The case study pavilion, constructed in a very short time, for low cost and with relatively unskilled labor, demonstrates that the integration of algorithmic form-finding techniques, CNC fabrication workflows, and innovative PETG folded mold techniques enables the practical realization of freeform funicular structures in precast concrete.

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DIGITAL PLASTER:
A PROTOTYPICAL DESIGN SYSTEM

ABSTRACT

Contemporary computational design processes offer more potential in the design of formally complex architectural outcomes when material processes and fabrication techniques are incorporated within a digital working methodology. This paper discusses the research project "Digital Plaster," which showcases the development of a complex design system of cast forms based on the integration of digital and analog techniques. As a computational model it embodies the input of the fabrication and structural form-finding processes in flexible formwork plaster casting within an algorithmic behavior self-organizing system of architectural matter. Such an emergent system is defined by the synergic relationships of its parts throughout the whole process and acts upon its evolutionary growth. (CTRL+M 2011; Negroponte 1970).

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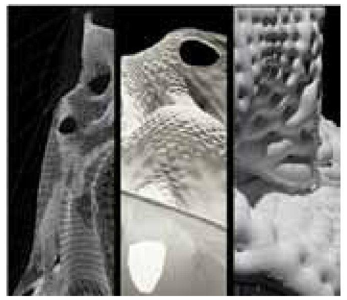

figure 1

1 INTRODUCTION

Materiality acquires a catalytic position in the formative design by being integrated from the beginning within a design-based form-finding process. A number of advances have been made in plaster or concrete casting of complex architectural forms that can now be extended into generative computational processes due to technological advances in analog and digital applications and material science. *Digital materiality* can now be explored, offering fundamental insights into contemporary computer-aided design processes and their implementation within architectural practice.

Digital Plaster, a master's thesis project undertaken by the team *CTRL+ M* in the Design Research Laboratory (DRL) at the Architectural Association School in London (2010–11), communicates a design methodology approach that attempts to develop an architectural system utilizing custom simulation design software that incorporates structural form-finding and fabrication constraints for flexible formwork plaster casting.

This research removes hurdles in the fabrication and design of complex formed cast architecture and introduces a dynamic approach that incorporates *analog constraints* as *digital design opportunities* within a formation methodology. The research proposes an architectural machine that embodies the design intent within dynamic patterns of forms. The complexity of the result reflects the circular causality the methodology implements between analog and digital experimentation, where both material investigation and digital algorithmic design inform each other in a continuous feedback. Such architecture is defined through a dynamic composition of processes and can be conceived as a complex and responsive model with context-dependent design results. Both structure and surface constitute a dynamic system from composite material of nonpredefined elements. Performance expands beyond the limits of its structural notion and encompasses qualities of space and form along with the sustainability of the system's fabrication intelligence.

The reality is that architects must engage with numerous fields of expertise and synthesize their respective constraints within each project. Embedding such constraints within a *dynamic design process* would empower architectural innovation to make these constraints intrinsic to design intent and therefore create its own definitions of space and structure each time. Such prototypical design strategies that negotiate the boundaries between matter and nonlinear formative processes are able to describe and ascertain the architects' emotive intent to create unprecedented qualities of space. Thus, this paper explores the relationships embedded in the nature of matter—the cast flexible formwork in this case—both in analog and digital formative methodologies that have a discrete design intent.

2 RESEARCH CONTEXT

2.1 A Design Methodology

The body of this research encompasses a series of research strands including material experiments, computational simulation of material behavior, and algorithmic intelligence of a self-organizing system. Based on the material study of cast plaster in flexible fabric formwork, it explores a digitally controlled design and fabrication process that refines the process of making by building its results on a time-based deployment to a phase-changing material that constantly changes its attributes. This *material behavior* is the catalytic effect that informs the spatial and formal configurations of this design system. Analog form-finding experimentation becomes the starting point of formation where a set of parameters is defined to regulate the results between the constraints of fabric patterning and material attributes. The design of patterns constitutes the mapping method throughout the whole process, from the genotype into a phenotype, from digital to analog and vice versa. Along with the *pattern language* that embraces the architectural design and fabrication intention, *digital simulation* constitutes a technically advanced tool for the evaluation and therefore the optimization of the final results of the fabric and plaster composite system, through various generative techniques (*Figure* 1).

figure 1

Digital Plaster. The three discrete patterning scales, from left to right: organizational pattern, digital materialism pattern, the material experiments pattern.

2.2 An Architecture Machine

According to Deleuze and Guattari, a living organism that grows without genealogy has the rules for growth embedded in each part of its system; hence, it is possible to guess the next step after stopping the growth at a particular time (Deleuze and Guattari 1988). This perception about evolution has been used in the architectural design process in the form of a diagram that could evolve according to its own rules and in response to the environment. However, there is a split between process and materiality because it becomes a concrete moment and is no longer responding while the process is evolving continuously. In order to break that split, Negroponte introduces the concept of the "architectural machine," incorporating what the computational tools could change in the design process, turning the conventional space into a computational space (Negroponte 1970). This is how the power of computation enables architects to design dynamic objects where the architectural object responds instantaneously to the changes of the process and consequently to the programmatic problems. However, the components are restricted in terms of movement; hence, the system is conditioned not only because of the nature of the material, but also because of the limitations of technology. In talking about such constraints in construction and fabrication technology, one has to realize the potentials of common material properties in order to consider incorporating them in a dynamic concept of machinic architectural design that could be actualized. In Digital Plaster this dynamic approach is achieved through multiple scale (multiscalar) patterning techniques throughout the whole process, from fabric patterning to algorithmically generated digital patterns to spatial organization patterns, which do not result in a static form but in a non-ended digital materiality.

