ADAPTIVE TECTONIC SYSTEMS:
PARAMETRIC MODELING AND DIGITAL FABRICATION OF PRECAST ROOFING ASSEMBLIES TOWARD SITE-SPECIFIC DESIGN RESPONSE

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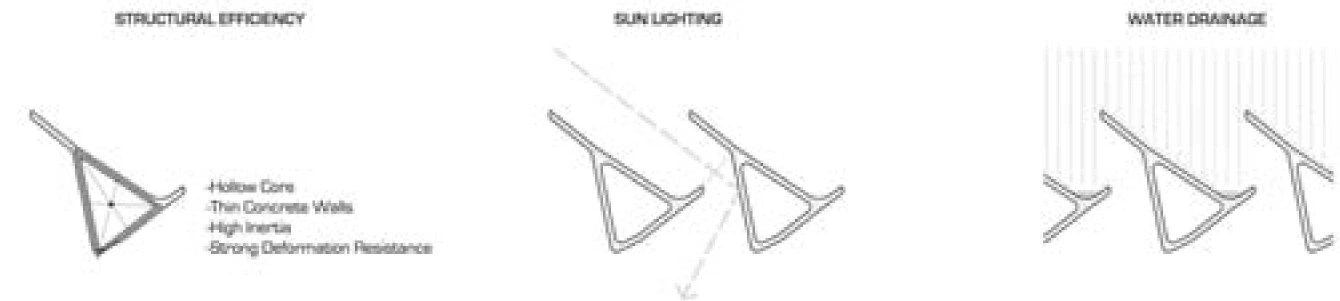
1 Images of Miguel Fisac's "bones"

ABSTRACT

In order to design adaptable systems, the requirements include flexible models to generate a range of alternative configurations, analytical engines to evaluate performance, and well-defined selection criteria to identify suitable options. In most cases, design processes driven by performance concentrate on environmental or structural parameters; fabrication often remains disconnected from the generative process. Nonetheless, as design-to-fabrication methods become more robust, it is possible to extend the digital process to introduce fabrication variables to the definition of the project. The main focus of the research presented in this paper is the development of a digital and material workflow that connects design, structural and climate-specific topics (such as sun lighting and water drainage) toward producing a range of efficient structural and spatial assemblies.

A case study serves as the main support for this investigation. Miguel Fisac's "bones" is a lightweight roof system developed during the 1960's, which had a very well-calibrated structural, natural-lighting, drainage and construction performance, as well as a highly refined spatial output. The system, despite its intelligence, lacked the flexibility possible today: using digital technologies, it can adapt to a significantly wider range of applications. Using "bones" as a starting point, this research develops a design-to-fabrication workflow that attempts to move forward tools, material systems and processes to enable an adaptable tectonic system.

This paper describes the background research, concept, form-finding, construction process, methodology, results and conclusions of the investigation.



2 "Bones" system: target variables

1 INTRODUCTION: TOWARD ADAPTIVE TECTONIC SYSTEMS

In constantly changing environments, successful systems are necessarily adaptive: they must adjust to the local conditions they occupy. In architectural design, different interpretations of this principle have been pursued. One approach considers the capacity of a building to adjust to immediate environmental factors in real time (van Timmeren 2009). Another branch considers the ability of abstract and flexible material systems to actualize according to the specific requirements of each local condition (Foreign Office Architects 2003). The research in this paper is framed by and aims to foster the second position.

Early approaches to digital design and fabrication took advantage of technology to explore complex forms, describe them with precision and attempt to make their construction feasible; in most cases, little consideration was devoted to performance other than aesthetic effects. A more recent approach to computer-aided design focuses on the use of digital tools to quantify and increase performance of design solutions (Oxman 2008). In these performance-based methods, rigorous selection criteria are crucial to determining which of the endless parametric variations should be chosen. Today, dynamics of structures and energy flows can be simulated, visualized and represented with precision. For this reason, structural and environmental parameters became main determinants of projects. However, the construction process, a central constituent of design, is too often disconnected from the performance-based workflow that informs the project. This condition raises a key question: What innovative digital processes might bring tools, materials and assemblies—construction processes—into the workflow that steers adaptive systems?

In order to introduce construction variables into the selection process, digital models should extend beyond the purely digital domain and claim control over the fabrication phase (Gramazio and Kohler 2008). Therefore, the inclusion of material and assembly variables in a design-to-fabrication workflow becomes essential.

The research presented here proposes a design methodology that is centered on the optimization of a discrete number of strategic target variables to drive the generation of the project. This approach to design is supported by four pillars: a precise selection of these variables, an adjustable fabrication system, a flexible parametric model that can adjust to variations and a seamless exchange of information between digital models and fabrication devices. A pre-digital material system serves as a starting point for the proposed workflow developed throughout this investigation. Miguel Fisac's "bones" was selected because of its highly rational yet very elegant architectural solution.

