Digital Tectonics:  
structural patterning of surface morphology

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Abstract
The computer in architectural design has shifted from its role as a merely representational device to that of a tool for instrumentalized simulation and fabrication. The desire to make buildings look like a rendering, or to produce photo-realistic images and walkthroughs has given way to an opening of the potentials of software to assist the designer with managing complex geometries, parametric organizational diagrams, structural analysis, and integrated building systems.

Simulation has become the means by which virtual space becomes more than just a mirror of reality. It becomes the space within which different potential realities can be tested and evaluated before they are materially implemented. In architecture, information derived from material constraints to site conditions can be constantly fed into the computer models to provide an accurate update, which in turn introduces feedback into the overall design, and change can then be registered in the detail. Therefore, simulation becomes a way of assessing the developing performance of the project and the limits of a spatial system through a direct engagement with the underlying
geometry of the design. In this regard, virtual space becomes fluid and dialogical within the design process. There is no longer a reliance upon incremental scalar increase in order to arrive at greater degrees of fabrication accuracy, but rather, a more dynamic and non-linear cause and effect methodology is now possible. It is through this lens that several different methodologies for implementing and evaluating simulation for the purpose of generating a digital tectonic are being presented through this research. While there is no definitive conclusion for an idealized tectonic or fabrication technique, themes start to emerge and overlap dealing with structure, material, pattern, geometry, and parametric control.

One of the objectives of our research is not to rely on the digital model for the final assessment of aesthetic and tectonic fitness of a design. Rather, it is understood that a degree of manual intervention and improvisation that goes along with architectural production in general is required and desired. Authorship of the design is not exclusively parametric but is understood as performative. Performance criteria, while quantifiable within the digital environment, can still be assessed and responded to in a qualifiable sense in the physical environment. The degree to which this interplay between analysis and interpretation increases or decreases with the scale and complexity of the project is constantly re-evaluated.

With the projects executed at the Tulane School of Architecture (Fig. 1), the fence surfaces retain a manageable complexity and anthropomorphic scale of assembly that enables the students to combine computer-assisted fabrication with constructed approximations that were determined in the field in a more ad-hoc fashion. The limits and potentials of the available materials intervene in the process and contribute to the character of the results. This is possible in a project of this nature, and it is our desire to retain this spirit of improvisation and material feedback, as we delve into more complex projections and explorations. The use of digital modeling techniques thus articulates this complexity so that links can be made between patterns, force, form, and ambient site constraints. This is done in order to describe a flexible
Woven Patterns

The interest in patterns is primary in that they are essential to the structural framework of natural and artificial systems. We can no longer reduce things to singular elements but instead see that everything is made up of a series of interrelated parts that perform together as a collective whole with a shared intelligence. From the cellular structure of living organisms to the networks that make up our connected society, patterns are always the agents that allow the total assembly to evolve and adapt to a changing environment.

We are exploring the difference within geometrical variation between patterns and the ability for them to become inherently structural through overlap and weaving. The grid is the obvious point of departure. It is the essential basis for the expansion of systems in metric space (Fig. 2). A grid that becomes stretched in one direction becomes a lattice, which begins to embrace diagonal geometries (Fig. 3). By adding curvature to the elements, the total arrangement takes on a clear directionality (Fig. 4). The notion of weaving in this manner evokes the instrumentality of the loom that organizes material along the lines of a grid of warp and weft fibers that bind to form textiles. This basic configuration leaves open the possibility of varying the material of the fibers in any direction to produce an infinite degree of figured motifs.

Of particular interest is the relationship between an underlying framework that consolidates the reductive alignment of pure repetition and a more variegated system on the surface. It implies a different way of looking at the architectural relationship between structure and ornament that we can exploit and modify. With a fairly regular substrate as the underlying armature, other more complex, or even random, patterns can be expressed on the surface. Nested radial arrays (Fig. 5) and even arabesque (Fig. 6) patterns can be applied. Hexagonal lattices are extremely efficient in their incorporation of rectangular and triangular geometric properties (Fig. 7). These designs share the woven qualities of simpler grid or lattice systems, but potentially perform more integrally and offer other opportunities for aesthetic exploration.
While this description seems to reinforce Gottfried Semper’s categorical delineation of framework and enclosing membrane we would assert that a subtle but important redirection has occurred. While Semper defines the enclosing membrane as woven in nature and subservient to the articulation of the frame, the woven patterns of digital tectonics potentially allow for a synthesis between the framework and the membrane resulting in a structural and ornamental co-dependence (Semper 1989, p. 101-104).

