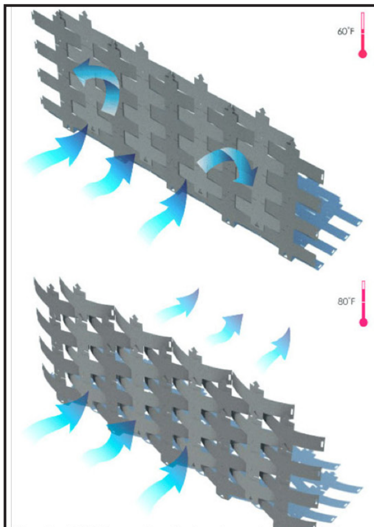

Fig. 2: TBM curving behavior when heated.

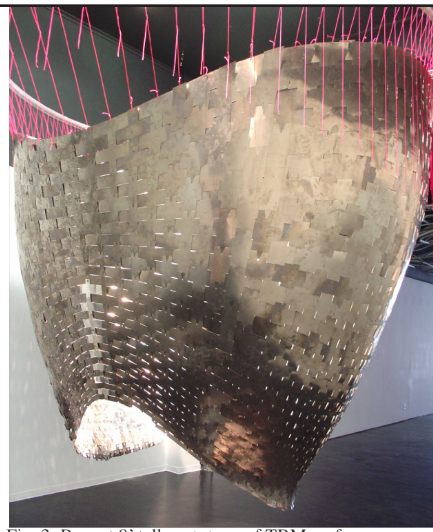
Fig. 3: Recent 8' tall prototype of TBM surface.

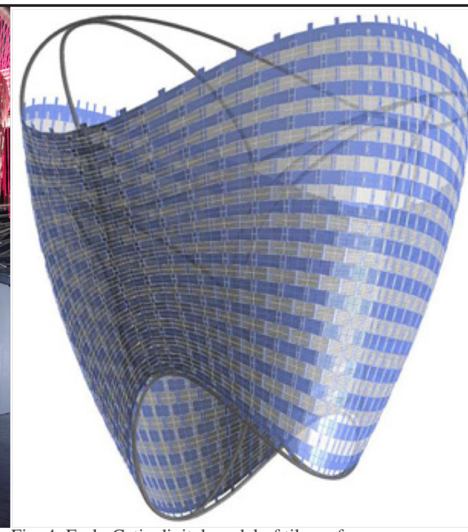
Fig. 4: Early Catia digital model of tile surface.

values and parameters, or how interactive materials and systems respond to outside influences. "In its shift to the performative, architecture has moved its attention from the transcendental and heroic projects of modernism to a more situational and material understanding of architecture as a performative act, a kind of choreography of active systems in the environment."[4] Although Stephen Turk speaks of this performative act in terms of the critical history and design of tables, namely the *Wave Table Project*, this same idea of performance can be applied to many areas in the discipline of architecture.

The *Armoured Corset* project exemplifies the comprehensive nature of current sustainable design in buildings skins as a contemporary case study of performative architecture. Rather than present it as the definitive performative architecture project, this article simply tracks the development of one bio-inspired study that seeks a way to self-ventilate buildings through its skin and, indirectly, to reduce the need for artificial cooling and additional energy/emissions waste. It relies on the movement of a simple smart material called thermobimetal (TBM). As the outside temperature rises, each of the TBM tiles curl, opening up gaps in the surface and allowing air to pass. Like an organic skin, this inorganic matter reacts smartly to temperature change, mimicking the opening and closing of surface pores.

Throughout the development of the project, it is clear that focusing on one aspect of design would be useless, if not impossible. Like many things in nature, the answer lies in the polarity of complexity and simplicity. "Simplicity as an emanation of intelligence finds its expression in the formulation of simplicity as the art of the complex."[5] Form, structure and material have to be developed holistically. When understanding the complex performative principles of these three parts simultaneously, a simple, comprehensive system will be the resultant with less waste and higher performance. Thinking of materials as something independent of form and structure is naive when looking at biological models. "Biological organisms have evolved multiple variations of form that should not be thought of as separate from their structure and materials. Such a distinction is artificial, in view of the complex hierarchies within natural structures and the emergent properties of assemblies. Form, structure and material act upon each other, and this behavior of all three cannot be predicted by analysis of any one of them separately."[6] This is the charge of this case study.

