Designing and Manufacturing the material in the Digital Age

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Abstract

The paper discusses the newfound capacity to digitally design and manufacture materials, their properties and effects. It surveys recent experimental efforts in material production and presents student projects aimed at designing and manufacturing surface effects using increasingly accessible digital fabrication technologies.

Introduction

New forms of architectural expression, new means of conceptual and material production, and advances in material science have led to a renewed interest among architects in materials, their properties and their capacity to produce desired surface and spatial effects. New materials, for example, are offering unparalleled thinness, dynamically changing properties, functionally gradient composition, and a rich repertoire of new surface effects.

Of particular interest are composite materials whose composition can be engineered precisely to meet specific performance criteria. These layered materials, commonly used in automotive, aerospace, shipbuilding and other industries, are experimented with for possible architectural applications, as they offer the unprecedented capability to design material properties and effects by digitally controlling the production of the material itself. Among composites, the polymer composite materials, or simply plastics, are being considered anew by some architects, primarily because of their high formability, relatively low cost, minimum maintenance, and a relatively high strength-to-weight ratio.

As a result of these developments, the building skins are beginning to have not only expressive formal qualities, but also new tectonic composition; they are acquiring a new complexity as digital and mechanical networks become embedded into their (composite) layers. The first experimental building skins with dynamic behavior are also beginning to emerge, challenging the prevalent assumptions about the tectonics and the permanence of material conditions in
buildings. In addition, the first projects that exploit the newfound capacity to digitally design and manufacture highly crafted surface effects are being built, featuring, for example, series of panels with repetitive, yet unique decorative relief or cutout patterns, stratified surface configurations, etc., hinting at the emergence of new “ornamentalism” in contemporary architecture.

**Structural Skins**

In some of the recently completed projects, such as the Media Center at the Lords Cricket Grounds in London, UK, designed by Future Systems, the curvaceous building envelope was being explored for its potential to re-unify the skin and the structure, in opposition to the binary logics of the Modernist tectonic thinking. The structure becomes embedded or subsumed into the skin, as in semi-monocoque and monocoque structures, in which the skin absorbs all or most of the stresses.

These developments in cladding are driven in part by technologies and concepts from other industries, such as the “stressed skins” long used in automotive, aerospace, and shipbuilding production. In airplanes, for example, the cage-like structure called airframe, made from aluminum alloys, is covered by aluminum panels to form a semi-monocoque envelope in which the structure and skin are separate tectonic elements but act in unison to absorb stresses.

The principal idea in monocoque structures is to conflate the structure and the skin into one element, thus creating self-supporting forms that require no armature. That, in turn, prompted a search for “new” materials in architecture, such as high-temperature foams, rubbers, plastics and composites, which were rarely used in the building industry until recently. These new materials, however, require curvilinear geometries to enable the monocoque skins to perform structurally. Thus, an interesting reciprocal relationship is established between the new geometries and new materialities: new geometries opened up a quest for new materials and vice versa.

**Liquid Materiality**

Commonly available materials, such as fiberglass, polymers and foams, offer several advantages over materials that are typically used in building industry. They are lightweight, have high strength, and can be easily shaped into various forms. For example, the physical characteristics of fiberglass make it particularly suitable for the fabrication of complex forms that have emerged over the past decade in contemporary architecture. It is cast in liquid state, so it can conform to a mold of any shape and produce a surface of exceptional smoothness – a liquid, fluid materiality that produces liquid, fluid spatiality.

The liquid materials that have aroused particular interest among architects today are composites whose composition can be precisely designed and manufactured to meet specific performance criteria (figure 1), and whose properties can vary across the section to achieve, for example, a different structural capacity in the relationship to local stress conditions and surface requirements.

Composites are actually solid materials created, as their name suggests, by combining two or more different constituent material components, often with very different properties. The result is a new material that offers a marked qualitative improvement in performance, with properties that are superior to those of the original components.

A composite material is produced by combining two principal components – the reinforcement and the matrix, to which other filler materials and additives could be added. The matrix is, typically, a metallic, ceramic or polymer material, into which multiple layers of reinforcement fibers, made from glass, carbon, polyethylene or some other material, are embedded. Lightweight fillers are often used to add volume to the composites with minimal weight gain, while various chemical additives are typically used to attain a desired color or to improve fire or thermal performance.
The actual components made from composite materials are usually formed over CNC-milled moulds, as in boatbuilding to produce boat hulls or large interior components, or in closed moulds by injecting the matrix material under pressure or by partial vacuum, as is done in the automotive industry for the production of smaller-scale components. In the building industry, composite panels are produced either through continuous lamination or by using the resin transfer molding.