Traditionally, structural patterns are defined in metric space and require prescribed repetition and a higher degree of redundancy for structural integrity. Pursuing a reconfiguration of component relationships, and thus formal outcome, forces are dissipated through a system in multiple directions and transferred to the substructures. Structurally patterned modularity is deployed at different scales, in various configurations, with adjustable degrees of density and directionality. Specifically, it is now possible to see the joint, or point of intersection as a more dynamic aspect in the tectonic definition. No longer bound by identical repetition, the joint must now be capable of providing iterative difference if it is to respond to the surface transformations resulting from the structural and ornamental interplay.

**Structural Morphologies**

Gothic cathedrals are clear expressions of the use of a branching structural logic as the primary driving force behind the creation and disruption of the classical tradition of architectural construction. The lines of force are directly registered on the surface. The relationship between structure and ornament is effectively blurred. The stereotomic construction techniques of the time were pushed to their limit. Each modular masonry unit is unique and seams are absorbed into the overall fluidity of the ascending spatial system (Fig. 8 & 9).

More recent architects such as Antonio Gaudi (Fig. 10 & 11) and Frei Otto (Fig. 12-14) carried this sensibility into their practices, not as a Neo-Gothic stylization, but as a fundamental departure from the branch of modernism that inherited its basic structural underpinnings from classical architecture. They were engaged with a mode of experimentation with physical models that directly measured the effects of
forces on networks and membranes, inverted them into compression, and translated them into radically different material constructions. This difference was due to available construction technologies, cultural influence, and structural capabilities due to scale. From similar points of departure, they reached vastly different results. It is this interest in the translation of similar analytical models into different material manifestations that is critical to the thoughtful interpretation of digital diagrams and models into constructed realities.

Specifically, our focus is on fabrication techniques that develop out of digital modeling processes, and how they might begin to be analogous to these precedents that are incredibly inventive form-finding, structural articulation, and construction strategies. The evolution and definition of the surface geometry is subject to programmatic and spatial criteria. For the scope of this exploration, the concentration is on the rendering of the surface through the modularity of patterns and developing structural systems that are locally responsive to global differentiation.

Surface Evolution and Definition

The computer has made parametric surface modeling using topological geometry second nature. The straight and flat geometries of Euclidean space are challenged when deformation is understood as degrees of difference rather than formal aberrations. This by no means should privilege a particular geometry a priori as superior on aesthetic grounds, but selection should be based upon programmatic and organizational responses to a given situation. Thus, idealized geometries perpetuated and universally accepted by modernism can now be challenged as no longer possessing the cultural, spatial, or structural relevance. Specifically, structural systems are now able to be generated and analyzed based on greatest efficiencies in material, form, and economy. As demonstrated in Otto's work, structural systems are not necessarily dependant on Euclidean geometry but can now be evaluated based on efficiency. Parametrically modeled structural systems that achieve increased levels of complexity are therefore not exclusively selected because of form but rather performance.
The use of the computer is directed toward the design of spatial systems through simulation. This pushes the applications beyond representation and moves toward the way that Gaudi and Otto used analog techniques of deriving physical form and construction systems from physical models. Our goal is to move from digital models to physical constructions through interpretation, translation, and fabrication. The computer affords a more efficient management of complex geometry. It has the unique ability to separate different levels of articulation into layers that can be analyzed individually or in combination with others to develop relationships between overall form, and its effects on localized components. The advancement of software to implement associative geometry in models allows the designer to constantly register the effects of small-scale incremental change that follows parametric adjustment of the entire system.

One example of how software can demonstrate the parametric adjustment is thermo-graphic curvature analysis (Fig. 15 & 16). This is particularly useful for measuring the degree of curvature in a surface. This is quantitatively beneficial for determining the accumulation of potential bending stress and material strain that develop. This information is useful in determining ways to absorb and transfer forces through material responsiveness and component design. It can be used to measure the qualitative effects of the interplay between force and form as well. Forces such as gravity, live and dead loads, wind, etc., are augmented by discrete forces that are the influence of dynamic programmatic and contextual influences that shape the spatial system. A structure that is optimized for essential equilibrium to extrinsic forces is further deformed by information and influence intrinsic to the specificity of use, scale and responsive design intentions.