BIOMIMETICS: RESPONSIVE SYSTEMS AND BREATHING THROUGH SKIN

Even during the modern movement, exterior walls in architecture were designed to be static and rigid. Visual access between interior and exterior environments was open with the use of glass and steel, but artificial climate control still determined the impenetrable limits of those glass walls. As times change, more recent public interest in sustainable design, energy conservation and zero-emission building design has infused the industry with renewed impetus to seek alternative solutions. With the emergence of new smart materials, the evolution of digital technologies evolving and availability of mass-customization methods, those same walls can now be designed to be responsive, interactive and even porous, much like human skin. As a "third" skin (the "first" being human skin, the "second" clothing), architecture can, in effect, bring man closer to nature by elevating the sensitivity of the building surfaces. Wedged between two dynamic natures, man and his environment, the building skin can no longer remain static or foreign. "Living organisms rely very little on energy to solve technical problems, and it should be the *main* objective of biomimetics to show how we can similarly rid our technology of the energy requirement, thus giving us a more sustainable future on this planet."[7] When designing building skins, the logic of biomimicry is undeniable.

Skin is the mediator between the body and the environment, between the inside and the outside. It is the visual manifestation of a mass or volume, giving form to a grouping of organic cells. "Life is made possible by membranes. Part of their function is to provide a surface on or from which interactions and reactions can occur and be controlled, and part is to provide selective barriers to keep reactants together and the rest of the world out."[8] In architecture, the basic purpose of this skin or membrane is no different than that of animals or of humans. Not only specializing as a covering, the skin acts a barrier that can selectively modulate the passage of physical, mechanical and chemical stimuli, such as heat, water, force, and other organisms in both directions. The function of each direction can be dramatically different and, inevitably, the requirements in conflict. These conflicts have been largely resolved in nature by evolution, but absent in building technology. Rather than mimic efficient systems in nature, many of our technological developments, including building skins, have become overly complex and heavy with many unnecessary layers like a potato chip bag, as pointed out by the author of *Biomimicry*, Janine Benyus. In her TED Global 2009 talk in Oxford, she makes a colorful metaphor, between two images on her slide--a bag of chips and a beetle:

> This beetle, unlike this chip bag here, this beetle uses one material, chitin. And it finds many, many ways to put many functions into it. It's waterproof. It's strong and resilient. It's breathable. It creates color through structure. Whereas that chip bag has about seven layers to do all of those things. One of our major inventions that we need to be able to do to come even close to what these organisms can do is to find a way to minimize the amount of material, the kind of material we use, and to add design to it.[9]

Like the beetle described by Professor Benyus in her lecture, bullfrogs, earthworms, bats and other animals have permeable skins that allow the exchange of gases. They can virtually breathe oxygen through their skins, but lack the structural integrity present in the beetle's exoskeleton. Inspired by this comprehensive capability of the beetle's shell, the TBM *Armoured Corset* study attempts to make a dynamic porous system that at times allows the passage of air, but contains its own structural stability. Hung in tension and following a catenary curve, the prototype does not require any additional structural element to hold its shape. The mere flattening of the tiles when cold contributes to the tautness of the form while the curvature of each piece when hot allows the overall form to shrink and shrivel. With the help of gravitational forces, the shape of the prototype could adjust to any temperature without the rigid framework of an additional structural form. Like the beetle's shell, the simple surface resolved multiple issues by taking into consideration form, material and structure simultaneously.

