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Digital Tectonics as a Morphogenetic Process

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Abstract

Tectonics is a seminal concept that defines the nature of the relationship between architecture and its structural properties. The changing definition of the symbiotic relationship between structural engineering and architectural design may be considered one of the formative influences on the conceptual evolution of tectonics in different historical periods. Recent developments in the field of morphogenesis, digital media, theories techniques and methods of digital design have contributed a new models of integration between structure, material and form in digital tectonics.

The objective of this paper is to propose and define *tectonics as a model of morphogenetic process*. The paper identifies and presents the manner in which theory and emerging concepts of morphogenesis as well as *digital models of design* are contributing to this new model. The paper first analyzes the historical evolution of tectonics as a concept and characterizes the emergence of theoretical framework reflected in concepts and terms related to morphogenesis.

Keywords: tectonics; digital design; form finding; emergence; self organization; digital morphogenesis; digital tectonics; architectural structural design;

1. Introduction

Tectonics is a seminal concept that defines the nature of the relationship between architecture and its structural properties. The changing definition of the symbiotic relationship between structural engineering and architectural design may be considered one of the formative influences on the evolution of this concept in different historical periods. Throughout history, tectonic discourse has continually redefined the elements of the tectonic relationship as well as their prioritizing. In the past decade the theories and methods of digital design have contributed new meaning to the term tectonics which reflects changing perspectives of the relationship between architecture and structural engineering and, in turn, profoundly influencing the digital design methods that support design practices.

The objective of this paper is to analyze the evolution of the concept and to characterize the emergence of a contemporary theoretical framework for its usage as reflected in the terms, *digital tectonics* and *digital morphogenesis*. We demonstrate how this concept reflects a new level of integration between structure, material and form that has emerged as a result of digital media and technologies upon methods of design. The paper identifies the manner in which *digital models of design materialization* are contributing to new content of tectonic as well as to new definitions of *digital tectonics as morphogenetic process*. It is the ability to integrate form material and structural simulations that supports morphogenetic design process.

2. Tectonics: the Ontology of Structure in Architecture

The paper first presents and analyses various historical positions and precedents of the concept of tectonics. In this analysis we explicate the changing content of tectonic interpretations of the relationship of architecture, structure and construction. The evolution of tectonic theory since the 19^{th} Century and through the modern period has exhibited a dynamics that radically transformed the character of tectonic theories as well as the nature of structural thinking. The nature of the ordering of structure, material and construction evolved from aesthetic and cultural interpretations of expressive qualities to physical relationships of structure, material and form. It is the simulation of dynamic models of these relationships that underlies the contemporary emergence of digital theories of tectonics. Thus we can say that the digital is completing a transformation of the ontology of structure from a logic of order to dynamic models of material and structure. It is this major conceptual transformation of the relationship of material and structure to space and form that supports digital morphogenesis.

2.1. Vernacular Architecture and Tectonic Expression

The origins of tectonic expression appear to reside in vernacular building traditions which strive to achieve an integration of the material, the structural and the constructional. It is the frequently minimal and direct expression of this content that is characteristic of the vernacular and a source of tectonic expression. Vernacular architecture represents the essence of material technologies in being a pure and, generally, a direct expression of the structural and constructional potential of the material. Vernacular construction encompasses both the structural system and the constructional process which are closely integrated. Building proceeds as materialization essentially without design, it being frequently the fruit of craft traditions. It is craft that elevates material to the technologies of material systems. In the vernacular these material technologies become building systems. Such systems more or less directly express both the material origins and the constructional process. In its direct expression of material, structure and construction, the vernacular is a "poetics", or essential and sublime expression, of the constructional potential of the material. In the traditional Japanese house, for example, "construction is an essential component of space as well as the major source of form" (Engel, 1961).

2.3. Tectonics as a Form of Cultural Interpretation

The term tectonics was derived from the Greek word, *tekton*, meaning carpenter or builder. The *tekton* later became the archi-tecton, or master builder (Frampton, 1995). Historic usage adapted the term to transform the concept from that of builder to that of an *integrated building system*, particularly in 19th C. interpretations of Classical architecture. Gottfried Semper (1803-1879) referred to tectonics as a phenomenon that defined the use of different materials in architecture as a cultural phenomenon thus introducing an early cultural interpretation of tectonics. In the modernist period tectonics, structure and construction have been interpreted as providing to architecture an *expression of the play of forces*.