figure 2

2.3 Form Finding—Analog Machines

The methodology is based on material behavior of analog *form-finding experimentation*, in which the form follows the flow of physical forces, as pioneered by Antoni Gaudí and Frei Otto in their conceptual physical models (Gaudí and Bohigas 2002). Gravity and material properties were embedded within their working methodologies, allowing them to shape their architectural solutions through the negotiations of these relationships. The catenary model that Gaudí (*Figure* 2) utilized to define the organization of a network of hanging chains according to the tension on their local connections was intensified by strategically added weights, which allowed him to generate a variety of building proposals. He managed to achieve innovative compression structures through inverted models. These analog machines enabled better understanding of the interrelationships of material properties, at different scales of complex architectural space.

2.4 Shell Structures Prototypes

The structural stability and the morphogenetic forces of the shell structures prototypes acted always toward the optimization of a dynamic shape. One of the pioneers of the geometric shell structures, Felix Candela (*Figure* 3), gained his reputation mostly through his double-curved hyperbolic paraboloid large-span shells. These structures required not only complex mathematics and engineering calculations but also the use of excessive formwork. Heinz Isler also explored free-form reinforced concrete shells following form-finding experimentation according to physical laws instead of mathematical definition. He employed inverted catenary principles to determine the geometry of pure compressive shells using highly complex rigid formwork to construct these. The main criteria for material and economic efficiency of constructing thin-shell reinforced concrete structures were to minimize the cross-section and material use.

2.5 Reinforcement Types

As mentioned above, the emergence of material properties, in this research, is intensified by the use of soft responsive formwork that allows the material to compute its most efficient distribution under gravity within the limits of the flexible fabric. It is a fact that the need for high complex scaffolding during construction eliminates the emergence of the formative process. Moreover, thin-shell structures

figure 2

Antoni Gaudí, "Hanging model" of proposed Colonia Güell Chapel.

figure 3

figure 4

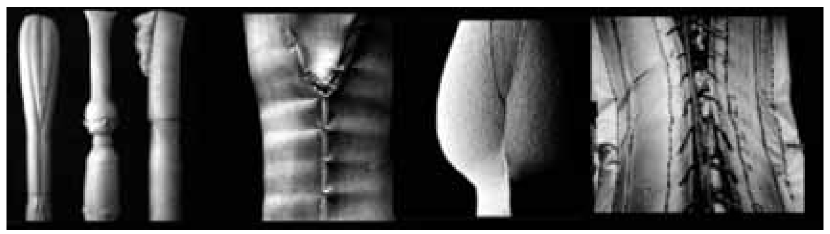

figure 5

are conventionally reinforced and prestressed, whereas the use of fabric within the composite system of fabric and concrete can serve as reinforcement. The material distribution observed on the section of a cast analog model is based on the patterning technique where the inherent logic of material efficiency and structural performance are expressed through the redundancy of material—be it fabric or concrete. Pattern is a design tool, which negotiates the threshold between material's capacity in organization and spatial differentiation. It pursues the system's equilibrium between structure and ornamentation. Fabric can serve as formwork and reinforcement simultaneously, creating more structural potentialities over the steel-reinforced concrete. Thus, in this research the potentials for use of reinforced concrete are growing with the use of fabric formwork as the reinforcement happens during the casting. "It may be noted that although reinforced concrete has been used for over a hundred years and with increasing interest during the last few decades, few of its properties and potentialities have been fully exploited thus far. Apart from the unconquerable inertia of our minds, which do not seem able to adopt freely new ideas, the main cause of this delay is a trivial technicality: the need to prepare wooden forms" (Nervi 1958). This quotation highlights the instrumental role of fabric formwork in the development of the structural stability of nonstandard forms.

2.6 Fabric Formwork

The complex process of forming displays emergent behavior as the material negotiation between the flow and weight of concrete and the elasticity inherent within the fabric continuously informs the process of formation. Thus, the interaction of material and technique influences the design and fabrication process. Fabric formwork is based on the consideration of edges and pattern. Concrete and fabric negotiate the form, which is articulated by the constraints of edges and the pressure points; hence the edges or seams and the pattern become structurally operative tools such as pre-tensioning and stretching. Furthermore, the challenge of fabric formwork lies in the connection of fabric-cast elements and the ability to control and design the detailing of these parts. Miguel Fisac used fabric formwork for elaborate surface cladding in multiple scales and ranges of expression. In the 1960s and 1970s he used flexible plastic sheets to cast wall panels (*Figure* 4).

figure 3

Felix Candela, Chapel Lomas de Cuernavaca, 1958.

figure 4

Miguel Fisac, Centro Social de las Hermanas Hospitalarias.

figure 5

Mark West, "Cast Models" at the Centre for Architectural Structures and Technology (CAST), University of Manitoba.

Following this lineage is contemporary researcher Mark West at the Centre for Architectural Structures and Technology (CAST) at the University of Manitoba. West is seeking innovation in both architectural form generation and building technology, using flexible formwork casting techniques to create columns, panels, and beams at scales of up to 1:1 (*Figure* 5).

