Digital Design and Fabrication of Freeform Concrete Blocks

The experience of ‘Cobogo Trança’

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This paper describes the methods and results of an experimental workshop held at the Department of Architecture of PUC-Rio devoted to exploring design alternatives and digital fabrication techniques to produce concrete façade elements for the Consulate General of Portugal building in Rio de Janeiro, Brazil. The workshop aimed the adoption of advanced computer-aided design and production methods within a rare and innovative university-industry collaboration context in Latin America. The paper aims to discuss contemporary concrete casting methods and its applicability, as well as the achievements and pitfalls of the adopted technique. The results are discussed under the light of Antoine Picon’s notion of contemporary ornament and Branko Kolarevic’s perspectives on digital imprecision.

Keywords: digital fabrication, free-form concrete block, design education, interdisciplinary collaboration

INTRODUCTION

Digital fabrication is unquestionably the main force behind architectural innovation in the past two decades. It has been enabling architects and engineers not only to solving existing problems more rapidly and efficiently but more than that to inspire professionals to address new design issues. Every day, new researchers on digital design and fabrication technologies are stimulating the development of a broad range of interests and strategies in order to materialize increasingly complex and customized solutions in architecture (Duarte et al. 2004).

Tectonic and material aspects have been at the center of most recent discussions, considering both innovative and traditional building materials. Despite the growing interest in new materials, reinforced concrete still is the most widely used in construction today. Throughout its history, concrete has been subjected to massive research addressed to investigate performance aspects as a construction material, aesthetic expression and tectonic potential in architecture (Peters et al. 2017). In addition to its significant impact on building culture worldwide in the last hundred years, reinforced concrete is a frequent structural material choice since almost any shape can be achieved by pouring concrete into a formwork.

In contrast, the zenith of the concrete shell structure is long gone (Peters et al. 2017). The world-
wide popularity of concrete guarantees a relatively low cost of productions inputs. However, the historical decrease of concrete shells is usually imputed to the high costs involved in producing complex, time-consuming formwork (Peters et al. 2017).

The introduction of digital fabrication processes into the vast realm of concrete construction opens up a myriad of opportunities for built environment renovation, but at the same time, presents particular difficulties, since the interaction of digital technologies with analog manufacturing remains rather unexplored (Martins et al. 2014). Digitally generated designs tend to have limited relation to the efficient modes of production typically used in contemporary concrete construction. Addressing the need for innovation in the casting of concrete is an important measure (Kristen et al. 2013).

This paper describes the methods and results of an experimental workshop held at the Department of Architecture of PUC-Rio devoted to exploring design alternatives and digital fabrication techniques to produce concrete facade elements for the Consulate General of Portugal building in Rio de Janeiro, Brazil. The workshop aimed the adoption of advanced computer-aided design and production methods within a rare and innovative university-industry collaboration context in Latin America, involved both Brazilian and Portuguese teachers, the main architect of the building project, the contractor, and institutional authorities. The built façade is shown in Figure 1.

**THE TASK**

The main task was to create a ‘cobogo’ brick for the expansion building. ‘Cobogo’ is a perforated wall element created in Brazil in the 1920’s. The ‘cobogo’ acts as a brick yet allowing air circulation and light penetration, performing an important environmental role considering the tropical climate. It became very popular during Brazilian modernist movement, when architects created many different ‘cobogo’ shapes and designs, in distinct materials, such as ceramic, concrete and glass. Despite its traditional character, several contemporary Brazilian architects use ‘cobogos’ in their façade designs, for both functional and aesthetic reasons.

The workshop had two goals: to create an outstanding, unique ‘cobogo’ brick and to establish the appropriate technique to fabricate the full-scale piece, considering local conditions, materials, and budget. The elected material was concrete for several reasons. Concrete is a very important material for both Portuguese and Brazilian contemporary architectural culture. The expansion-building concept was to create a solid yet discreet volume with a tectonic expression that would not interfere in the existing historical construction. A concrete ‘cobogo’ should perfectly integrate with the proposed architecture. Additionally, the plasticity of concrete would allow students to experiment virtually any shape. The pieces were to be placed at the main entrance; hence, safety issues were mandatory.

From the architecture point of view, the main challenge was to create a strong contemporary design that could evoke the Portuguese tradition. The nature of the ‘cobogo’ brick in the light of digital design and fabrication techniques implied a parametric tessellation design concept, yet closer to Picon’s notion of contemporary ornament (Picon 2014), in which structural and functional approaches also communicate with an ornamental dimension. Patterns as renewed expressions of ornament are embedded in several examples of contemporary architecture, such as Zaha Hadid’s King Abdullah Financial District and Sleuk Rith Institute. Assuming Picon’s viewpoint, the propositions had to tune in with this particular feature of contemporary architectural production, i. e. “the capacity of what used to be considered as pure structure or pure functional to appear ornamental” (Picon 2014).