It is possible to see the foundations of such investigations in the IBM Building in Pittsburgh, Pennsylvania, by Curtis and Davis Architects, 1965 (Fig. 17). While this project does not focus on curvature aspects of thermal mapping, it is the first known example of an exterior vertical space frame that uses steel of three different strength levels in its structure. Because of these two factors, the building’s exterior shell and structural system are required to only touch the ground at 8 points. Thus, the variation of the steel
psi, color-coded in red, blue, and yellow (Fig. 18), demonstrates a potential genesis not just for structural efficiency but for structural heterogeneity as a means of producing structural innovation. While the vertical space frame is articulated with the same repeated profile in cross-section the variation in the steel properties begins to provide an overall freedom in the frames articulation, specifically in how and where it touches the ground. Thus, two readings could emerge out of this precedent if applied to the thermal curvature analysis. The first would be material properties being analyzed and selected to preserve uniformity in the surface components while allowing greater degrees of curvature and loading as a result the strength of the cross-section. Secondly, the cross-section could be maximized or minimized to act as a legend for the latent structural forces resulting from the curvature of the surface, thus making analysis and structural performance criteria legible.

Space frames offer the potential to articulate structural response in the depth of the surface. The magnification of the fibrous cellular structure of bone tissue reveals nature’s brilliance in the proliferation of repetitive members that manage differential loading conditions through their relentless redundancy and randomness (Fig. 19 - 22). We also know from Otto’s description of diatoms in the article Animate Structures and Technical Structures, that lessons of the maximized material-to-strength ratio are clearly evident in a multitude of organic and biological examples (Roland 1965, p. 114). It is of particular interest to understand the resulting surface curvature in these examples to be the product of the section profile of the diatom. In this regard, it is possible to conceptualize the fabrication of highly specialized space frame modules that, similar to the diatom, result in a complex surface geometry.

Ultimately, our investigations aspire to deploy patterns spatially for the purpose of exploiting variable thickness and surface articulation to escape superfluous redundancy and also to develop a closer relationship between structural configuration and localized variation in modes of occupation and program.
**Geometric Mapping**

The link between our interest in repetitive patterns and surface morphology is synthesized with geometric projection and mapping. This powerful digital technique enables us to integrate geometry defined in metric space and directly coordinate it with its correlating location in topological space subject to a defined surface configuration. The link between structural modularity and spatial fluidity is manifest as a continuously differentiated field or array of interrelated elements that carry the arrangement of the 2D patterns into 3D space. The geometry is rendered as individual strands that are woven into an integral system. The examples shown display two different approaches to the technique: projection (Fig. 23) and mapping (Fig. 24).

Projection lays the pattern directly on the surface in plan. The pattern elongates in areas where deformation and curvature are the most extreme. This corresponds to the zones of bending stress intensity in the thermo-graphic analysis. It is analogous to draping a fabric with flexible fibers over a virtual landscape. This is most applicable to situations where the architectural response is to create a field of structure that has similar properties in multiple directions with a loose boundary condition—a mat of structure as opposed to something directional.

The mapping system takes a pattern defined in metric space within a boundary that corresponds to the proportions of a surface that has more specific edge constraints (Fig. 24). The XY configuration of the curves is mapped onto the UV coordinates of the surface. This corresponding relationship retains the integrity of the woven pattern, which is desirable for directional, vector-defined surfaces. A process evolving from path to surface and pattern to structure, merges the specificity of the form of the surface with the repetition of the array (Fig. 25).