Forms emerge through the material negotiation of matter following force paths of tension and compression forces. From an aesthetic point of view, the composite system offers the qualities of handmade fabrication, individuality, and specificity through its pattern. Pattern as an architectural term refers to the standardized design norm. However, in this case, fabric pattern realizes ornamental qualities, which deform the space and structure perception. The quality of this architectural matter is enhanced by the effects of differently scaled patterning that differentiate the types of form. "The desire for form is also a desire for meaning" (Gleiniger 2009), and therefore the meaning of form lies in the structural operation of its pattern. In this case the ornamental character reveals the potentialities of fabric-reinforced concrete as a structurally and formally meaningful composite system. From object scale to building scale, digital plaster acquires its experience through patterns that embed structure, ornament, and function. The phenomenological effects of this composite material system are unforeseen qualities. Both Mark West and Miguel Fisac took further the fabrication and morphogenetic process based on fabric formwork and the dynamics of this method in analog. A great example of this dynamic analog process constitutes the P-Wall designed and produced by Andrew Kudless (Kudless 2006). Finally, these advanced construction techniques call for a digital design methodology developed and derived from the same principles of flexibility and material self-organization, through which the analysis of all different scales of the formation will be possible and therefore adaptable to the design requirements and intents. An extensive investigation of a prototypical design system such as Digital Plaster is developed on these paths, aiming to establish a nonlinear design approach.

figure 6

3 MATERIAL SYSTEM—PATTERN I

During this research project, which incorporates fabric formwork fabrication methods within a generative digital design process, that formation process undergoes a series of three negotiations toward an architectural design solution. Configured in different scales, from space to organization to structure, the pattern is the element that negotiates the relationship between the stages of design. First, the scale of material experiments with patterns at the scale of 1:1, which develops an understanding of controlling parameters in fabrication; second, the digital simulation of pattern and material behavior; and third, the spatial organizational model. The last constitutes a patterning language, which allows for strategic design deployments as architectural interventions that utilize the material technique.

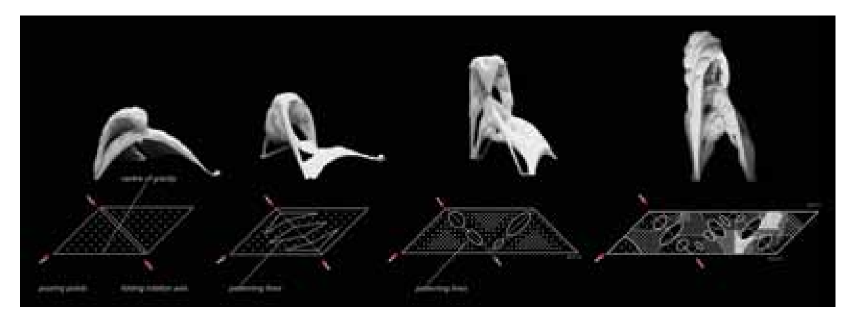

figure 7

figure 6

Digital Plaster: Analog experimentation process during the phase casting.

figure 7

Digital Plaster: Catalog of models and patterns of analog experiments according to the folding technique.

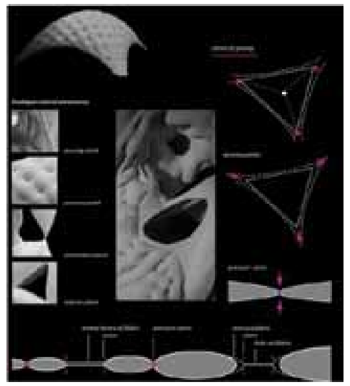

figure 8

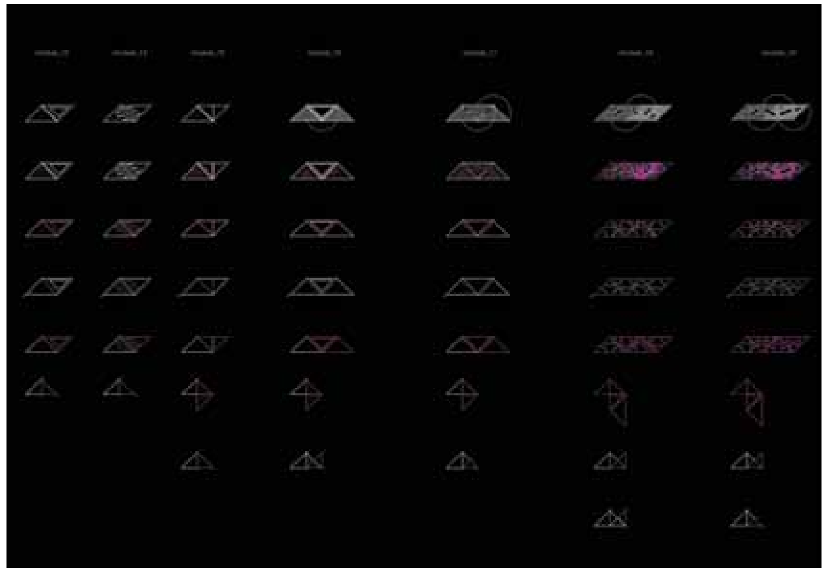

figure 9

figure 8

Digital Plaster: Studies of different fabric patterning techniques and control parameters of the casting process.

figure 9

Digital Plaster: Catalog of patterns of analog experiments according to the folding technique.