By mimicking, or, in some cases, conceptually abstracting systems found in nature, architects, designers and researchers may be able to discover more efficient models of sustainability. Like the beetle in Professor Benyus' lecture, the quest for making a skin that breathes, that is strong and resilient, that is waterproof, is the motivator for this TBM project. Clearly, the surface had to be responsive to allow the passage of air, but restrict the invasion of water. In order to allow the body to breathe, the surface is thermally activated so that areas on the surface, like pores, could open up when the temperature, inside or out, got too warm. These openings would allow hot air to escape and cooler air to enter. Julian Vincent, director of the Centre for Biomimetic and Natural Technologies at the University of Bath, examines the shells of ants, beetles and butterflies and suggests the following: "An external skeleton is a barrier to transmission of sensory information about the external environment. The resolution here is achieved by

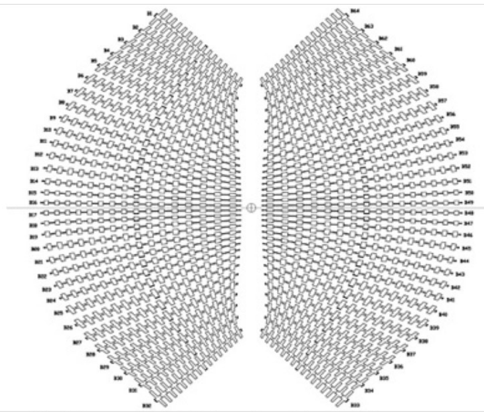

Fig. 5: Laser-cut digital file for early prototype model.

Fig. 6: Process of assembly from top to bottom.

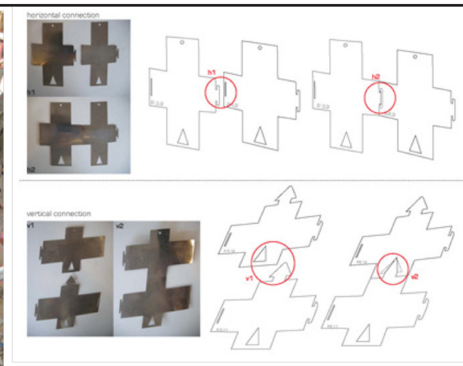

Fig. 7: Sample of tab-slot connections of individual tiles.

having holes through it (an Inventive Principle of "porosity"), although the holes have to be carefully designed if they are to give reliable information, be sensitive and not weaken the material."[10] In some ways, the openings in the TBM surface can also allow the passage of sensorial features such as temperature, scent, and humidity. Further development of the control of the openings will better enhance the development of this project.

DIGITAL TECHNOLOGY: FROM TESSELLATION TO FORM-FINDING

Digital technology, like other representational methods in the past, is moving in the direction of connecting the construction industry closer to that of design. Even though for many years the realization at full-scale of complex computer-generated forms resulted in high costs, faulty construction and compromised results. The improvement in digital software, computer-aided manufacturing techniques and methods of design thinking have reduced the error margin, allowing architects and designers to consider building designs like never before. Advocates of parametric design support the idea that a machine, as in the computer and its software, "could procreate forms that respond to many hereto unmanageable dynamics. Such a colleague would not be an omen to professional retirement but rather a tickler of the architect's imagination, presenting alternatives of form possibly not visualized or not visualizable by the human designer."[11] Projects of unfathomable complexity in shape and form are being generated by use of these advanced softwares. It is rare that an architecture schools would lack the proper hardware, software or fabrication machines, as they attempt to move ahead of the industry in preparation for the next generation of computer-aided design and manufacturing tools.

CATIA (Computer Aided Three-dimensional Interactive Application) was the software by choice in the development of the *Armoured Corset*. This powerful program provided the ability to produce multiple variations on surface patterns when instantiated across a field, where each tile is different in shape and size. Multiple variations of different surface and tiling patterns were produced and studied before finally reaching a model ready for mass customization[12]. "Parametrics allows designers to consider a myriad of detailed versions of a design, with any version poised to be fabricated using CNC technologies. Some designers call it 'versioning'."[13] Until the 'versioning' process was exhausted, it was impossible to settle on a single model to build. Because each model took days to instantiate, unforeseen delay in the development in the project was due to 'versioning'. Newer hardware and more powerful computers would make this process more efficient.