2 MATERIAL SYSTEM CASE-STUDY: FROM STRUCTURAL RIGIDITY TO PARAMETRIC FLEXIBILITY

2.1 MIGUEL FISAC'S "BONES"

As a case study, the current research revisits the *huesos varios* (Spanish for "various bones") developed by the eminent Spanish architect Miguel Fisac during the 1960's. The "bones" form an elegant and efficient structural system for long span roofs (González Blanco 2007). This specific precedent was chosen because it proposes a discrete and well-identified set of target variables (structural efficiency, sun lighting and water drainage) which lead to very clever and elegant design solutions. In addition, the conception of the bones system as a series of similar yet different projects was aligned with the premises of this research.

> The pieces that I have obtained using this architectonic-static means have resulted in sections with forms very like the bones of vertebrates. It is not that I wanted to make them like bones; it is just that they turned out that way. That makes you think that, naturally, some parallel exists. You could interpret it as proof that this is the right path; it corresponds to concepts which we see in nature (Fisac 1966, 36).

The "bones" system consists of a string of identical concrete voussoirs that are posttensioned to assemble long beams (Figure 1). A group of tension cables keeps the voussoirs together, reduces the risk of cracks, and therefore improves the waterproofing of the concrete. The key point of this system is a smart and meticulous design of the cross section, which solves several structural and construction problems: the pieces are hollow, making them lighter while keeping a high moment of inertia; the asymmetrical geometry creates openings for natural lighting; the valley collects and drains the rainwater; and the curved geometry improves the acoustic performance of interior spaces (Figure 2).

The major limitation of the system lies in its inflexibility. First, it works almost exclusively for linear arrays of beams for flat and orthogonal slabs, which limits the building typologies that could potentially adopt this structural system. Fisac's attempts to materialize a radial array presented unresolved technical issues in relation to the joints and it was not very successful in aesthetic terms (Tejada House, Madrid, 1967). Additionally, the light wells created by the system are homogeneously distributed, which makes natural light uniform and thereby produces a system too rigid to accommodate different programmatic functions.

2.2 PARAMETRIC CONTROL OVER GEOMETRY AND FABRICATION

A project called "Fisac Variations" was designed as a proof of concept to investigate the potential of directly linking parametric modeling with robotic fabrication. The aim of this project was to bring construction variables to the center of adaptable systems' design.

The custom code for an uninterrupted digital workflow proposed by Fisac Variations combines form generation, structural analysis, geometric definition, CNC code generation and robotic fabrication within the same open-source computational environment. This integrated procedure aims to increase adaptability while ensuring fabrication feasibility and stimulating design innovation.

Using advanced digital tools, Fisac Variations focuses on four target parameters: structural efficiency, natural light control, water drainage and fabrication feasibility. The main goal of the project is to develop a system that can adapt to a wider and more complex range of structural, programmatic and organizational requirements.

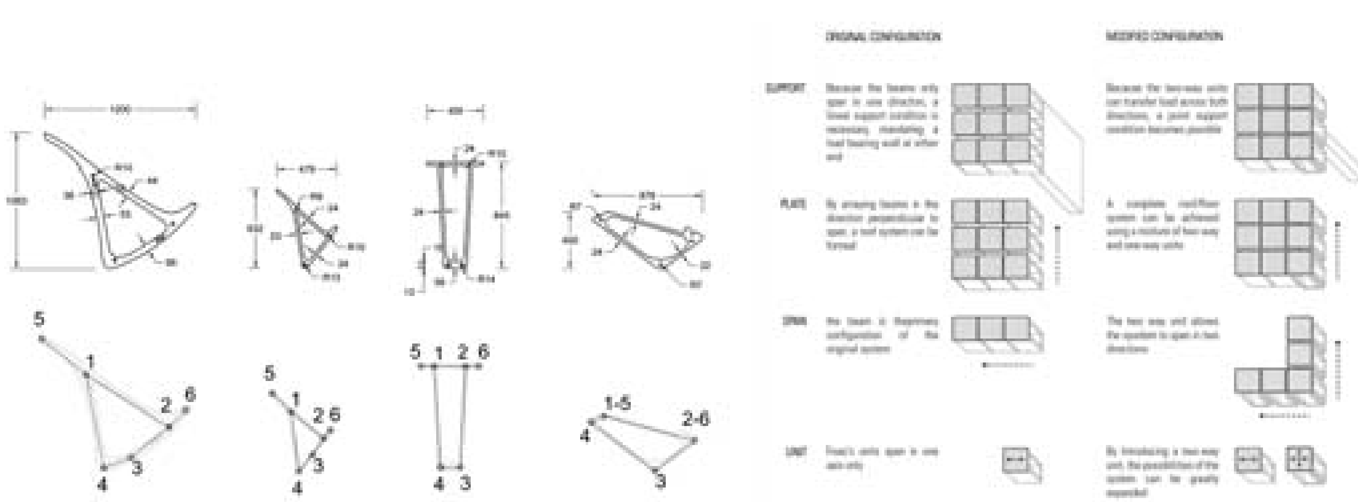
The result is a flexible construction system open to accommodating diverse programmatic functions. The structural performance of the system, which was limited to long span beams, expands to more efficient forms that can follow natural stress lines, minimizing the bending stresses and allocating material specifically where needed. Natural light and water drainage can be also customized at each point of the structure. The construction process is automated as the model embeds production constraints and CNC code generation.