From the production point of view, students were asked to solve constructions issues derived from the proposed shape, consequently to deal with material aspects of concrete bricks’ production and formwork pouring. At present, when new digital techniques are constantly broadening the expres-
sive and formal possibilities of curved shapes, brick-work is still constrained by formal limitations (Inbern 2014). The formwork types traditionally available (timber and steel) introduce significant geometrical constraints to explore new formal possibilities. Such restrictions explain the dominance of undifferentiated repetition in most concrete constructions (Imbern 2014).

The participants were also confronted with the productive method limitations at the construction site. Thus, their investigation faced the challenges of making a feasible innovative piece and engaging a production system that could be easily implemented with current hand-labor. In this sense, it was imperative that the desirable formal complexity would be accomplished through a design procedure that would be still feasible to fabricate under low-tech conditions with minor modifications in the manufacturing method.

WORKSHOP BACKGROUND

The Portuguese chief architect, Pedro Campos Costa, idealized the workshop, performed in close association with the Architecture Department of PUC-Rio. Casais Brasil the construction company in charge of the building renovation sponsored the workshop. The studio was made possible through collaboration between Architecture, Design and Engineering departments. The three departments made available their labs, machines, and tools, including a table size CNC milling, plastic 3D printers, a high definition resin 3D printer, a large-scale CNC milling machine, a laser cutter and traditional woodwork tools.

The workshop preparation began in April 2016. The groundwork period was essential to evaluate the production time needed, required materials and planning class’s exercises. The original ‘cobogo’ designed by the architect was used for testing purposes. Several scaled formworks in 1:3 scale were produced to testing concrete mixture and the surface finishing. The test period revealed that the main challenge would undoubtedly be the full-scale formwork’s manufacture.
The workshop ran in the last two weeks of August 2016. Close to 30 graduate and undergraduate students from different fields and institutions attended the studio. The chief Portuguese architect and instructors from distinct backgrounds, such as architectural history and theory, concrete engineering, parametric modeling and digital fabrication, work together leading students into an experimental exploration of interdisciplinary design.

METHODS
As explained before, students were asked to test new possibilities of designing and building complex forms with ceramic elements, solving the architectural, structural, and production issues involved. Moreover, they were stimulated to explore advanced geometric modeling, parametric design and rapid prototyping in the generation of digital and physical models. These models would later be used to define digital fabrication strategies and to produce the information required for constructing the formworks.

The heterogeneous group of students from Design, Engineering and Architecture Departments, in different levels of graduation and almost none of them with previous experience in advanced modeling, parametric design or digital fabrication, required a well-structured teaching strategy. Since the majority of participants were architecture students, the group was strategically divided in a way that every team had one design student and one engineering student. The interdisciplinary teaching approach and the mix of students from different fields was later proved crucial to obtaining the outstanding results.

The teaching program for the intense workshop was divided into four modules:

1. The architect opened the workshop with a lecture about the assignment, regarding the symbolic and traditional issues that the proposed ‘cobogo’ should relate to. The lecture was followed by a discussion on Portuguese contemporary architecture aspects and its relations to the global state of the art.
2. Students had three full days of Rhino and Grasshopper classes focused on parametric tessellation tutorials. Mediating light, air and intimacy is a core function of ‘cobogo’. To address these aspects, Grasshopper’s plug-in Ladybug was used to test the performative behavior of the assembled pieces.
3. Concrete specialist engineering teachers instructed students about concrete properties, structural requirements and casting methods. They also assisted students during the conceptual design phase in order to orient formal decisions mediated by performance aspects.
4. Students were instructed in digital fabrication processes available for production. The notion that material behavior and formal intentions guide fabrication strategies was reinforced. Students learned how to convert and prepare complex geometry in SprutCAM Software. Distinct digital fabrication methods were used, thus CNC milling method prevailed.

In the first week, participants developed design concepts and several prototypes to test ideas. Students were encouraged to mix traditional analogic techniques with parametric design and digital fabrication, including hand sculpting, paper folding, 3D printing, laser cutting and CNC milling. as can be seen in Figure 2. Many students used the physical models to understand material behavior and tessellation logics. Figure 3 shows students testing tessellation compositions in both analogic and digital methods. The hands-on approach was essential for unskilled students to understand how parametric relationships could be elaborated. The design concept phase was undertaken in short-term feedback cycles. For each cycle, students delivered a full project development, including design results and fabrication strategies. After each cycle, the problems were analyzed and new solutions were integrated into the following round.