3.1 Material Experiments

The first stage of the process (Figure 6) investigates forming through machinic operations on matter. The flexible formwork casting system is based on patterning techniques, including parameters such as pressure points, conn The development of a folding technique (Figure 7) applied on a continuous piece of Lycra fabric serves as mold for a number of connected surfaces. ection points, and pouring points that vary in number, location, and height.

The material experiments are based on a module of a minimal surface defined by three suspended chains, according to Gaudi's catenary technique for studying the formation process in structures in suspension under gravity. Multiple modules constitute a catenary network of interdependent surfaces that deform individually yet as part of a larger population. This modular catenary system is inverted and forms the setup for the flexible formwork casting system. The initial experiments are based on a format of a 42 × 42 cm equilateral Lycra fabric triangle with a 2 cm grid (Figure 8).

The use of flexible formwork casting as a technique is based on the inversion of the surface formation found in suspension into a structure under compression. The objective of the material experiments is to minimize the cross-section by applying various stitching techniques that are defined by different parameters. The combination of a different set of control parameters within the flexible formwork casting system results in a high variation of unpredictable outcomes of patterns and analog models (Figure 9) In this sense, matter and its self-organizational properties are used as an operative tool within the design process.

3.2 Controlling the Material Distribution

The goal of material experiments is to control the cross-section of the individual surface through patterning at a local scale and the deformation of surfaces at a global scale. The gravity of the plaster deforms the grid of the flat patterns after casting according to the center of gravity of each suspended fabric form (Figure 10). The only constrained points that are not deformed under gravity are the pouring points, which also constitute the suspension points that support the fabric formwork. Thus, the deployment of the material gets more intense from top to bottom, where it is less constrained. The cast models represent the state of equilibrium between fabric and dry plaster, revealing the intensity of the compression and tension on an unprecedented form.

3.3 Time-Based Deployment

Casting in phases is derived from the necessity of material such as plaster to dry and acquire its optimal stability performance; a period of time is needed for these phase-changing properties. Therefore, the formation of complex patterns and the complexity of their fabrication method required a technique in which time plays a key role. This method became a very significant characteristic of the design process and fabrication, which determines the hierarchy of the elements of each form. The initial phase of the cast can serve as scaffolding for subsequent castings (Figure 11). In this way the architectural system has the capacity to grow and evolve over time, by reinforcing structural parts through the generation of new elements, and to adapt to specific site and programmatic conditions.

figure 10

Digital Plaster: Analog experimentation with the "folding" fabric technique according to the deformation of the folded fabric pattern under gravity.

figure 11

Digital Plaster: Before and after moments of casting (in time phases) the first and the second level of patterned surfaces.

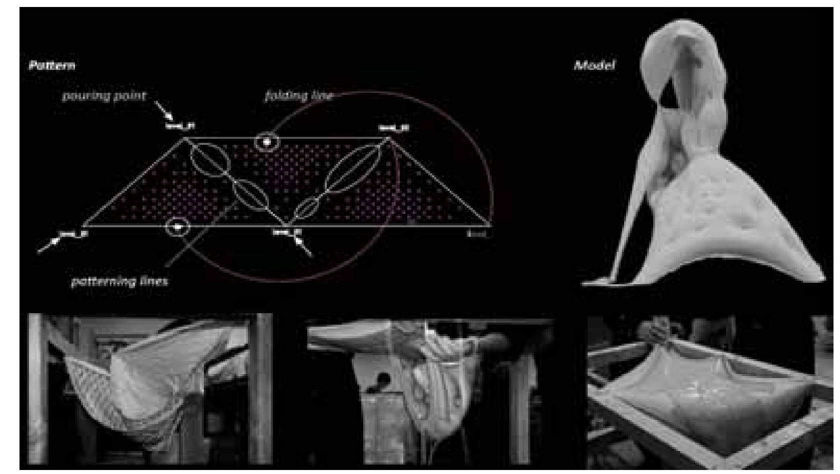

figure 10

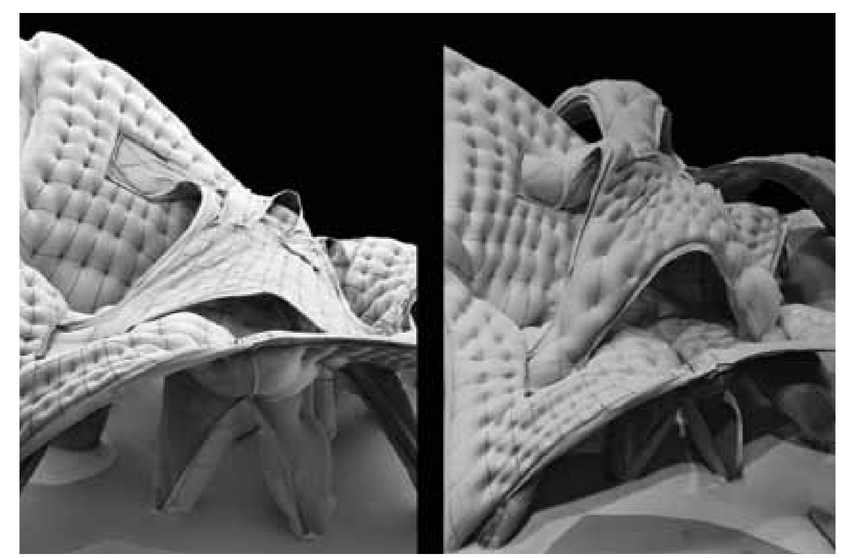

figure 11

figure 12

Digital Plaster: Systemic relations of material system. The agent-based material simulation describes the relationships of the casting material properties during the casting.

figure 13

Digital Plaster: Systemic relations of material system. This agent-based simulation describes the hierarchies of control variable of the casting technique.