Because the TBM material is manufactured in 12" wide rolls, the only way to produce a continuous surface of this material was to make it out of smaller units, or tiles, something that can easily be done with the computer. In order to reduce the surface to its most efficient form and economical use of material, tessellation of the surface, or a puzzling of tiles in a tight formation, was the only option. This process is common when making a curved surface out of flat pieces, where the expected result is a faceted or crude surface that is not smooth or precise. In the case of the TBM material, the sheet metal continuously curls as the temperature changed, making it impossible to design

Figs. 8, 9, 10: Various views of recent prototype.

the surface to have a continuous curve, or even a faceted one. Dimpling, crimping, shrinking and warping were part of the accepted aesthetic of this surface in order for the ventilation feature to perform properly. A larger aesthetic tolerance for surface change and movement was more appropriate when considering the decretization[14] of the surface, which best integrated the form and material behavior together. In his article "Polymorphism," Achim Menges describes the conceptual idea behind the evolution of such architectural systems as akin to natural morphogenesis, as "hierarchical arrangements of relatively simple material components organized through successive series of propagated and differentiated subassemblies from which the system's performative abilities emerge".[15]

Redundancy for air flow/constriction purposes and for structural stability was critical, which prevented the surface from being reduced to a single layer. The thickness had to be doubled. In addition, restricting the basic tile to a single shape would require simplicity, even though the variability within that simple shape alone was infinite. A basic cross-shape, assembled in a basket weave method, best allowed each tile to curve unimpeded and to expose openings in the surface for air to flow freely. The connection detail of the tiles to each other (see section following on structure) was a clean, but intelligent slot and tab system with no additional materials added. These small connection elements complicated the CATIA file even further since every dimension varied from tile to tile. The CATIA model not only had to instantiate the basic tile shapes visible on the surface, it had to regenerate every dimension of each tile, tab, slot, etc., in a model where every tile was different. Taking hours to generate, the various surface models were well worth it. Without the use of powerful tools like CATIA, this study could not proceed.

Once the tiles were complete in the CATIA model, they were individually unrolled (they are modeled on a curved surface), numbered and nested on sheets for fabrication. The power of the computer was revealed. "Drawings are being augmented--if not entirely replaced--by processes that permit 3-D fabrication of complex forms directly from architect's data."[16] Sent directly to a laser-cutting facility, the fabrication process was quick and affordable. The amount of material used was efficient and waste was minimal (and recyclable). "Working digitally enable[d] movement from one representational format to another--for example, from digital model to vector-line file to manufacturing method. This series of translations allow[ed] for a more fluid fabrication process while significantly reducing the labor associated with taking one type of design medium and turning it into another."[17]

MATERIAL DEVELOPMENT: SMART THERMOBIMETALS

Once merely an element to build shelter, materiality has now become instrumental in the design of building skins. The experimental attitude to materiality has architects considering the use of materials in new and unexpected ways, in unconventional situations and conditions. Many of these newly developed materials are capable of reacting flexibly to the external conditions physically or chemically in response to changes in the temperature, light, electric field or movement. The term Smart Materials has been used to define these materials that have changeable properties and are able to reversibly change their shape or color. These materials are important to architectural skins in that they allow the building surface to be reactive to changes, both inside and out, automatically. "Energy and matter flows can be optimized through the use of smart materials, as the majority of these materials and

Fig. 11: Visible curling of the thermobimetal tiles at 100, 90 and 80 degrees farenheit.

products take up energy and matter indirectly and directly from the environment."[18] This multi-faceted investigation focuses on the development of an old industrial smart material used in a completely innovative application—for architectural skins.

Thermobimetals have been used since the beginning of the industrial revolution. A lamination of two metals together with different thermal expansion coefficients, it simply deforms when heated or cooled. As the temperature rises, one side of the laminated sheet will expand more than the other. The result will be a curved or curled piece of sheet metal. Reacting with outside temperatures, this smart material has the potential to develop self-actuating intake or exhaust for facades. Available in the form of strips, disks or spirals, thermobimetals are commonly used today in thermostats as a measurement and control system and in electrical controls as components in mechatronic systems. So far, however, few applications in architecture have been documented. Automatically opening and closing ventilation flaps have been developed and installed in greenhouses and for use as self-closing fire protection flaps, but nothing has been published on the development of this material for building skins.