The second week was devoted to refine the designs based on critiques and to produce 1:3 scale samples in plaster, using digitally fabricated formworks in EPS (Expanded Polystyrene Foam). Considering the limited amount of time available, the teach-
ing method focused on imparting basic knowledge of material properties. During this period, the main strategy was to place the future digital development of large-scale prototypes with real construction materials and constraints at the center. This approach provided the means to rapidly evaluate the spatial and architectural qualities of projects, fabrication requests, assembly possibilities and joining interface with the existing building.

The adopted strategy defined a direct relation between material behavior, form and construction technology, “which has become increasingly relevant in the contemporary concept of digital materiality” (Gramazio and Kohler 2008). Figure 4 shows the participants and the models produced in two weeks.

**MOCK-UPS AND RESULTS**

From September 2016 to February 2017, the team produced eight full-scale formworks. The chief architect defined the block size. Each brick had 48 x 48 centimeters front by 30 centimeters depth. Four out of five proposed designs, plus the original piece designed by Campos Costa were fabricated. The formworks were filled with concrete at the construction site. Figure 5 shows the concrete blocks out of the formworks. Each formwork consisted of a 3D milled polystyrene core, corresponding to pieces’ voids and wood sheathing. EPS was a favorable choice since it is inexpensive, light weighted and faster to mill. The material also proved to be capable of resisting the casting process forces and at the same time, sufficiently soft to be accurately milled into a complex surface.

The machine available to perform the task was a large format CNC router. This machine imposes a series of restrictions on the manufacturing process. Each design required a specific sectioning process to eliminate negative angles. This strategy also avoided double-faced milling processes with three-axis CNC machines which are inefficient and time-consuming. In addition, the machining height was limited to only 8 cm on Z-axis. It means that the pieces had to be submitted to a second sectioning process. To reach the 30 centimeters block depth, each piece was split in at least four parts. The most dramatic situation was a 24 parts split to produce a single piece. Even though the modeling and the CNC control tend to be very precise, imposing several subdivisions to a milling process may result in a very imprecise outcome due to microscale errors accumulation.

After completing the milling process, and assemble the parts together, it was necessary to regularize the surface to ensure a perfectly smooth finishing
and to seal the EPS completely against chemical attacks from concrete mixture reactions. Many hours of manual labor were devoted to completely regularize EPS surfaces. The EPS surface was first completely sealed with water-based resin to avoid absorbing the plaster.

Then, it was required several layers of water-based plaster followed by sanding to completely remove both joining marks and milling pattern marks. After completely dry, the surface received several coats of water-based resin. The customized wood sheathing completed the formwork fabrications, as can be seen in Figure 6.

At the end of this phase, the architect decided for one of the students’ design. The selected ‘cobogo’ was inspired by the combination of two strong Portuguese symbols: the “knot” from the “Great Navigations” and the traditional art of weaving, originating the “braided” pattern. The result is a composition of two distinct ‘cobogo’ bricks that could be combined in different ways to generate thousands of compositional possibilities. The tressed pattern was named by the chief architect as “Cobogó Trança” in Portuguese or “Braided Brick”, in a free translation. Ironically, it was the only piece that had not been produced until then.

From February to May 2017, Portuguese and Brazilian parties collaborated to develop a suitable formwork design, while the Portuguese bunch executed the design adjustments. The original shape gained uneven contours. Furthermore, some design modifications to accomplish structural requirements were in task, such as the introduction of lateral holes to accommodate a post-tensioning system during assembly, shown in Figure 7.

The mock-ups’ formworks of the elected pieces
were extremely challenging. Literature provides many examples of concrete casting techniques using digital technologies (Peters et al. 2017; Martins et al. 2014; Kristen et al. 2013). There are four main concrete casting systems: rigid and flexible formworks (Peters et al. 2017); dynamic formation (Kristen et al. 2013) and additive fabrication based, i.e., 3D printing. The most innovative systems usually rely on robotic fabrication or laser-based additive fabrication. All the methods described by these researchers successfully demonstrate new approaches for the fabrication of double-curved concrete pieces, which combine century-old fabrication techniques with contemporary digital technologies (Kristen et al. 2013). However, the limitations in the achievable curvature and resolution on each described research prevented the adoption of such techniques considering the level of details and complexity of the braided brick. In order to obtain the desirable smooth finishing surface, addictive 3D printings methods were also discarded. Additionally, the available amount of time for fabricating 120 pieces needed, plus the handwork pouring method adopted at the construction site had to be considered.