3. IMPLEMENTATION

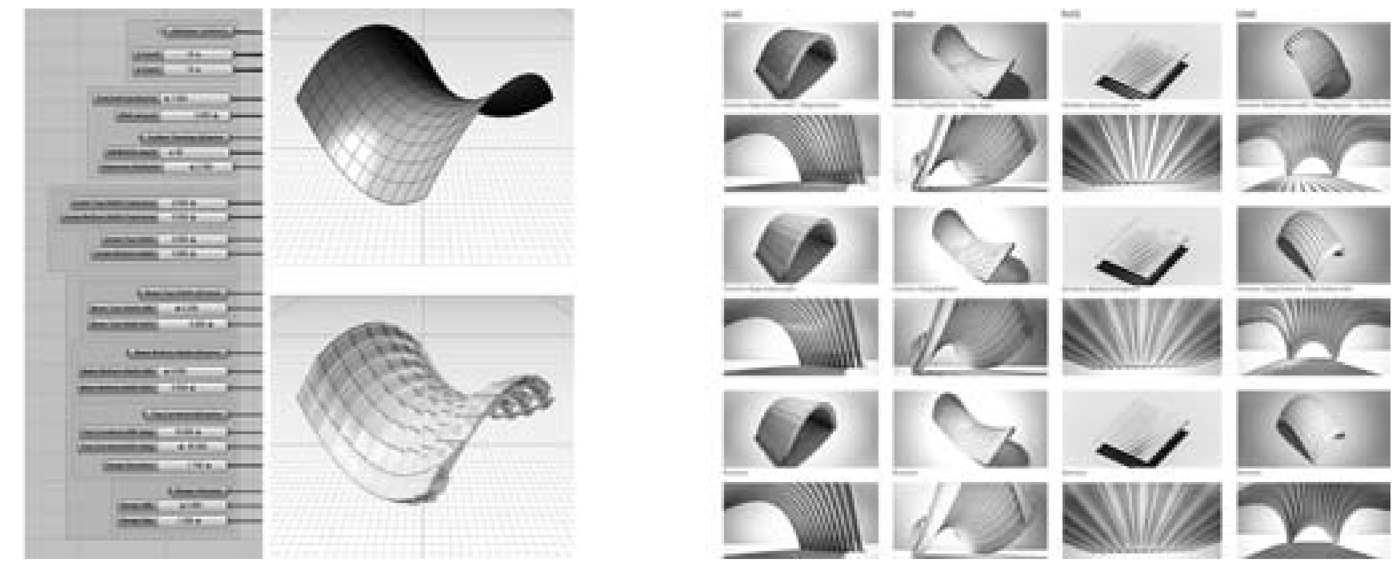
3.1 DIGITAL DESIGN: SYSTEM GENEALOGY

Fisac Variations is designed to adapt to a wide variety of surface geometries, from flat to negative Gaussian curvature. The form generation and geometrical development process takes advantage of an associative model that encodes the clever cross-sectional features of the original system into a section with six control points (Figure 3a). These variable sections can differ along the span of the beams and each pair of them defines a voussoir through a loft operation. Thus, this process allows for gradual variation between pieces and specific control of their performance, with the ability to modulate the geometry in response to particular structural, spatial and lighting requirements.

Another innovation that the project introduces to the original system is the concept of "girders," a technical improvement, which



3ab Left: Parametrization of the "bones" series' six control points; Right: Topological variation by introducing a girder unit



4 Detailed control over structural, lighting and drainage performance, with a wide range of spatial outputs

enables the connection between pieces in two directions (Figure 3b). This feature eliminates the need for continuous linear supports in the extremes present in Fisac's original system. Both voussoir and girders are arranged into a quad, a rectangular array of pieces that creates a quadrilateral surface. The girders, located on the edges of the quad, confer the latter with the capacity to work in association with others and therefore to proliferate into more complex spatial and programmatic organizations (refer to Section 6.1).