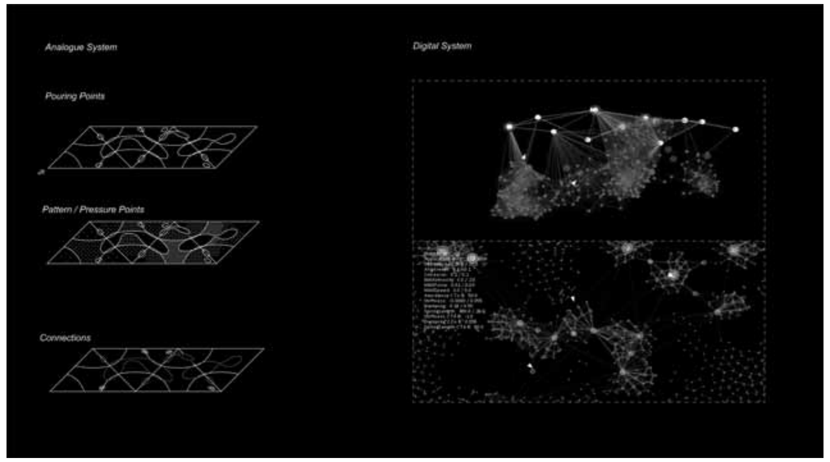

figure 12

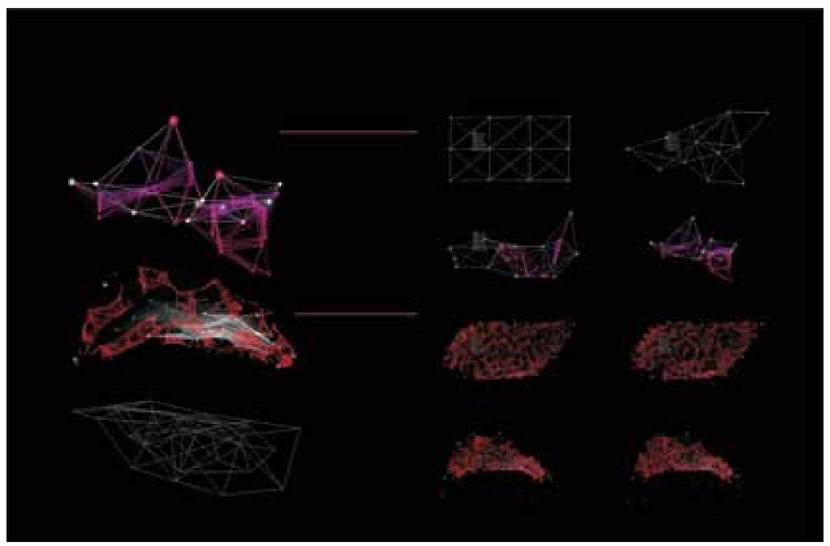

figure 13

4 DIGITAL MATERIALISM—PATTERN II

4.1 Material Agency

The concept of material self-organization or material agency has been discussed in modern science and philosophy in the context of nonlinear evolutionary theories. In this context Digital Plaster is based on the generative potential of material computation to inform the design process. The simulation techniques that are utilized are incorporated at different scales of material organization that operate at different stages of the design process.

4.1 Systemic Relations—Agent-Based Material Simulation

A simulation of the connections between the flexible formwork casting system variables into an agent-based system is the first level of analysis of algorithmic relations. The flexible formwork cast system parameters—i.e., distance between pressure points and pouring points—inform the agent-based system in which simple interactions of agents follow simple rules. Based on the principle of analog experimentation, the hierarchies of this system simulate the material behavior during the casting. Even though this bottom-up approach provides a more realistic representation of the nonlinear properties of material complexity, this agent-based system of simulation remains an introduction to the simulation techniques (Figures 12 and 13).

figure 14

figure 15

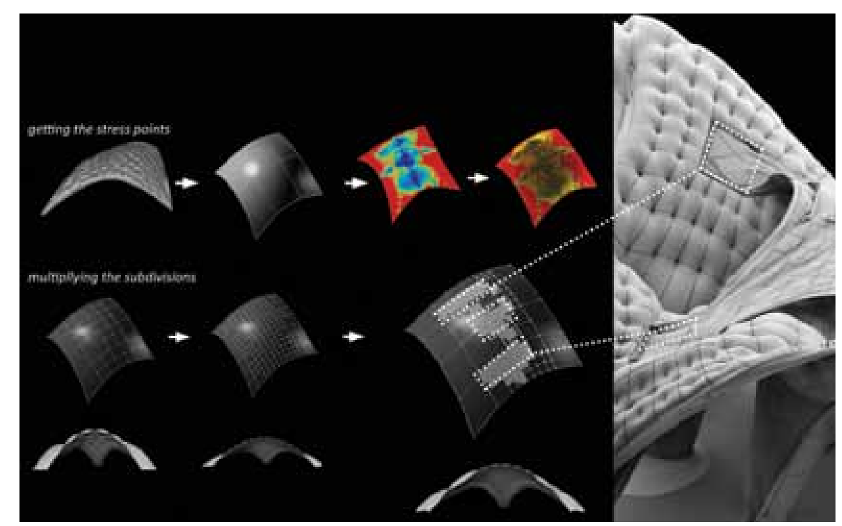

figure 16

figure 14

Digital Plaster: Physically based digital simulations of the casting technique that test the material performance. From left to right: (top) particle simulation; (bottom) inflation of pattern testing the phase cast; (right) inflatable patterns simulation for the fabrication technique.