2.3. Modernist Theories of Tectonics: Modern Form as Structural Form

The interpretation of tectonics as the active role of structural form in the development of architectural form (Frampton, 1995) transcended the purely visual or experiential content of tectonics. This position considered tectonics in architecture as *an essential element in the development of modern architectural form*. Frampton thus emphasized a more proactive role for structure and construction in achieving a potential "*poetics of construction*" as a foundation of modern architecture. This expanded interpretation also brings it closer to a contemporary definition in which digital fabrication and construction (in addition to structure) are viewed as an integral part of digital tectonics. For Frampton the prominence of the integration of structural and constructional contributions with architectural form, space and order is one of the unique contributions of modern architecture. He argued that modern architecture is more about structure and construction than space and abstract form. In this he departs from the position of other major theorist/historians of modern architecture such as Pevsner and Giedeon. However, his theory maintains an equilibrium between structure/construction and space/form.

2.4. Tectonics as Form-Finding Process: a Tectonics of Material Structure

Contemporary theories begin to shift the structure and form interpretations of Frampton and others to a more complex interpretation of the relationship between structure and materials in processes of form generation. Here, of continuing relevance to contemporary thinking is Gottfried Semper's, *Four Elements of Architecture,* of 1851. The distinctions between, and relationships of, mass building, skeletal structure, and enclosing woven membranes furnished an enduring typology in which tectonics was the form and expression of the integration of these elemental material sub-systems. These generic modes of building technology had an affinity for modern componentized systems as well as a contemporary (digital) interest in the phenomenon of the potential of woven materials.

Gaudi's (1852-1926) use of physical modeling is considered to have introduced the *method of form-finding experimentation* as a process of design. In other words, he may be considered to have contributed to the emergence of a *method of structural tectonics*. In such a method, *the modeling enabled the study of the structural influence of changing tectonic relationships*. Frei Otto expanded these classical relationships between form and structure in his pioneering experimental and research-oriented approach to material form-finding in structural design. These historical case studies of *tectonic modeling bear relevance as precedents to current simulation modeling approaches in digital tectonics*. Thus the transition of the modeling of material behavior from analogue to digital models is a fountainhead of contemporary digital modeling and its integration in design.

2.5. Early Attempts to Define Digital Tectonics

With the rapid development of digital media and computational techniques in architecture first attempts to define digital tectonics have appeared in recent years. Different theoretical approaches to concepts such as *form-making* (Beesley, 2000) or *form-construction* (Liu and Lim, 2006) have recently been proposed as characterizing digital tectonics. Both of these approaches address the growing importance of the relationship between digital methods of design and their implications for making, or computationally controlled constructional processes. Leach, Turnbull and Williams, 2004 propose digital tectonics as a paradigm shift of design thinking. Characterized as a *structural turn*, they propose that there is an increasing importance of structure and materials in current design and the new creative synthesis of architecture and structural engineering. They also refer to the "technological possibilities afforded by the digital realm".

2.6. Digital Tectonics: Tectonic Relationships as a Foundation of Digital Morphogenesis

If tectonics is the nature of material relationships that underlie the structure/architecture integration, how can we adapt this general concept to the digital? Rather than interpret digital tectonics as the phenomenon of a cultural shift, we propose that the methodological content resulting from emerging methods and technologies is *providing new digital processes and representational potential that is establishing a new tectonics*. It is this new design methodological content that is integrated computationally with new material, structural and constructive potential that constitutes the contribution of digital tectonics to digital morphogenesis. This *virtual materiality* also contributes to the enhanced collaboration of the architect and engineer (and other emerging design specializations) by enabling (digital) design approaches based upon materiality.

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The interpretation of digital tectonics as an *enabling materiality* that supports experimental design can be seen as analogous to physical form-finding (Nerdinger, 2005; Berger, 2005). Following this assumption, we analyze and attempt to establish a linkage between traditional experimental form-finding and digital tectonics. Through the reinterpretation of form-finding methodologies we develop the concept of *digital morphogenesis* (Oxman, 2009). The recent development of form-finding processes in digital structural design exploits the contribution of digital tectonics to digital morphogenesis.