The code—based on McNeel Rhino/Grasshopper, Microsoft C# and ABB Rapid Code—defines a collection of beams, organized according to a quadrilateral input surface called a "quad." To generate the geometry, the Grasshopper definition can take two different pieces of data: a custom quadrilateral surface or four vertex points. If a custom quad surface is used as an input, the given surface is discretized into a number of segments and corresponding fabrication curves. Alternatively, if four vertex points are used as input, an additional step allows the user to specify the geometry of the edge curves.

The script provides detailed control over strategic parameters to increase the performance of target variables, that is, structure, natural lighting and rainwater flow (Figure 4).

Structural performance is controlled through depth and thickness of the sections, which are linked to the span and the curvature of the input surface. Structural constraints, such as the maximum curvature that beams and girders can describe in plan, are coded as geometric thresholds. For example, in order for the voussoirs to be post-tensioned, the deviation should not exceed 10 per cent of the span.

Additionally, the capacity to determine location and size of openings for natural lighting, as well as the flow of water, is controlled by Microsoft Excel spreadsheets that regulate the height of points five and six of the sections, affecting the degree of aperture of the lips on each piece.

As a design output, the code generates a set of unique pieces adapted to their specific needs. The script also generates the connection between the voussoirs: a set of keys that facilitates the assembly and improves the structural performance.

3.2 ROBOTIC FABRICATION

The development of fabrication methods that can accommodate customized components is essential to generating flexible material systems. In the case of Fisac Variations, robotic fabrication can solve several tasks, including mold making, concrete casting and vibrating, as well as unmolding and handling of the voussoirs. Due to the limited scope of this project, the focus was on adaptable mold making, with emphasis on the development of scripts that automatically convert the three-dimensional geometric information into robotic instructions to cut expanded polystyrene molds (Figure 5).

Through this automated process, the relatively simple yet customized cutting sequence of each piece was precisely executed by a six-axis robotic arm. For each unique voussoir, a customized mold is fabricated by cutting the EPS with a hot wire bow attached to a robotic arm (Figure 6), a well-known technique that is fast, precise and potentially recyclable since its scrap can be easily collected and added to different construction products. The use of robotic wire cutting of EPS, while not novel,[1] seems to be an adequate use of this material as an inexpensive substrate for the precast molds.

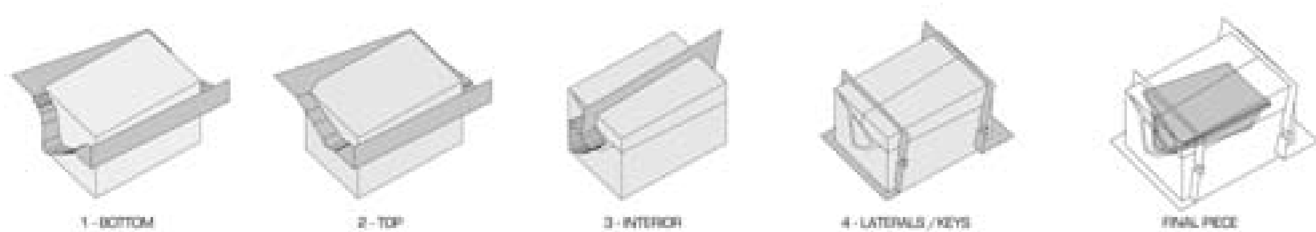
The selection of a six-axis robot for the fabrication process is based on its versatility and on current advances in direct control from parametric models (for example, Brell-Cokcan, Braumann 2010; Schwartz 2013). Precise mold making was consigned to robotic fabrication, while the assembly of the custom pieces relies on a combination of mechanical and manual methods.

> Robotic fabrication is the future, to complement conventional construction methods and craft-based fabrication. Chisels and robots do not exclude each other; they each have their place. As robots re-enter construction it is crucial to know when and when not to use them (Bechthold 2010, 121).

4 TECTONICS: CONCRETE CASTING AND OFF-SITE/ON-SITE ASSEMBLY

The EPS molds are cast with concrete to produce the highly-customized voussoirs. During the 1960's, when Miguel Fisac developed his "bones," the minimum thickness and the maximum size of the voussoirs was limited by the concrete performance and the vibration techniques available at the time. Today, high-tension and self-compacting concrete mixtures combined with efficient assembly lines facilitate the process and open a new spectrum of sizes and thicknesses. Also, the pieces are not hollow as in the original system: after casting, the core is left to fill the cavity (Figure 7).

The assembly sequence is as follows: first of all, the voussoirs corresponding to a beam are interlocked on the ground using the EPS mold as a support. Secondly, they are posttensioned to assemble each beam individually. This process can be done either off-site or on-site.[2] Finally, after putting all the beams in their final



5 Robotic cutting sequence

6 Wire cutting tool and initial cutting tests

position—with or without the use of scaffolding, depending on the support condition—the girders are post-tensioned in the opposite direction, perpendicular to the beam's connection.