**Functional Integration and Variance**

The fusion of the structure and the skin in monocoque and semi-monocoque envelopes is changing the design of structures and cladding. The new thin, layered building envelopes are made of panels that provide not only enclosure and structural support, but also contain other systems typically placed into ceilings or floors.

It is the functionally gradient polymer composite materials that offer the promise of enclosures in which structure, glazing, and mechanical and electrical systems are synthesized into a single material entity. The SmartWrap project (figure 2) by KieranTimberlake (http://www.kierantimberlake.com/SmartWrap/index.htm), a Philadelphia-based design firm, explores what its authors call the “building envelope of the future” – an ultra-thin composite material that integrates separate functional components of a conventional wall into a single element. The polymer based material consists of a substrate (the same material used in plastic soda bottles) and printed and laminated layers that are roll-coated into a single film, which, besides providing shelter and interior climate control, can change color and appearance and provide light and power. Light and heating technology are simply printed on.

By optimizing material variables in composites for local performance criteria, entirely new material and tectonic possibilities open up in architecture. For example, transparency can be modulated in a single surface, and structural performance can be modulated by varying the quantity and pattern of reinforcement fibers (Bettum 2002), etc. Structural polyurethane foam, for example, produced by reaction injection molding (RIM), enables a wide range of density and rigidity to be designed and engineered into a wall panel.
Two liquids are injected into the mold, reacting upon entry and forming the polyurethane with the desired properties. (A polyol and an isocyanate mixture are used in a product called Baydur, manufactured by Bayer, Germany.) A solid surface with foam core is easily achieved using this process.

Several experimental techniques based on sprayed concrete were introduced to manufacture large-scale building components directly from digital data. A fairly recent additive technology called contour crafting, invented and patented by Behrokh Khoshnevis from the University of Southern California, allows fairly quick layered fabrication of highly finished buildings (Khoshnevis 1998). Contour crafting is a hybrid automated fabrication method that combines extrusion for forming the surface shell of an object and a filling process based on pouring or injection to build the object’s core. Computer-controlled trowels, the flat blades used for centuries to shape fluid materials such as clay or plaster, are used to shape the outside edges (rims) of each cross-section on a given layer, which are then filled with concrete or some other filler material. Since material deposition is computer-controlled, accurate amounts of different materials can be added precisely in desired locations, and other elements, such as various sensors, floor and wall heaters, can be built into the structure in a fully automated fashion.

By producing materials in a digitally-controlled layer-by-layer fashion, as in additive fabrication, it is possible to embed various functional components, thus making them an integral part of a single, complex composite material. This, in turn, implies designing with heterogeneous and non-isotropic materials, i.e. with materials that do not have the uniform composition and properties. In other words, variation is present not only in spatial layouts and surface articulation, but also in material composition. Such variability presents a radical departure from the present normative practice, but it also offers design challenges and opportunities that are presently vigorously pursued by the “digital design avant-garde.”

**Adaptive Skins**

Other possibilities are opened up by materials that change their properties dynamically in direct response to external and internal stimuli, such as light, heat and mechanical stresses. Designers are experimenting with materials such as “plastics that undergo molecular restructuring with stress,” “smart glass that responds to light and weather conditions,” “anti-bacterial woven-glass-fiber wall covering” and “pultruded fiberglass-reinforced polymer structural components.”

Michael Silver’s Liquid Crystal Glass House (figure 3, http://www.vrglass.net), designed for a site in Malibu, California, has a responsive, constantly adapting electronic building skin made, as the name suggests, from the panels of liquid crystal glass, which consists of a layer of liquid crystals sandwiched between two sheets of glass, enabling a digitally-controlled shift from transparency to opacity and vice versa. The interconnected liquid crystal glass panels are computationally controlled and can create different patterns of transparency and opacity, producing an envelope that is infinitely variable and visually unpredictable.

New skins can change not only their transparency and color, but also their shape in response to various environmental influences, as the Aegis Hypo-surface project by Mark Goulthorpe shows. It features a faceted metallic surface, actually a deformable, flexible rubber membrane covered with tens of thousands of triangular metal shingles, which can change its shape in response to electronic stimuli resulting from movement and changes in sound and light levels in its environment, or through parametrically-generated patterns. It is driven by an underlying mechanical apparatus that consists of several thousand pistons, which are controlled digitally, providing a real-time response.