The Beijing Olympic Stadium, recently proposed by Herzog & de Meuron Architects, exhibits the potential to deploy this process of projection on a colossal scale. From an initial glance at the renderings, the design appears to employ a random assortment of geometric trajectories that coalesce into a nest of structural tracery, which simultaneously forms the
envelope and superstructure for the massive sports arena. While the conceptual process began in this manner, it became clear through the collaboration with Ovre Arup’s structural engineers that this primary reading could be coupled and maintained with the addition of a simple radial geometry, which could counteract the rotational forces generated by the inherent torsion of the stadium’s overall form. The following series (Fig. 26) roughly describes the process of geometric mapping and surface articulation that produced the final version. The overlay of the two systems (radial and random) produces an interesting hybridized condition whereby the random array dominates the general visual reading of the arrangement of the structural system (Fig. 27 & 28). Actually it is the radial pattern that manages the primary distribution of forces while the random pattern operates as a meshwork that reinforces that whole through redundancy.

This process has influenced our own work, as displayed in this competition proposal for the roof of a covered swimming pool. The digital design process blurred the distinction between the forming of the landscape that contained the water and the layers that eventually became the roof structure. The global surface geometry of the site was influenced by a series of parameters that produced differentiation across the diverse zones of activity and orientation in relation to an adjacent waterfront. A localized system of repetition was projected into a series of layers that were delaminated from the surface of the landscape to produce unobstructed interior occupation (Fig. 29). The resulting geometry was developed into a space frame of variegated thickness that began to fold down vertically to connect to the ground below. The free span capabilities of the structure were augmented by the complexities produced by the interplay between the landscape, water surfaces, and play of light through the structure (Fig. 30). The project was modeled with a 3D print to visualize some of these effects (Fig. 31 & 32).

**Structural Articulation**

The challenge of integrating these powerful tools into architectural production is ultimately evaluated in how they can be built. The scale at which the processes are applied determines how they are structurally articulated. The size of the pattern/module, thickness
of members, types of joints, and inherent structural stability of the results would differ as one moved from the small scale to the extremely large scale. The concentration then focuses on using the computer to derive the geometry of the members and joints and how that information can be transferred to templates for digital fabrication. The definition of the structural member's profiles generated along vectorial paths is accomplished with the software's ability to derive a surface along a curve based upon a given cross-section (Fig. 33). For example, a member derived from a square section can be separated into individual surfaces and each can be unrolled into a flat template. This has profound implications for enabling the fabrication of forms that have complex 3D geometries from 2D profiles that are cut and assembled to assume the desired shape when their edges are joined. The degree to which the member is segmented must be subject to the scale of the construction and the extents of available cutting equipment and materials (Fig. 34).

For the scope of this investigation, a critical fabrication decision regarding the relationship between the geometry of the components and the points of connection has interesting conceptual implications on how the geometry derived in the computer is interpreted in construction. If, as Kenneth Frampton has pointed out, “Semper's privileging of the joint as the primordial tectonic element, as the fundamental nexus around which building comes into being, that is to say, comes to be articulated as a presence in itself,” then the points of connection would fundamentally articulate the difference in the digitally developed tectonic (Frampton 2002, p. 95).

Joints and fastening systems have always been and still are the locations where success or failure in a structural system is first manifested. In the desire to maintain fluidity and continuity in the architecture, the seamlessness between of the members and the joints is imperative. In the interest of managing complexity, the location of where differentiation in the system is articulated is critical. One approach would be to maintain the curvature in the members and flatten the joints so that the members engage the component at the same angle on incidence (Fig. 35). The other method would use straight members and triangulate the joints to allow multidirectional axes.
of convergence (Fig. 36). The curved member/flat joint method is most effective when spline geometry is sought in the resulting surface. These assemblies would require a high degree of customization in the fabrication of the members as described in Figure 34. Other systems such as cladding would have to assume a high degree of flexibility, but innovations in stress skin using pneumatic diaphragms offer new structural potentials on the level of enclosure systems. The straight member/triangulated joint alternative requires the NURBS surface to be converted with polygons into a faceted surface. This relegates the absorption of difference into the transformation of the component. Consequently the mass-customization possibilities of digitally assisted fabrication are centered on a more manageable scale, but the tessellation of the final surface will not ultimately be fluid.