5 SYSTEM PERFORMANCE

The system introduces variability in both the overall and the module geometry. Accordingly, the movement of the six points that determine the encoded cross-section produces differentiated beams, allowing customization of the interior space morphology as well as fine-tuned control over structure, water drainage and natural lighting (Figure 8). Currently, requirements for each different target are coordinated by the designer. It is the ambition of the project to automate this procedure with an iterative process capable of evaluating the performance of each target automatically and finding the fittest configurations.

Fisac Variations is capable of being adapted to a wide range of span lengths and structural typologies, from flat slabs to compression-only structures to free-form surfaces. The rainwater can be canalized into desired paths through the subtle movement of the lips that form the upper surface of the pieces. The same feature also permits adjustment of light entrance, admitting gradual or abrupt variations, in harmony with space use and distribution. At an architectural and spatial level, the range of variations provides the project with a new expressive quality and flexibility to adapt to topological and functional complexity.

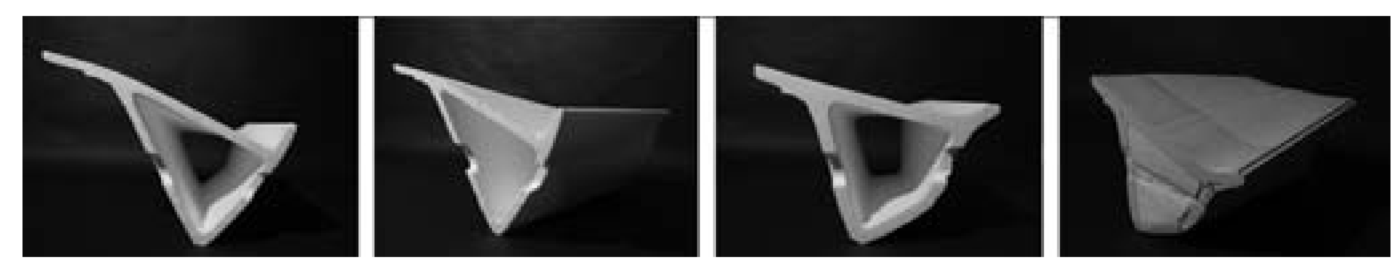
6 DESIGN SPECULATIONS

6.1 PROLIFERATION

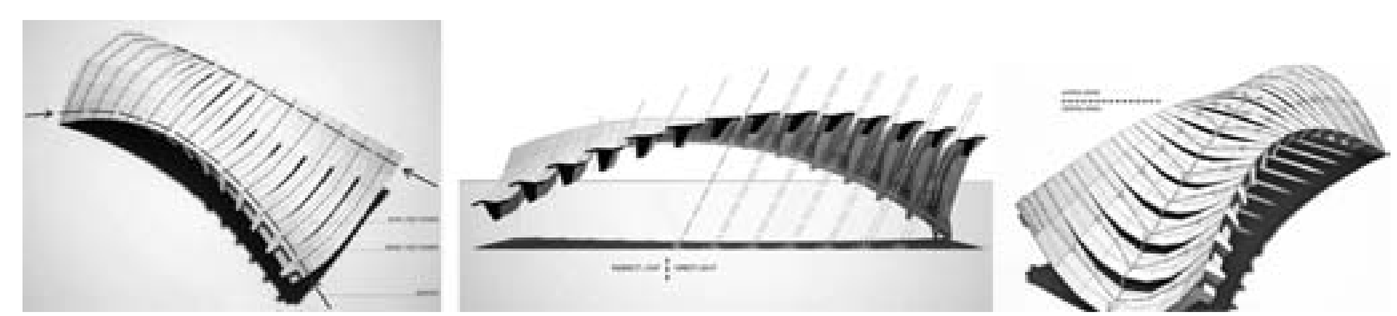
As a building system, Fisac Variations can achieve complex organizations through the proliferation of quads into larger fields. This feature expands the range of application of the system, potentially allocating multiple programs into complex spatial configurations. Figure 9 describes examples of possible compositional strategies.