Goulthorpe’s Aegis Hyposurface dynamic skin, a highly complex, electro-mechanical hybrid structure, whose sensors, pneumatic actuators, and computational and control systems provide it with what could be called smart behavior, points to a material future in which a building envelope could become a fairly thin, single intelligent composite material with a neural system fully integrated into its layers, a possibility already demonstrated in the SmartWrap project by Kieran Timberlake.

Intricate, smart, adaptive and other terms are used today to describe a higher form of composite materials that have sensors, actuators, and computa-
tional and control firmware built into their layers. According to another definition, intelligent materials are those materials that possess adaptive capabilities to external stimuli through built-in intelligence. This intelligence of the material can be programmed through its composition, its microstructure, or by conditioning to adapt in a certain manner to different levels of stimuli. The intelligence of the material can be limited to sensing or actuation only. For example, a sensory material is capable of determining particular material states or characteristics and sending an appropriate signal; an adaptive material is capable of altering its properties, such as volume, opacity, color, resistance, etc. in response to external stimuli. An active material, however, contains both sensors and actuators, with a feedback loop between the two, and is capable of complex behavior – it can not only sense a new condition, but can also respond to it.

Crafting the Surface

The digitally-driven production processes introduce a different logic of seriality in architecture, one that is based on local variation and differentiation in series. In buildings, individual components could be customized using digital technologies of fabrication to allow for optimal variance in response to differing local conditions in buildings, such as uniquely shaped and sized structural components that address different structural loads in the most optimal way, variable window shapes and sizes that correspond to differences in orientation and available views, etc.

For Bernard Cache, objects are no longer designed but calculated, allowing the design of complex, variable shapes and laying “the foundation for a nonstandard mode of production” (Cache 1995). His objectiles are non-standard objects, mainly furniture and paneling, which are procedurally calculated in modeling software and are industrially produced with numerically-controlled machines. For Cache, it is the modification of parameters of design, often random, that allows the manufacture of different objects in the same series, thus making the mass-customization, i.e. the industrial production of unique objects, possible.

In many of his objectile designs, Cache exploits the decorative effect of the tooling path patterns that can be produced in the material by CNC milling machines
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Different series of panels are produced with repetitive, yet unique decorative relief or cutout patterns, striated surface configurations, etc. These material effects are directly related to how the surfaces are crafted in CNC milling. In CAD/CAM post-processing software, a NURBS surface is interpreted and converted into precise tool paths that produce a corrugated pattern in the material. In a typical CNC production, however, the desired outcome is a smooth, featureless surface which is produced by using milling bits with a fairly small radius and tool paths that are closely spaced. By designing the tool paths carefully, richly patterned surfaces can be produced by carefully choreographing the milling sequence. Slight deviations in tool paths can produce surprisingly interesting effects in the material. The same two-dimensional (XY) tooling pattern, if varied in Z direction for each manufactured instance, can produce a series of repetitive, yet differentiated objects. This and similar carefully crafted tool path strategies have been used by Cache very effectively in a number of his objectiles. Similar patterning techniques were used by Greg Lynn for interior wall panels (figure 5), as an “ornament [that] accentuates the formal qualities of the surface” (Leach et al.).

There are now several commercially available product lines that feature paneling systems with repetitive and differing patterning produced in automatic fashion through CNC milling (figure 6). Cache’s Objectile website, for example, permits customers to design their own patterns by varying the parameter values that control the geometry of patterning. The parameter values are then automatically transmitted to the fabricator and translated into CNC machine code for manufacturing.

Another technique that Cache used was to work with flat-sheet laminated materials into which a certain topographic design is inscribed through milling, producing a contouring effect that reveals the laminate in subtle ways (figure 7). In some projects, he used a parametrically controlled and varied spline curve to inscribe it into series of solid panels or to carve out complex shapes that can produce intricate screens with repetitive, yet differing patterns. Belzberg Architects produced fabric-like effect in wood panels for the Patina Restaurant in Los Angeles by laminating standard wood planks and then CNC milling the desired “topography” in the resulting laminate.

Figure 6. CNC-carved panels that are commercially produced in variable series (Esthetic Panels, courtesy of Marotte, France).

Figure 7. Cache’s laminated objectiles.