Thermobimetals can be a combination of any two compatible sheet metals. The combinations of metals with different expansion coefficients and at various thicknesses can produce a wide range of deflection. TM2, the ideal thermobimetal for this investigation, had the highest amount of deflection in the temperature range of 0-120 degrees Fahrenheit. The low expansion material is called Invar, which is an alloy of 64% iron and 36% nickel with some carbon and chromium. The high expansion material is a nickel manganese alloy composed of 72% manganese, 18% copper and 10% nickel. This bi-metal is also called 36-10 and the ASTM name is TM2. Made corrosion-resistant by plating with chrome and copper, this material is available in sheets or strips in several thicknesses. It can be fabricated into disks, spirals and other shapes. The amount of deflection varies dependent on the size of the sheet, the air temperature, the position of clamping and the thickness of the material. The thickness selected for this study is 0.010" .[19]

Shapes are much easier to represent digitally than material properties, environmental characteristics, and aspects of physics and gravity. "Parametrics can effectively model only *quantitative* characteristics. Parametric models leave aside the qualitative and immeasurable things considered by architects during the design process that make for a complete work of architecture."[20] Digital modeling was not going to solve all the potential problems. Friction, gravitational forces, and material flaws could not be applied to the computer model. The only option for further testing was building prototypes, the old fashioned way, by hand. It was "impossible to achieve a *direct* correlation between digital data and a constructed building. Interpolation, based on an understanding of construction tolerances, material behavior, and the ergonomics of building assembly, will always be required."[21] As it turned out, the weight of the material, combined with friction forces, added a remarkable amount of tensile force, preventing the tiles from curling at the manufactured temperature. Instead of operating at 70˚F, the tiles began to curl at 85˚F. Without the building of the prototype, the true performance of the surface would be unknown and the digital model unreliable. "But, as nothing in "real" reality is truly exact, and as the software is fully exact, we also had to define small gaps to account for "errors" in the production and assembly, such as adding the paint or varnish after machining, which can make the parts sufficiently thicker to introduce inaccuracies into the process."[22]

As more research in material development is being produced and more prototypes built, architects will be able to anticipate potential problems and hazards to incorporating new materials in architecture. Perhaps, the precision of the digital medium will eventually be able to accommodate the inaccuracies of real construction, in both material behavior as well as human error.

CONCLUSION: FURTHER RESEARCH

Making building skins breathe is the motivator for this project. Unabashedly infused with biases towards designing sustainable architecture, this small project is indicative of the current culture's broad mindedness push for responsibility as a standard. It attempts to take a small bite out of the enormously wasteful industry of building construction and limit its focus on finding ways to reduce the need for artificial cooling by making self-ventilating walls. Biology is the source of inspiration, TBM material the enabler and the design team the drivers, but the digital medium undeniably affects the aesthetics of the skin. The final surface pattern, form and fabrication could not have been completed without the reliance on this powerful tool. Regardless, the ends justify the means. The prototype is stunning.

Many areas of this research project can be developed further before it is ready for public consumption and standard architectural application. New weave patterns, material laminate systems and overall shapes/forms can be tested with the aid of various engineers and consultants. Every piece of new data or information leads to alternative connection details, tile shapes and curling patterns. Learning new complex digital software is critical to this process.

Plans to add waterproofing strategies and insulation layers is in the making. In anticipation, preliminary studies on stacking and sloping of the tiles derivative of simple roof tiling, have already begun. With the study of additional tile shapes, transforming the originating form from two- to three-dimensional, the hair/skin of polar bears can be simulated, utilizing the air gap to cool or, in some cases, insulate the interior space. The ideal intention of the wall system design would be to treat air as a critical cooling and insulating material and to eliminate the need for any additional materials. In order to support this goal and for comparison, it is necessary to study alternative insulating and sealing materials to increase usability of the wall at extreme temperatures and to enhance the performance of the thermobimetal surface by increasing the difference in expansion coefficients on either side of the layered tile system—retarding the temperature change on one side of the metal while allowing the other side to heat/cool quickly. The result will be a larger change in dimensional size of the tiles, an advantage for insulation or for ventilation, depending on the design intention.