6.2 SCALES OF APPLICATION

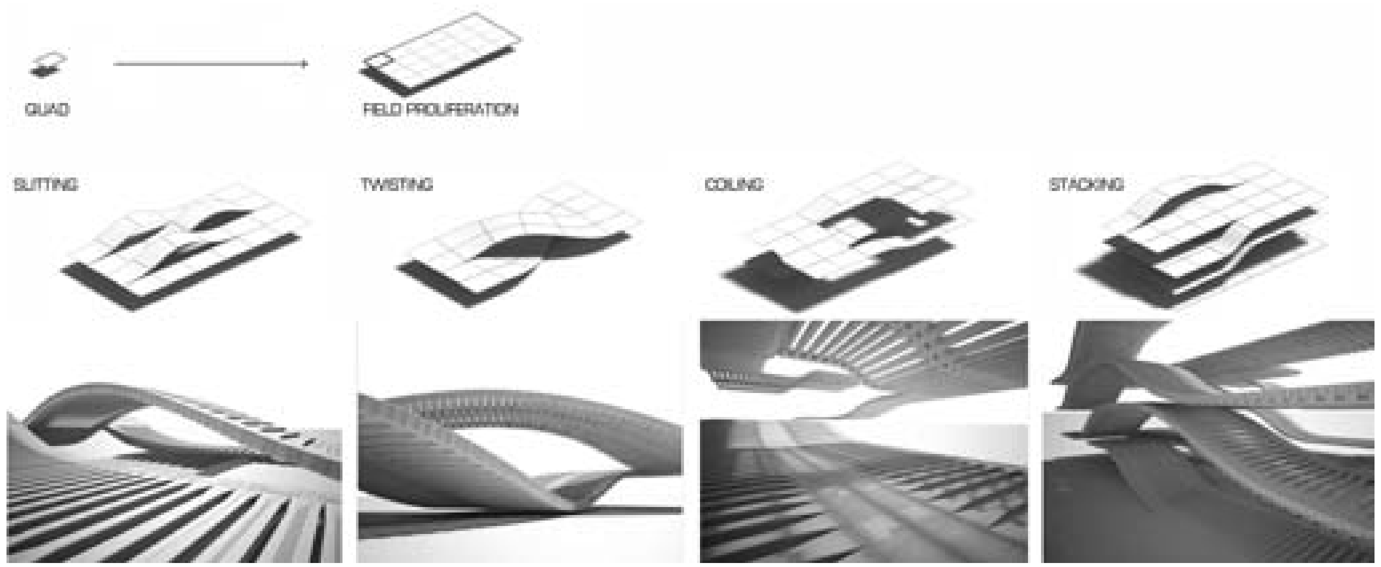
Because of the discretization principle under which the geometry is conceived (explained in detail in Section 3.1), the same quad can be subdivided into different numbers of voussoirs. By augmenting their quantity, the geometrical resolution gets higher, enhancing detailed control over the system performance described in Section 5. Nonetheless, the pieces become smaller, increasing fabrication and assembly complexity. As a consequence, the final number of modules is a negotiation between these two factors. From a speculative perspective, possible applications of the system can range from domestic to infrastructural applications (Figure 10).



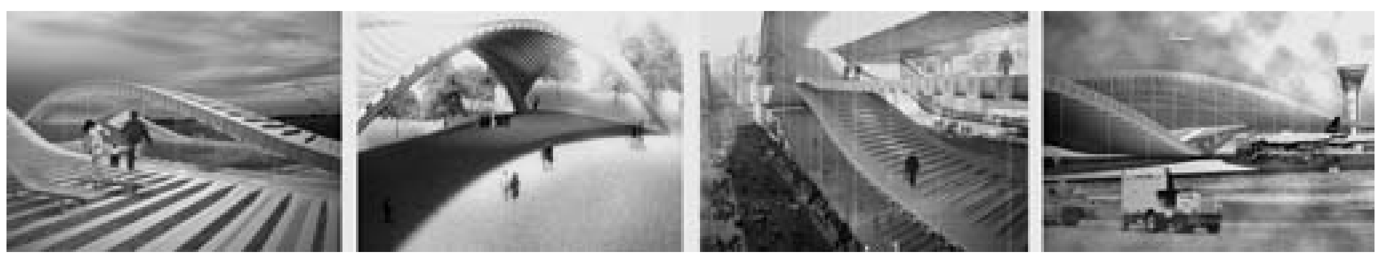
7 Full-scale voussoirs—wire-cut EPS (left) and cast concrete (right)