While exhibiting fabrication complexity and formal specificity in both examples, it is possible to investigate some of these issues in very simple manual connection methods. Frampton has articulated the notion of binding as possessing a cultural and spiritual significance in his introduction to early Japanese societies in *Studies in Tectonic Culture*; however, the use of a binding connection in both the Japan Pavilion in Hannover, Germany by Shigeru Ban and Frei Otto (Fig. 37), and the Tulane School of Architecture fence (Fig. 38), demonstrate a different reading of this tectonic expression (Frampton 1995, p. 14-15). This reading, rather than cultural evocation, potentially hybridizes the performative configuration of Figures 35 and 36 with a very primitive fastening technique. The use of a bound connecting joint between members permits the fluid lattice curvature to be the result of inherent material properties of the component section modulus, as is demonstrated with the paper tubes or the PVC pipe, similarly to Figure 35. The binding of the crossing point with string or chord subsequently allows a high degree of customization and specificity in the configuration of the joint itself, similar to the way Figure 36 functions.

While the binding is a shared joint technique, it is also possible to refer back to the previous set of derivations demonstrated in Figures 23 and 24. Ban’s work with paper lattice structure, like much of Otto’s work, focuses on self-supporting grid shells constrained by a
rigid boundary ring. It is the patterned characteristic of the lattice, combined with component elasticity, that produces the surface deformation. General uniformity in pattern is required so that structural forces can be distributed throughout the surface. While these forces are not necessarily uniform, the interconnectedness of the non-hierarchical system is what provides structural rigidity. In this manner the mapping technique of pattern, as illustrated in Figure 23, is consistent with this particular reading. Conversely, the Tulane School of Architecture fence surface articulation is dependent upon a primary set of structural members. While these primary members are actually the resultant of figured L-shaped members of steel tube it is the subsequent curvature of secondary PVC pipe that provides the formal deviation in the surface (Fig. 39).

A more concise expression of a formed structural framework is the *Playa Urbana | Urban Beach* installation at PS1 by Bill Massie (Fig. 40). In this instance Massie uses CAD/CAM technology to fabricate digitally-generated profiles that serve as the primary armature supporting the enclosing surface. In this regard the steel armatures serve as ribs that collectively define the surface deviations. Much like Figure 25, it is possible to see the combined resultant of this hierarchical method for generating a fluid surface.

**Fabrication Strategies**

Manual construction techniques interfaced with CAD/CAM techniques, as demonstrated in the fence structures (Fig. 1) or in the *Playa Urbana* structure (Fig. 40), represent a critical juncture in the digital tectonics exploration. In both cases the 3D geometry is the result of combining specific material properties with 2D CAD/CAM design explorations. This manifestation seems particularly central to the research in that the combination of techniques provides innovative results that would not be possible if each technique was pursued independent of the other. Although inherent material properties have traditionally played a critical role in geometric expression, conventional methods of organization are no longer capable of handling the formal complexity resulting from the digital exploration. Conversely, CAD/CAM technologies, especially CNC milling machines, are reliant upon subtractive surface generation that results in surface puzzles. While the complexity is now achieved, there is a degree of ambivalence towards the material properties playing a role in the parametric design result.

Skeletal structures in particular provide a congruent synthesis of the digital and physical context (Fig. 41). These investigations, serving as a precursor to the larger fence explorations in Figure 1, are not to be understood as models but rather as full scale examinations of the bending and anchoring characteristics of wood when part of a larger lattice structure. Again, these examples are similar to the Gaudi and Otto models, in that the rendering of the surface is through the modularity of patterns and increment. However, it is the exploration of the program (e.g. circulation corridors) that required the point of origin to be digitally initiated so volumetric strategies could be generated in the 3D digital space, organized and then translated into XYZ serial profiles for the purpose of fabrication.

Much of the discussion surrounding emergent digital fabrication has focused on a continued hierarchical relationship between CAD/CAM technologies and materiality. In the early stages of development, and almost as a territorialized defense, the digitized models were developed and then filtered through output devices that anticipated the most neutral of material properties. New technologies assumed new forms, and thus attempted to assume new materialities. For early pioneers of digital form, this proved to be too large a step, and the subsequent outcome was little more than representational mimicry. The seeds, however, were planted for the following generation of designers who have started to return to a more rigorous and integrated understanding of the various industries of architectural production. This shift signals a distribution of responsibility and knowledge as well as a more pliant methodology between CAD/CAM technologies and material properties.