3. Form-finding: Tectonics as Design Method

Form-finding models were used as an *experimental models* which exploits physical (analogical) modeling as a basis for design. There are three important variables in designing such analogical models: form, structure and materials. These variables in form-finding and their relative prioritizing determine the way in which the model functions. How these three variables are ordered and extrapolated will also determine the continuing relevance of form-finding to digital tectonics and digital morphogenesis.

3.1. Historical Precedents of Form-finding

Gaudi's development of catenary curve models (weighted hanging chain, wire and rope models) are a canonical example of an important early modern example of scale models employed experimentally for spatial/structural design purposes. Experimental models were also employed for engineering studies for the vaults of the Sagrada Familia Church (Burry, Burry and Faulí, 2001). The major use of form-finding models as design media are associated with Frei Otto and his many experiments carried out at his Institute for Light-weight Structures (ILS) at the University of Stuttgart. These experiments contributed to the definition of an expanded range of form-fining objectives beyond that of the statically derived shape derivation of catenary models. Catenary models are employed to generate free-tension structures. Employing diverse materials including cables, rope, chains, soap films, rubber, fabrics and wire meshes the experimental devices were employed to study both structural behavior and material behavior. Executed with scientific precision, the analytical design studies employed sequential generate and test procedures the results of which were carefully measured and documented.

Perhaps most noted among the form-finding research methods of the ILS were on the one-hand, work on cable network and membrane structures, and on the other hand, general studies on the problem of minimal surfaces. In order to establish a classification of form-finding tectonic approaches, it is interesting to demonstrate how these two problem types generate tectonic approaches (design methods). We have classified these form-finding tectonic approaches as: Structure-first, Material-first and Form-first. These approaches are essentially different and the distinctions between them will become highly relevant for digital morphogenesis.

3.2. Three Form-finding Tectonic Approaches

Structure-first is an approach to form-finding in which the morphological principles of *classes of structures* (principles of light-weight tension structures in Otto's case) are the basis upon which the model is established. *Prestressed syclastic (or anticlastic) cable nets* or *membrane structures*; *lattice shells* and *lattice domes*; *two and three-dimensional lattice structures*; and *branching* (tree) *structures* are examples of such generic forms of light-weight structures. The definition of the sub-classes of each class (e.g. radically supported, single mast cable net structures – as in the ILS structure in Stuttgart) enables the beginning of the modeling process. Many of the ILS drawings illustrate the comparative study of variations within classes of structures. These variations are defined by the essential variables of the class, such as number and locations of supporting elements. Being characterized by rational methods of typological design, this method of form-finding was most fruitful for Otto.

Material-first is an approach to form-finding in which the material may be selected in order to analyze and establish structural principles. The soap bubble and wire frame models or the fabric membrane models which were used to study minimal surface structures were classic examples of material-first form finding.

Form-first form-finding defines the case in which certain geometric factors of form have been established early in the design process (e.g. the free-form shell structure of the Mannheim Multihalle, or the overall shape of the Munich Olympic Stadium) and the structural principle and material must accommodate the form. It is also possible to state that at some point in the design process after establishing an overall form, detailed models are employed to analyze decisions of structure and materials (e.g. the famous detailed models of the structure of the Munich Olympic Stadium).

3. Morphogenesis

3.1. Introduction

The term morphogenesis today represents a body of key concepts relevant to the theory and methods of digital design (Weinstock, 2006). *Digital morphogenesis* is proposed as an emerging body of methods and techniques related to the morphological formalisms and representational models of *digital tectonics*. Together digital morphogenesis and digital tectonics create a powerful paradigm of architectural/structural design. In the following section we present certain of the basic concepts of morphogenesis and consider the relationship of these concepts to digital models and media.

3.1. Theoretical Foundations

Many of the key concepts of morphogenesis come from the field of developmental biology. Principles of structural and material order in biology and the natural sciences are also present in the study of biomimetic principles. Natural structure is employed today as a basis for the definition of geometry, pattern, form and behavior in design. Definitions of the major concepts of morphogenesis relevant to design are presented below.

- Form-finding vs. form-making

Form and behavior emerge from process. Traditional form making is defined as a formal process for the generation of form before or *without an analytical process related to the form.* In contrast to form-making form-finding is defined as form that emerges under influences of contextual conditions through evolutionary process. We have also seen that form-finding is an experimental iterative, sequential (evolutionary) process of generate and test that can be supported by design machines. Furthermore, from the ILS experience, design machines can operate in three modes: structure-first, material-first and form-first each of these having a different relationship to context and to tectonics.