figure 15

Digital Plaster: Low-resolution polygon geometry through approximation from the analog models to the digital modeling.

figure 16

Digital Plaster: Patterning generation technique after stress analysis of the individual shell surface, based on an generative algorithm.

figure 17

Digital Plaster: Catenary network that derives from the catenary forms according to the material experiments. Lower: bigger population of a spatial organization network.

figure 18

Digital Plaster: Dynamic surfaces network formation as an agent-based self-organized system that is informed by the surface structural analysis to evolve in time.

4.2 Physical Simulation—Dynamic Nets

Physically based simulation techniques play a significant role in the formative process (Figure14). Based on parameters such as liquid flow, direction of gravity, and flexibility of the fabric, they lead to a better design evolution. The first stage of casting simulation in the dynamic software environment is based on a numeric approximation of the physical forces during the casting method. After a constant calibration of the material attributes to regulate the forces' interaction at the same time, as well as the patterning configurations, the cast process becomes more accurate and the simulation (cast) of more complex surfaces is now possible. Therefore, material experiments are now used to depict the dynamic effects of material formation, not to test the fabric pattern. Despite the technical challenges, simulation in dynamic environments is a design tool that represents a digital form-finding technique that becomes accurate to inform coherently the process of design. The structural behavior of the shell structures is developed through numerical methods and algorithms that are based on the finite element and fluid dynamics analysis methods. The calculation of the surface deformation after casting improves the pattern design and becomes the input for the next step of the simulation. Although the development of a very accurate (to the actual digital casting) simulation is yet to be achieved, the unprecedented digital models are part of the evolution of the design process.

4.3 Informed Geometry

The next stage of the process is targeting the evaluation of the structural performance of a low-resolution polygon geometry surface. The low-resolution polygon geometry is extracted approximately from the simulated pattern (Figure 15).

The optimization of the pattern is an important part of the final design. The process connects the structural analysis of the form with the distribution of control points on the surface. An algorithm is utilized to relate the stress point values extracted from the structural analysis to the number of subdivisions on the surface. The lower the value of stress on the area of the surface, the higher the number of subdivisions (the thinner) generated on the surface and vice versa (Figure 16). The aim of this stage is the analysis of the singular form for the design of a network of forms that has distinctive thickness and scale. The design of the connections of different stages of the cast is based on the evaluation of the maximum deformation of the surface.