One such example of this might be the work that is being produced by Peter Testa and the Emergent Design Group. Specifically, the work being developed on the Carbon Tower prototype (Fig. 36) seems to be of particular importance. Devyn Weiser’s background in apparel design and weaving technologies, combined with Peter Testa’s architectural expertise vis-a-vis his working relationship with Alvaro Siza, both combined...
with the collaborative efforts of Over Arup partners, has rendered a speculative and innovative result that illustrates a more hybridized approach to digital fabrication technologies. Testa describes the working methodology for the Carbon Tower: “each element has the ability to act, to change the overall constellation of networks. Contrary to conventional architectural systems, the ability to act is not inherent in the element, but is a consequence of its position in the network. The network is not seen as a structure so much as a set of transformations and exchanges between elements and systems” (Testa 2004, p. 56). By allowing the working methodology to exist as a dynamic network of exchange, a multi-valent outcome emerges.

Material properties, production cost, structural innovation, sustainability, and formal intention all collectively negotiate a non-linear approach to digital fabrication. To that end, the definition of digital fabrication technologies shifts away from a specific focus and instead opens the exploration up to a multifarious design methodology.

**Conclusion**

It is our goal to use the variegated modes of physical fabrication and computer modeling techniques presented here to continue testing the evolution of surface morphology. This continued reliance on *cause and effect* methodology is privileged and productive because this combination facilitates the articulation of structural patterning and geometric mapping. These aspects of the research serve as good examples by which a digitally informed fabrication can start to develop. Ultimately, it is the power of the computer to simulate and iteratively reconfigure through parametric control that brings in increasingly innovative means by which digital space and analog space start to inform each other and produce a resulting new tectonic.
References

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Figure 1. Construction Fence prototypes – Tulane School of Architecture. Photo by author.
Figure 2. Standard Grid. Illustration by author.
Figure 3. Stretched Grid. Ibid.
Figure 4. Curved/Stretched Grid. Ibid.
Figure 5. Nested Radial Array. Illustration by author.
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Figure 7. Hexagonal Lattice. Ibid.
Figure 8. Gothic Cathedral interior.
Figure 10. Cantenary string model for the Sagrada Familia Church, Barcelona - Antonio Gaudi. Photos from Lightweight Construction in Architecture and Nature-Natural Structures Exhibition and Publication.
Figure 11. Attic vaulting in La Pedrera Apartment Building, Barcelona - Antonio Gaudi. Ibid.
Figures 12, 13 & 14. Controlled force tests conducted on lattice structures – Frei Otto. Photo from Institut für leichte Flächentragwerk, Stuttgart.
Figure 17. IBM Building, Curtis and Davis Architects, 1965. Photo from Southwestern Architectural Archive, Tulane University Libraries, Curtis and Davis Collection.

Figure 18. Color codification illustrating vertical space frame steel psi. Ibid.

Figure 19. Pelvic bone structure of a bird. Photo by Andreas Feininger.

Figure 20. Cholla cactus. Ibid.

Figure 21. Doubly-curved shell lattice. Photo by Frei Otto.

Figure 22. Fibrous lattice structure. Photo by Frei Otto.

Figure 23. Differentiated field – projection. Illustration by author.

Figure 24. Structural array – mapping. Ibid.

Figure 25. Process illustrating the evolution from path to surface, and pattern to structure. Ibid.

Figure 26. Structural analysis of shell comprised of radial and random patterns. Ibid.

Figure 27 & 28. The Beijing Olympic Stadium proposal by Herzog & de Meuron Architects. Image from Herzog + de Meuron Architects.

Figure 29. Differentiated field with a projected pattern. Illustration by author.

Figure 30. Space frame roof structure. Ibid.

Figures 31 & 32. 3D print of the roof study Ibid.

Figure 33. Vector profile for structure. Ibid.

Figure 34. Isolated surfaces of a single structural member.

Figure 35. Flattened structural joint. Ibid.

Figure 36. Triangulated structural joint. Ibid.

Figure 37. Japan Pavilion in Hannover, Germany by Shigeru Ban and Frei Otto. Photo by Hiroyuki Hirai.

Figure 38. Detail of seat joint – Tulane School of Architecture. Photo by author.

Figure 39. Assembly sequence and component index. Tulane School of Architecture. Illustration by author.

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