- Emergence

Classical definitions of emergence are related to phenomena and effects of part to whole relationships (local to global) and bottom-up processes. According to Holland (Holland 1998) the behavior of the whole is more complex than the behavior of the part and the effects of complex behaviors in the whole cannot be predicted from the parts. In developmental biology emergence provides explanations for dynamic evolution and growth of natural systems and phenomena. Topological form or structure may be maintained in the exchange between an organism and the environmental forces that act upon them. Emergence has theoretical relevance to behavior in complex systems, adaptive and dynamic processes.

- Evolutionary adaptive process

Evolutionary adaptive processes produce evolutionary transformations resulting in complex systems and behaviors. Evolutionary adaptive principles in developmental biology were demonstrated by D'Arcy Thompson in his seminal work using topology as a means for comparative analysis. His comparative analysis represents the morphogenetic relations between forms of sub-species that could be deformed into one another by topological transformations. The concept of emergence through evolutionary adaptive processes has relevance for the evolutionary structural modeling of the tectonic relationships between structure and material as seen at the ILS as well as in recent case studies of digital morphogenesis (Sasaki, 2007)

- Self-organization

Self-organization defines the principles of order of change and adaptation whereby evolutionary adaptive processes occur. These principles of relationship are related to tectonics and are among the content of digital tectonics. Self organization (in digital tectonic models) enables form-finding as a response to force, related to functional and physical context.

- Change and adaptation

Complex adaptive systems are generally heterogeneous and differentiated. They are frequently characterized by multiple inter-connecting elements with different behaviors. This degree of heterogeneity and hierarchical complexity is highly characteristic of contemporary structures. The morphological structures underlying the potential for evolutionary change (sequential transformative topological adaptation) underlies the computational modeling of digital tectonics.

5. Digital Tectonics

5.1. Introduction

We have seen from the ILS modeling history that particular structured relationships of structure, material, form are the basis for defining tectonic relationships. The representation of these structured relationships as what we have termed, *evolutionary models* enables the modeling of morphogenesis. Digital evolutionary models are models of *structural and material part to whole relationships that can be modulated (or evolved) parametrically*. In Classical architecture such relationships of part to whole are governed by *taxis* rules, which are based on formal pattern, or schemata. Digital tectonics is based upon *computational models of digital taxis*, being the relational rules and representational models of structural and material relationships. Spuybroek (2006) refers to such an approach to digital design as "having techniques that operate at a material level. It's about making matter think and live by itself."

5.2. Formal Tectonic Models of Structure and Material

Material structure also can constitute the basis for the incremental development of structure in emergence. Spuybroek (2006) refers to such relationships of material structure as "textile tectonics --- in which textiles are transformed into the tectonic through conventional textile techniques – weaving, bundling, interlacing, braiding, knitting, or knotting –effectively building structure-".

The ARUP AGU (Advanced Geometry Unit) has been a pioneering design research group which has advanced digital geometric modeling techniques for interactively designing complex skeletal and surface structures of non-typological structures. (Simmonds, T., Self, M. and Bosia, D. 2006) That is, the traditional elements of structural design, e.g. slabs, beams, shells, etc. can no longer be employed as a model for the design of complex structures and customized digitally scripted models must be developed on a project basis. One way to view such approaches to tectonic models is to consider this as *parametric prototyping*.

From an architectural point of view the current importance of digital tectonics as a form of knowledge in design has become an important subject of theoretical interest (Reiser and Umemoto, 2006). Within the context of professional engineering practice, various attempts to formulate structural morphological principles in the sense of Otto's work are being approached parametrically (Vanucci, N. 2008).

5.3. Digital Technologies for Tectonic Modeling

There are various digital modeling techniques which essentially formalize the digital taxis or the parts to whole relationships. Associative geometry is one such geometric approach which is currently supported by various computational technologies. However, increasing complexity and non-traditional methods are requied as Hanif Kara states: " The development of visual interfaces in computing allows engineers to control complex geometries that are no longer based on proportions and algebraic relations, but on approximation through calculus (Kara, H., 2008).