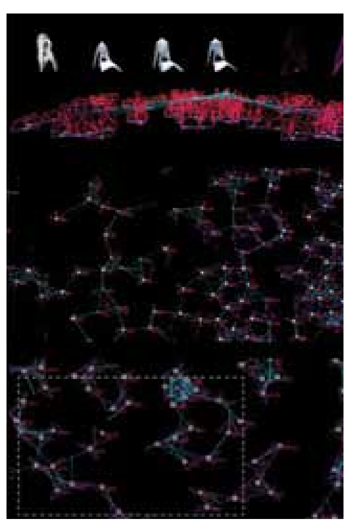

figure 17

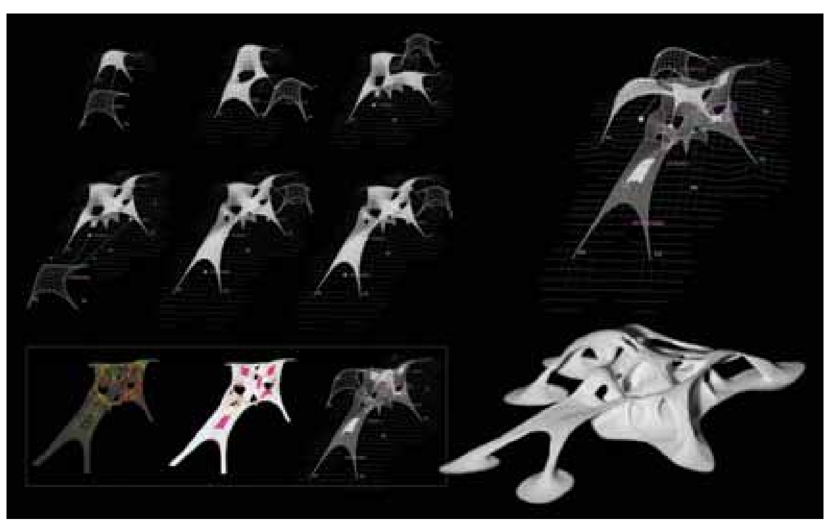

figure 18

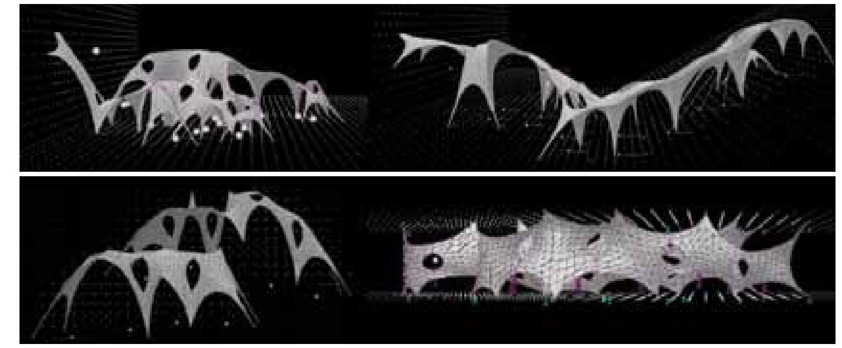

figure 19

figure 20

figure 19

Digital Plaster: Environmental adaptation of the dynamic surface network in different types of environmental conditions.

figure 20

Digital Plaster: Dynamic surface organizational network evolves into complex configurations over time.

5 ORGANIZATIONAL MODEL—PATTERN III

5.2 Agent-Based Simulation—Dynamic Particle-Spring System

At the scale of the organizational model, an agent-based system first represented as catenary networks and subsequently as dynamic surfaces configures the relationship between pattern and space. A dynamic particle-spring system is employed as a form-finding tool, simulating structural behavior of the catenary network (Figure 17) and the dynamic surfaces network (Figure 18). The particles are connected to agents who follow simple rules of movement and connection. While the physical properties of the system ensure that a continuous state of structural equilibrium is maintained, its intelligence—i.e., its self-organizing properties—provides it with the capacity to continuously evaluate and adapt to changing environmental and programmatic conditions, resulting in complex spatial configurations.

5.3 Architectural Prototypical Scenarios

These organizational patterns allow for strategic design deployments as architectural interventions able to negotiate diverse programmatic requirements of inhabitable spaces. Being able to readapt to changes in stress distribution, the system has the capacity to negotiate multiple terrain conditions (Figures 19 and 20). The different spatial configurations vary in scale and density of shell structures.

The system's prototypical approach is revealed through the different spatial qualities of density and scale that range from small units to large shell spans that configure continuous public spaces (Figures 21 and 22). The process generates enclosed spaces, stitched together with continuous and opened surfaces. Typologies include large-span shell structures and compressed multilayered vaulted structures.

figure 21
Digital Plaster: Architectural scenario for the big span space, used for big public programs.

figure 22
Digital Plaster: Architectural scenario for the dense space configuration of smaller span shell structures.

figure 23
Digital Plaster: Inflatable pattern for the facade openings uses the same patterning technique with the fabric.

figure 21

figure 22

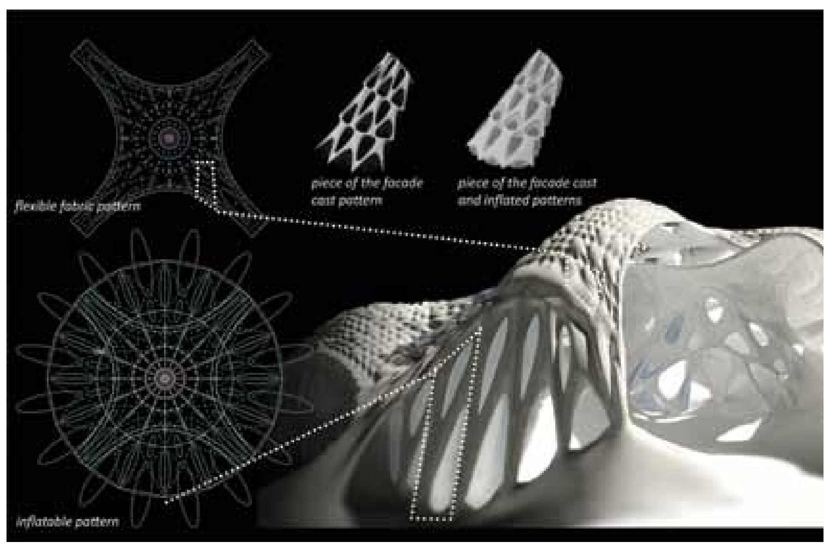

figure 23

5.4 Fabrication Technique

In order to understand and evaluate the efficiency of the pattern and therefore optimize it, the evaluation criteria are derived from the minimal cross-section according to the surface thickness. Optimal weight and avoidance of excess material are calculated to maximize structural stability and form evolution. The fabrication of patterns for single surfaces became a tool for understanding the geometry of the form that led to the 1:1 construction logic of more complex morphologies (Figure 23). The introduction of inflatable membranes facilitated the feasibility of the fabrication process at a larger scale. Patterned membranes are embedded in the fabric patterns and inflated during construction, helping the pattern to find its shape while reducing the dead load of the structure itself. At an architectural scale, the inflatable patterns are generating the enclosures of the openings of the structure. The continuous feedback between the several steps in the process ensures the best structural performance of the pattern at full scale.

6 CONCLUSION

The described design research methodology constitutes a unique way to generate the prototypical form through a coherent process of design through making. This nonlinear methodology allows the design to emerge from a material process that continuously changes its nature. This emerging materiality becomes the constraint in the digital or the analog process until the moment the system embodies it to generate its prototypical and dynamic behavior toward the programmatic requirements. This prototypical system reveals the qualities of a new architectural language where the multiple aspects and scales of a constraint become intrinsic to the design intent.