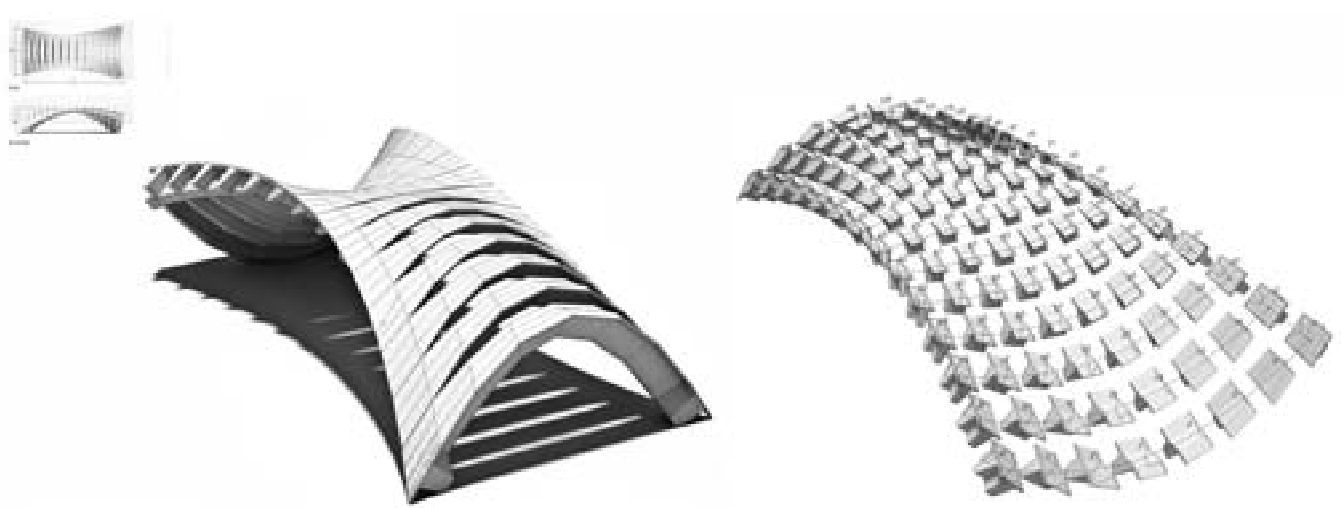
8 Structural performance (left), direct and indirect natural lighting (center) and water drainage strategies (right)



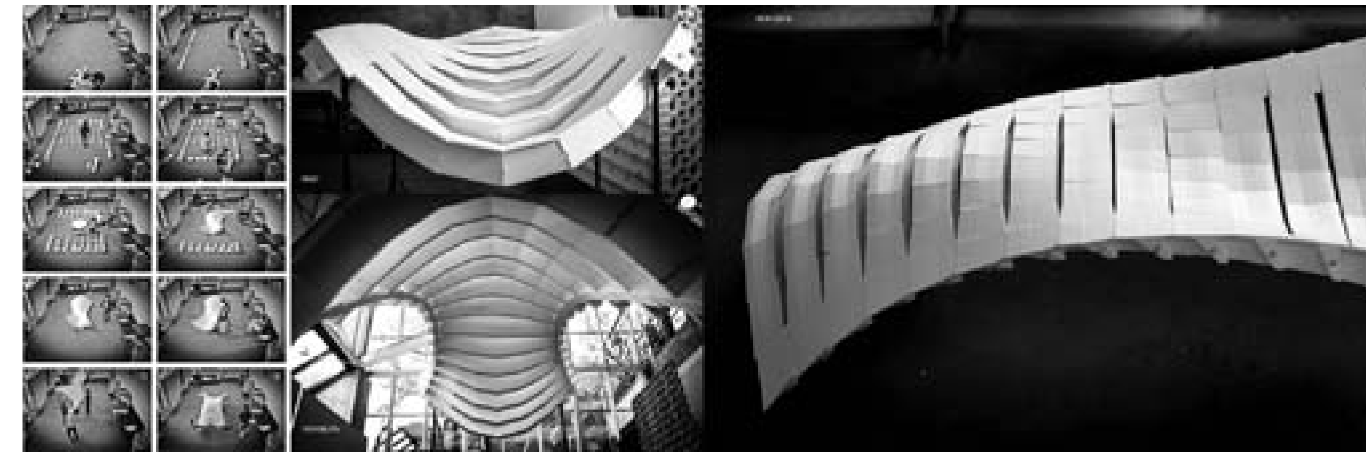
9 Quad proliferations



10 Design speculations at different scales: domestic, pavilion, commercial, airport



11 Prototype geometry and diagram of the differentiated pieces



11 1:5 Prototype in EPS

7 PROTOTYPES

Several building consultations with engineers showed initial feasibility for Fisac Variations as an efficient customizable structural system and established accurate thresholds for spans and geometrical variation. Finally, an EPS prototype was designed as a proof of concept of the adaptive system (Figure 11).

A 1:5 large-scale structure was built, satisfactorily testing geometric accuracy and post-tension feasibility, as well as aesthetic and spatial effects (Figure 12). A full-scale mold was cast and proved operative.