6. Digital Morphogenesis

6.1. Introduction

Methods employed by Gaudi and Frei Otto described in the previous sections can be considered the first morphogenetic systems that demonstrated processes of integrated self-organization employing form, material and structural principles. *Digital morphogenesis* is computationally supported morphogenetic design that exploits digital tectonic models. What we have described above as the experimental, iterative, sequential character of the form-finding generate and test procedures through analogical modeling at the ILS is an analogical precedent of digital morphogenesis.

Digital morphogenesis has been proposed as an emerging paradigm of *architectural structural design.* These developments are currently promoting a general basis for a unique model of digital design in which complex forms of structural ordering are the content. Digital models of morphogenesis are distinguished from general disciplinary design models in that they are designed to manage relational models of structural/material tectonics. Digital simulation becomes relevant when we can simulate the behavior of complex evolutionary systems driven, or controlled, by environmental forces (physical loading, thermal data, etc.).

Emergence and form-finding are two of the most significant theoretical concepts underlying the computational models of digital morphogenesis. Structural Morphology is the body of structural and morphological knowledge underlying digital tectonics. It has a key role in defining models of tectonics and their representation. In addition to this knowledge, computational models such as models of associative geometry provide the evolutionary potential in morphogenetic systems. Given these general theoretical principles, we can now proceed to consider the current state of the art in digital morphogenesis.

6.2. Digital Morphogenesis in Architecture

Topological systems overcome the limitations of traditional formal and typological models. Therefore, topological associative parametric and generative models are a foundation of most morphogenetic processes in design.

One of the most significant contributions to contemporary digital form-finding derives from the research work of Mark Burry in untangling the geometric and methodological mysteries of Gaudí's compositional strategies for the Sagrada Família Church. As a by-product of this research, he and his colleagues have developed general contributions to *parametric evolutionary design based on parametric variation in associative geometry technologies* (Burry and Murray, 1997; Burry et al. 2001; Xie at al, 2005)**.**

6.3. Digital Morphogenesis in Structural Engineering

One of the recent applications of this approach in architecture is found in the work of Mutsuro Sasaki (Sasaki, 2007). Sasaki has worked with Arata Isozaki, Toyo Ito, Kazuyo Sejima and other leading Japanese architects. Sasaki has recently employed two techniques: the first is the *Sensitivity Analysis Method.* The traditional method was based on the hanging model experiment employed by Gaudi and Heinz Isler to define the shape of free-form funicular surfaces. In this approach the final shape was modified and analyzed in an iterative process. The new digital version of this method is termed: *Shape Design Method using Sensitivity Analysis.* It employs principles of mechanical theory that minimize surface energy in the internal structure of a freely-curved surface (Sasaki, 2007).

The other technique is termed: *3D Extended Evolutionary Structural Optimization* which is extending the traditional ESO method. The traditional Evolutionary Structural Optimization (ESO) was used to generate the form. The form was related to mechanical behavior which simultaneously corresponds to shape modification. The new version of this method generates a rational structural shape. The extended method employs an evolutionary process which can be applied to a three dimensional structure.

The Shape Analysis Method is based on an iterative process that aims to achieve an optimal structural solution within the topological and architectural limits of a given architectural concept. A computational matrix is employed to calculate the structural form according to stress and deformation. Evolution in this method is interpreted by the employment of an iterative analytical method that is based on topology rather than geometry. Final form is generated by transformations keeping the same topological relations. An algorithmic method is applied which accommodates the evolutionary adaptive potential of the given design.

6. Conclusions

Digital morphogenesis has been proposed as exploiting digital tectonic models. This tectonic knowledge of material structures enables the model to control the process of evolutionary adaptation. Furthermore, the evolutionary adaptation process can be driven by calculations of force, or loading data. Beyond these capabilities we have also suggested certain of the limitations of digital tectonic knowledge, e.g., how to handle heterogeneity.

A further generic development of digital evolutionary morphogenetic models is the internal architecture of their evolutionary process, e.g., what kind of intelligence of the system selects adaptation strategies, etc. or is this a prerogative of the human design engineer interacting and guiding the system? An important set of questions relates to their potential for acting as generative systems; can such morphogenetic models transcend the typological orders of tectonic knowledge? It posits certain of the most theoretical and technologically demanding questions of digital design today.

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