The boundaries between the definitions of the structural elements and surfaces become ambiguous after the implementation of a design strategy based on material attributes. During these negotiations within the formative process, a proposed organization of architectural matter results and gradually resets its limits. On the other hand, fabrication becomes an issue of scalability, which—endorsed by simulation methods and structural performance analysis—makes the design more efficient and enhances its constructability. Design elements and variables of aesthetic qualities are utilized to keep an integrated language of making in the system. For example, the seams of the fabric patterns in design could work as structural "seams," i.e., hard profiles, that help the actual scale construction. In this way such a material complexity argues for its efficiency by advancing the system's consciousness for optimal performance. Based on algorithmic methods of a self-organizing system, this material agency of the Digital Plaster design system can incorporate in its ecology many aspects of design objectives of different scales and densities, from concept to fabrication. As unforeseen results evolve, the system argues for its prototypicality and uniqueness through its synergetic behavior in order to adapt in different conditions and provide the most efficient architectural solutions.

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APPENDIX

This paper is based on the design research of a master's thesis project, "Digital Plaster," of the Design Research Laboratory at the Architectural Association School of Architecture, undertaken by the team CTRL+M (Stella Dourtme, Claudia Ernst, Roberto Garcia, Manuel Jimenez Garcia).

Design Research Laboratory is a post-professional master's degree in Architecture and Urbanism at the Architectural Association School of Architecture in London.

Digital materiality refers to the Protodesign—Digital Materialism studio research agenda supervised by Theodore Spyropoulos (DRL master's program director) during 2011.

Multiscalar patterning refers to the different scales of the patterning methodology that can be applied to various scales, from the structure to the organization of architectural space.

Patterning is the stitching and sewing technique utilized during the analog research to tailor and pattern the second layers of flexible fabric formwork.

Form-finding experimentation is the technique utilized by architects as Gaudí and Frei Otto in the conceptual design of architecture via physical modeling processes that utilized natural forces. Their models allowed negotiated design criteria to be embedded within their working methodologies. These material models thus embodied design constraints that allowed for a negotiative process in order to arrive at an architectural solution.

The Centre for Architectural Structures and Technology is an architectural research laboratory that embraces both the poetic and technical dimensions of architectural design. The work of CAST seeks new boundaries for creative thought, design, and building technology through physical explorations of materials, tools, and building methods, the study of natural law, and the free play of imagination. (http://www.umanitoba.ca/cast_building/)

Material agency here refers to the autonomous material relationships that are represented by agents (individual elements) that negotiate their conditions according to their own "decisions." The final organization model is a product of this collective behavior indirectly controlled by each element.

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WORK IN PROGRESS

PARAMETRIC PRECAST CONCRETE PANEL SYSTEM

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ABSTRACT

The framework for this research focuses on the potential of utilizing a digital toolset to engage information within a surrounding context for the purpose of creating a more intelligent precast concrete panel system. The Parametric Precast Concrete Panel System *is an ongoing research project that parametrically defines geometry for the purpose of producing formwork based on quantitative information related to issues such as environmental control systems and sound abatement, as well as qualitative information such as nonstandard variation paneling and formal composition. (Figure 1)*

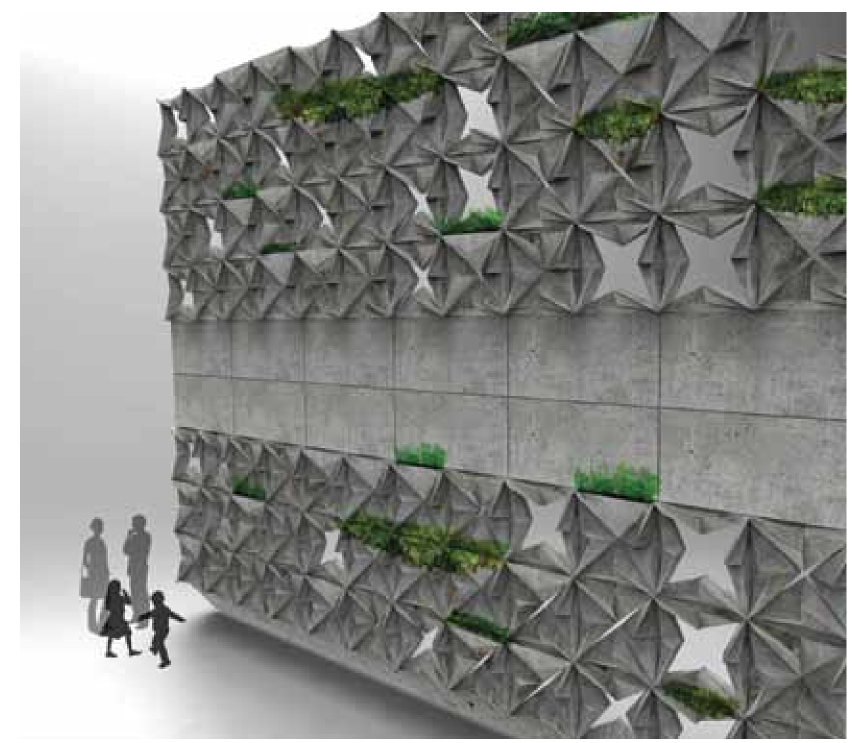

figure 1

figure 1

Aperture facade panel rendering showing variation in openings and integrated planting pockets.