Partnering with other researchers in the fields of material engineering, chemical engineering, aerodynamics, mechanical engineering or biomimetics (prosthetic research) will also take this research to new levels. Adding zero-energy actuating systems and high tech controls can bring us closer to the realization that architectural skins, like the Lycra skin system on BMW's GINA concept car that deforms to increase performance at different driving speeds, can adapt to changing environmental or programmatic conditions, automatically and smartly. It is not outrageous to imagine that buildings, too, can perform efficiently, effectively and responsively.

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ENDNOTES

1 Juian F.V. Vincent, "Biomimetics of Skins", *Functional Properties of Bio-Inspired Surfaces: Characterization and Technological Application* (London: World Scientific Publishing, 2009), p. 3.
2 Michael J. Crosbie, ArchitectureWeek, Page N3.1, accessed November 19, 2003, http://www.architectureweek.com/2003/1119/news_3-1.html.
3 Michael J. Crosbie wrote about a symposium entitled "*Performative Architecture: Instrumentality Plus?*," University of Pennsylvania, Philadelphia, October 10-11, 2003.
4 Stephen Turk, "Tabling Ecologies and Furnishing

Performances", Tilder and Glostein, eds, *Design Ecologies: Essays on the Nature of Design* (New York, NY: Princeton Architectural Press, 2010), p. 121.

5 Thorsten Klooster, *Smart Surfaces and their Application in Architecture and Design* (Basel, Switzerland: Birkhauser, 2009), p. 64.

6 Michael Weinstock, "Self-Organization and Material Constructions", in *Fabricating Architecture: Selected Readings in Digital Design and Manufacturing* (New York, NY: Princeton Architectural Press, 2010), p. 141.

7 Ibid., p. 5.

8 Ibid., p. 3.

9 Janine Benyus, "Biomimicry in Action", TedGlobal 2009 Lecture, July 2009, Oxford, UK, http://www.ted.com/talks/lang/eng/janine_benyus_biomimicry_in_action.html.

10 Vincent, p. 8.

11 Nicholas Negroponte, *The Architecture Machine* (Cambridge, MA: MIT Press, 1970), cited by, Branko Kolarevic, *Architecture in the Digital Age*, (New York: Taylor & Francis, 2005), p. 21.

12 Mass customization is a hybrid. It proposes new processes to build using automated production, but with the ability to differentiate each artifact from those that are fabricated before and after.

13 Dan Willis and Todd Woodward, "Diminishing Difficulty: Mass Customization and the Digital Production of Architecture", *Fabricating Architecture* (New York, NY: Princeton Architectural Press, 2010), p. 193.

14 Decretization is the digital definition of surface as a coordinated set of discrete parts.

15 Achim Menges, "Polymorphism", *Techniques and Technologies in Morphogenetic Design*, (London, England: John Wiley & Sons, 2006), quoted in Lisa Iwamoto, *Digital Fabrications: Architectural and Material Techniques,* (New York: Princeton Architectural Press, 2009), p. 38.

16 David Celento, "Innovate or Perish: New Technologies and Architecture's Future", in Robert Corser, ed., *Fabricating Architecture: Selected Readings in Digital Design and Manufacturing* (New York, NY: Princeton Architectural Press, 2010), p. 66.

17 Lisa Iwamoto, *Digital Fabrications: Architectural and Material Techniques* (New York, NY: Princeton Architectural Press, 2009).

18 Robert Kronenburg, *Flexible: Architecture that Responds to Change* (London, England: Laurence King Publishing, 2007), p. 216.

19 Engineering Material Solutions, http://www.hoodandco.com/, Attleboro, MA.

20 Willis and Woodward, p. 188.

21 Ibid., p. 183.

22 Bernard Cache, "Towards a Fully Associative Architecture," in *Architecture in the Digital Age*, p. 144, as quoted in Willis and Woodward, "Diminishing Difficulty," p. 184.