After some tests and debates, the team considered that the best procedure was to 3D mill the pieces to perfection and then extract the formworks’ molds from them, instead of milling the formworks themselves. In other words, unlike the traditional formwork milling process, the geometry to be milled was the piece itself, and not the corresponding void. However, to compose the final formwork, the cutting plane surface had to be included in the milling geometry, as to maintain the joining reference. Thus, the pieces were divided into two parts based on the curvature. As a result, a visible joint line between the two parts after concrete casting would result in a curve. After completing the milling operation, the formworks were then extracted with a vacuum-forming process. The pieces were milled in green MDF to withstand vacuum pressure. This material is far more resistant than ordinary MDF and it has proved to be an excellent milling material. Besides, it is much faster to mill than wood and the finishing result is excellent. Figure 8 shows one half milled in green MDF and the correspondent plastic formwork extracted by a vacuum-forming process.

One of the major problems of this method was the curvature of the edges at the cutting plane. The milling process always results in rounded edges, even if very small milling cutter width is used. The concavity was increased by the vacuum-forming process due to the plastic width and the natural material reluctance in bending to the mold surface. The rounded edges at the joining plan can be seen in Figure 9.
DISCUSSION AND CONCLUSIONS
Digital fabrication is one of the last expanded fields of CAAD. The first practices in digital fabrication in Latin America had a “strong global accent” (Sperling et al. 2015), focused on tools and devices. Initiatives with a “local accent” (Sperling et al. 2015) engaged with the local specificities in technological, cultural and social terms are very recent (Sperling et al. 2015). Hence, digital fabrication practices in Architecture in Latin America are incipient. Despite the growing number of digital fabrication labs in the world, only 5% of them are located in Latin America (Sperling et al. 2015). The region still has to face major challenges concerning economic investment in technology and infrastructure improvements.

This brief contextualization highlights the importance of concrete examples, like this one, to stimulating digital practices in “countries at initial stages of architecture digitalization” (Sperling et al. 2015), where discussions on digital tools are typically focused on productive issues, and not on computational design thinking or digital fabrication (Borges 2016). It also emphasizes the importance of fostering closer ties between architectural practice, academia and industry in a collaborative perspective in such countries. The success of this collaborative experience contributes to undermining local beliefs that the use of such technologies is a distant reality in developing countries or that it is impossible to produce digital architecture with local meaning as a counterpoint to the dominant vision of a European and North American on technology. Many benefits come from the multiplicity of angles, embedded with a close bond with the local reality and tactical view of technology. The future of digital fabrication in Latin America will definitely deal with enormous challenges ahead. The expansion of collaborative networks is essential to overcome obstacles and shall pave fruitful paths to explore.

Regardless of its regional importance, the fabrication process described in this paper enlightened a few aspects of broader interests. During the research for solutions, many examples of more advanced fabrication methods were considered. However, the peculiarities of the task at hand, both in terms of design and manufacturing conditions, made clear that sometimes, the most progressive technique is not the most suitable one. However, it does not diminish the relevance of the technological achievements of this enterprise.

Another important aspect is the precision issues regarding hybrid manufacturing processes, such as described. AD High Definition published in 2014 was dedicated to endorsed a “zero tolerance is design and production” in the digital age. We agree with Kolarevic’s counterpoint (2014) that “freeform high-definition fabrication requires an equally high-definition design context. Designing in this space not
only requires new methods and tools; there is also a need to relate back to function through human interaction. The precise 3D milling process described in this paper enclosed imprecisions to the formwork which, in turn, were easily solved by hand. The type of material also plays an important role when pursuing high precision fabrication methods. A certain level of imprecision is inherent when hand-labor and concrete are at the stage. As Kolarevic (2014) stated: tight tolerances (which should not be mistaken for no- or zero tolerances) are also tied to the kinds of materials used in tectonic assemblies; some materials, such as metals and glass, can be CNC machined with considerable precision (as opposed to concrete casting).”

Although materiality and means of production were a tangible concern, the defining issue favorable to picking ‘Cobogo Trança’ was undoubtedly its design qualities. Budget, site construction methods and time available restrictions prevented students to explore a full parametric variation. Nevertheless, these constraints did not stop students’ ingenious to overcome these obstacles. Two static pieces could create a complex movement. This contemporary architectural ornament was a successful product of parametric tessellation with a local accent, resulting in a very complex smooth surface yet full of expressiveness and symbolism. Tradition and novelty, rules and exception, precision and inaccuracy, digital and manual were blended together into tactile and affective dimensions. Far beyond the mere aspect of aesthetic delight, this mix stimulates the spontaneous faculties of the spectator in face of recognition and surprise.
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