Figure 8. CNC-cut halftone patterns in copper cladding for De Young Museum in San Francisco by Herzog & de Meuron.
Herzog & de Meuron have designed a copper screen for the new De Young Museum in San Francisco by digitally cutting out a halftone pattern, which creates a giant image when seen from distance, and dimpling the panels to create an intricate effect (figure 8). Using an in-house developed digital technique, the halftone image pattern is automatically translated into CNC cutting tool paths, making the production of the different screen panels entirely feasible, both technologically and financially.

A number of metal sheet manufacturers now offer corrugated, flat and curved aluminum (and other metal) profiles that can be perforated, drilled, milled, and anodized in a variety of ways. Virtually any corrugation profile may be produced including variations in frequency and amplitude of corrugation. As De Young Museum project by Herzog & de Meuron demonstrates, perforations of any pattern can be produced by CNC cutting. Typical applications include interior paneling, furniture, shelving systems, and partitions.

In addition to careful crafting of the CNC tool paths (whether for milling or cutting) for each object produced in series, particular attention must be given to the overall field effect that is created by assembling the seemingly similar objects into a larger composition. This field effect can be described as a secondary pattern that emerges through the composition of primary, object-related tool path patterns. In many projects, however, it is the field effect that is the primary surface effect that is sought out.

Manufacturing the Surface Effects

The different techniques of manufacturing surface effects using digital fabrication technologies were explored in a four week long term project within an elective course on digital fabrication at the University of Pennsylvania. Students had to define a parametric production process in which slight variations of parameter values, either incremental and/or random, would produce a series of differentiated yet repetitive objects. The produced objects were then organized in a grid-like configuration to produce a carefully choreographed field effect. By working in groups of two, students developed a geometric and manufacturing logic for producing different instances of a parametrically defined variable paneling system, in which the size
is fixed, but the relief or cutout patterns can vary. The emphasis was placed on the calculation of curved and variable shapes and their production using CNC tool paths precisely crafted in software and executed on a CNC milling machine.

One of the teams wrote a parametric script in Maya animation software in which surfaces undergo a series of transformations from flat plane to undulating topography. By assigning different values to the variables in the script, a series of different panel “topographies” can be created (figure 9). The panels were CNC-milled in wood to exploit the contouring effect afforded by the wood grain. In addition, various field effects can be produced by arranging the panels in different ways (figure 10).

Another team used the Artificial Intelligence (AI) plug-in for Maya to create particle emitters that were applied to the movement of the AI induced spheres. Particle trajectories were traced as spline curves and translated into CNC tool paths, with different bit sizes assigned to different colors (figure 11). Different “zero” points were established during the milling of the series, resulting in different patterns by varying the extent to which the milling bits were to enter into the material (figure 12).

The parametric setups can be surprisingly simple and can produce intricate results. By changing the radii of concatenated, mutually tangent arches in a wave-like configuration, a surprisingly interesting pattern can emerge when produced in the material (figure 13). That particular technique required precise adjustments of tool paths to account for the selected size (i.e. diameter) of the milling bit (figure 14).

A fingerprint pattern superposed in different ways over a selected topography (figure 15) was another design and production technique that was carefully developed, tested and calibrated for the right bit size, tool path steps and depth of milling. In another project, various radial geometries were superposed and shifted to produce another fairly simple variable patterning design (figure 16).
Conclusion
The developing materials and the digital technologies of production, surveyed in this paper, may substantially redefine the relationship between architecture and its material reality. Current research efforts, such as the SmartWrap project described earlier, point to a material future of architecture in which conventional building cladding will be compressed into a plastic sheet that is ultralight, fairly inexpensive, and that can be erected in a fraction of time compared to present practice. This is a dramatic technological development with a potential to transform all aspects of building design and production, with broad social, economic and cultural implications.

Closer to present, we already have the technological capacity to design and manufacture materials that do not have uniform composition, properties, and appearance. With digital parametric design and production, variation becomes possible not only in spatial layouts and component dimensions, but also in material composition and surface articulation, offering unprecedented freedoms from standardization that defined design and production for much of the twentieth century. Buildings will become not only intelligent and alive by responding dynamically to the internal logics and external influences of the environment, but also highly crafted in their appearance.

References


Design and Manufacturing was selected by blind-peer review for inclusion in the Research Presentations Section of the AIA-ACADIA Conference. It appears in this volume to correct its unintended exclusion from the Proceedings volume.
Figure 15. Patterning based on fingerprints draped over the designed topography.

Figure 16. Patterning based on superposed radial geometries.