8 FURTHER RESEARCH

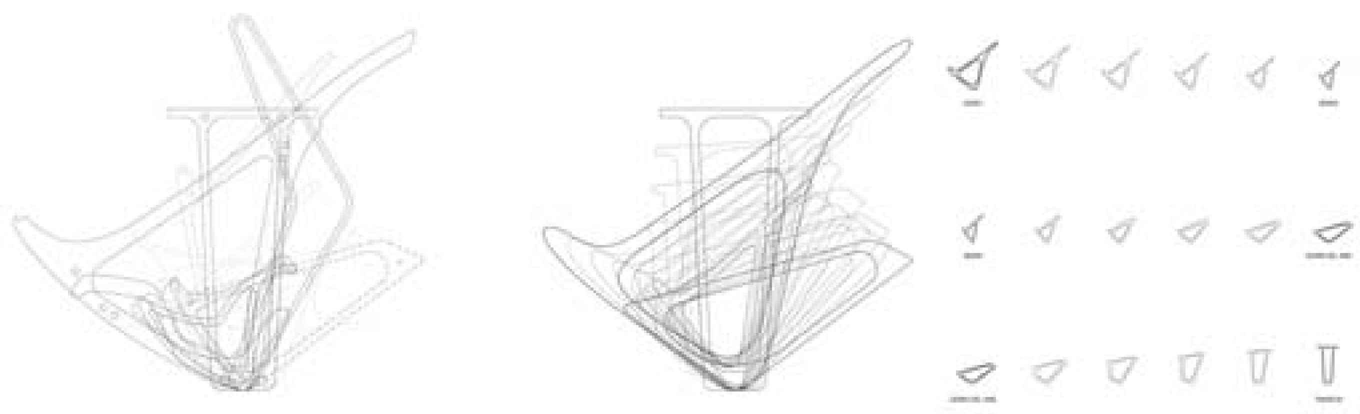
Several areas of investigation deserve further development in order to make the proposed workflow and building system fully operational. First, the integration of analytical tools to estimate structural and environmental performance into the same associative model is essential toward optimizing the continuous design workflow. In turn, this will allow the automation of the form-finding process, a core ambition of this research.

Second, increasing the scale of fabrication will require additional research on larger robotic shops and customized CNC wire-cutting machines. Finally, the development of the on-site assembly sequence, which includes transportation, placement and scaffolding, is in its initial stage.

From a wider perspective, to enlarge the contribution of this research and increase its value to other researchers pursuing similar problems, the proposed methodology and design procedures should be tested with other material systems. This would broaden the advantages of digital processes for adaptive tectonic systems.

9 CONCLUSIONS

It took more than ten years for Miguel Fisac to accomplish eleven variations of his "bones" system (Figure 13a). Today, using digital technologies, endless variations can be conceived in a much shorter time (Figure 13b). In digital design, the rate of variation is crucial for adaptive architecture: systems that mutate at faster rates have higher chances of success.



13ab Left: Original Fisac's "bones" sections; Right: Example of Fisac Variations' interpolated range

An important line of research in digital design considers architecture as adaptable systems with the potential to adjust to the specificities of each site and program. This approach is grounded in a set of computational methods. First, three-dimensional models allow designers to understand, describe and generate geometrical complexity. Second, analysis and simulations enable anticipation of the relationship between formal expression and the behavior of materials and spaces. Finally, digital fabrication facilitates the production of precise, nonstandard components.

When these methods are interwoven in a continuous workflow, fabrication information can retrofit the design of adaptive tectonic systems. A wider range of design possibilities and a faster pace of fabrication emerge. Revisiting Miguel Fisac's "bones" showed that this approach is feasible and that it can lead to the design of a system that can not only adjust to environmental and structural parameters, but also integrate fabrication variables into the generative process. Moreover, as with the case of Fisac's designs, the formal and expressive qualities of the adaptive models reveal that systems can drive structural efficiency into sophisticated architectural spaces.

From a broader perspective, this research proposes a framework for the development of new efficient, adaptive and feasible structural systems attainable only through the integrated use of digital design and fabrication. Instrumentally, the set of tools and workflows can be applied to other tectonic systems, expanding beyond the design procedure for a specific case study.

Ultimately, the approach to digital design proposed in these pages strategically deploys digital tools with the aim of bringing tectonic expressivity to structural materials, expanding the range of outcomes. Consequently, materiality as an immanent architectural constituent becomes the driver of adaptive tectonic systems.

10 ENDNOTES

1. Several projects of EPS cutting with a hot-wire cutter bow attached to a robotic arm have been developed during the last few years at the University of Michigan Taubman College of Architecture and Urban Planning Digital FABLab, directed by Wesley McGee.

2. While off-site assembly offers better performance according to building time execution, on-site assembly overcomes the transportation constraints typical of crowded urban centers—sometimes with narrow streets—by moving the voussoirs to the site one by one.

ACKNOWLEDGEMENTS

This paper presents the results of a project for the course SCI 0642300 (Re)fabricating Tectonic Prototypes, taught by Leyre Asensio-Villoria at the Harvard University Graduate School of Design. Her input and advice were pivotal for the development of this research.

The positive feedback of Hanif Kara, from London-based firm Adams-Kara-Taylor (AKTII), as structural consultant was also encouraging and helpful for the development of the system. For machine coding, Panagiotis Michalatos's support was of crucial importance.

Last but not least, the support of the Design Robotics Group (DRG) was vital for building the robotic tool.

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