Abstract. The introduction of digital tools in the production of architecture undoubtedly constitutes the main force behind contemporary architectural innovation. In addition, the interaction of digital technologies with analog craft manufacturing - a rather unexplored field of study - suggests a wide range of novel opportunities. This research focuses on developing a framework for deploying digital design techniques to the production of bricks under vernacular technology as a medium of achieving geometrical variations and functional complexity in domestic-scale projects.

Solid clay bricks are embedded in traditional ceramic-construction culture. Thus, this investigation faces the challenges of making a feasible innovative system in a country where digital fabrication is not an economically viable option, and engaging a design that can be easily implemented with current hand-labour. Consequently, the new bricks would be massively introduced in the construction market, allowing novel formal and functional possibilities for designers.

Keywords. Ceramics; brick; tectonic; digital tools; fabrication; vernacular technology.

1. Introduction: Toward digital masonry systems

Today’s explosive growth of digital technology has affected the core of architectural design. Certainly, digital tools offer new possibilities that were inconceivable only a few years ago (Picon, 2010). This research explores the creation of a new architectural language resulting from the merger of digital technology and masonry construction in order to reinforce the use of brick as a contemporary material, especially in developing countries where this raw material is widely available.
As initial statement, the influence of complex geometry in the development of different branches of contemporary architectural discourses is unquestionable. Notwithstanding, in the context of this investigation, complex form is understood as an enabler of new functional performances for masonry construction.

2. Research Framework

2.1. BRICK CONSTRUCTION

Masonry is one of mankind’s oldest materials and brick is the oldest manufactured product in use today. Regardless, there were two decisive episodes that contributed to undermine its predominance among construction materials:

- Its structural capacity was severely questioned after the Monadnock Building in Chicago, built in 1891. Additionally, the San Francisco earthquake of 1906 revealed the weaknesses of brick buildings in earthquake-prone areas. These problems were overcome by the introduction of steel reinforcement to resist shear and tensile stresses.

- At the beginning of the twentieth-century, the advance of new technologies as a consequence of the Second Industrial Revolution led to the decline of brick, which seemed almost irrelevant for the Modern Movement philosophy, with only few exceptions.

2.2. DIGITAL TOOLS

At present, when new digital techniques are constantly broadening the expressive and formal possibilities of curved shapes, brickwork is still constrained by formal limitations. Despite the fact that there are some examples of brick-architecture successfully surmounting with this issue, the experimentation with complex geometry is still problematic, especially in domestic-scale projects, where the radius of curvature tends to be smaller and the mortar cannot absorb the irregularities. This condition creates a negative feedback loop within the architectural practice since brick is the most common material available in emerging-economy countries. Finally, brick is currently associated with historic reminiscences; therefore its major implementation is linked to the production of architectural revivals of extremely poor design quality.

An innovation is needed in order to re-invigorate brick as a contemporary construction material. At present, the use of computer-aided design and analysis techniques allows for unprecedented degrees of efficiency in design and construction (Bechthold, 2008).
2.3. LINKING THE MODULE AND THE PATTERN

Diverse case studies of complex geometry are analysed in order to understand the intrinsic relationship between the module and the pattern of aggregation, and to define a potential area of contribution for the research (Fig. 1).

Fig. 1: The chart above maps the projects into a matrix that traces different paths followed by architects and designers while envisioning complexity in their buildings by combining the spectrum of variables that the module and the pattern exhibit.

3. Material System Genealogy

Conceptually, the proposed material system is divided into minor components that can be easily assembled, as a method to facilitate and enhance the construction of complex spaces (Fig. 2). This 'architecture of components' shares the strategy of facilitating on-site assembly with the work of Solano Benitez’s, who explored pre-assembled brick panels as a mechanism for enabling complex formations (Freitas and Hereñú, 2012).

Fig. 2: Bottom-up strategy. Assembly sequence proposed by the system: from module to component, then to architectural entity, and finally to architectural space.
4. Brick Metamorphosis

4.1. WARPED BRICKS PARAMETERS

The research procedure is divided into stages, starting by executing simple geometric operations onto current bricks and then studying possible (re)combinations, as well as structural, spatial and functional performances. The use of digital tools constitutes a key part of the process, to test not only the specific geometry of new bricks but also its aggregations and tolerances while proliferating.

Bricks are modified by the introduction of two dependent variables: the creation of a hole to place a post-tensioning reinforcement inside the bricks and the geometrical variation while keeping the capacity to be produced under low-tech manufacturing techniques. The starting point of the re-design of the bricks is to maintain the rectangular shape and the parallelism of two opposite faces, a property that allows the new pieces to work together with current bricks. Afterwards, the strategy adopted to generate a new geometrically complex brick is the rotation of one these faces (an operation that also modifies the other four, conceived as lofts between the first two). The result is a new module called "warped brick".

Multiple variations of bricks, according to the type of form and function pursued, can be controlled by two modifiers. The first one is the position of the rotational axis (Fig 3: a), which establishes three families of warped bricks: Heather, Stretcher, and Bed rotation. The second modifier is the angle of rotation (Fig 3: b), which changes the amount of torsion that the warped brick performs.

Once the logic behind this mutation process is defined, the criteria are turned into computer software parameters, using McNeel Rhinoceros and Grasshopper as digital environment for associative modelling.

Fig. 3: Warped brick genealogy: (a) geometrical operation; (b) module variation: from standard to warped bricks; (c) helicoidal assembly.
4.2. ASSEMBLY INTO COMPONENTS

The post-tension hole introduces a modification regarding traditionally bonding by enabling the assembly of warped bricks to form bigger components called "helicoidal-courses". This operation reduces the intensive use of hand-labour (compared with other techniques that deal with complex geometry on-site) since no special skills are required for its implementation. It also simplifies the requirement of formworks and scaffolding.

Geometrically, a helicoidal-course can be explained as a linear array of bricks arranged in continuous rotation, creating a slender building element that acts as an independent fragment of the overall construction assembly (Fig 3: c). As initial structural statement, the deviation of the helicoid should not exceed 10% of its span in order to the post-tension be effective.

The warped faces that rotate during the helicoidal-courses’ trajectory create a smooth surface continuity which rotates between horizontal and vertical positions, eliminating the rigidity and monotony associated with traditional brick constructions, introducing an architectural language characterized by the use of slender elements.

4.3. ARCHITECTURAL ENTITIES: (RE)COMBINATION OUTCOMES

The helicoidal components are assembled to conceive different architectural entities, divided into four categories -it could be more-, according to their functions (Fig. 4):

1- Continuous Facade: smooth ruled surfaces that allow geometrical continuity between horizontal and vertical position used to control natural light distribution in interior spaces (sunshades) or to allocate soil (green pockets) as a thermal insulation. Inspired by the work of Patrick Blanc, the system provides conventional masonry with the capacity to generate ‘vertical gardens’; these elements may become natural screens for aesthetic purposes as well as noise or thermal barriers (Dunnett and Kingsbury, 2004).

2- Three-Dimensional Screen Walls: outer-rotation warped bricks are assembled from simple associations to complex network formations. The thickness and density are controlled by the organizational pattern.

3- Turning Supports: helicoid courses are structurally compelling when working combined, creating an architectural language where structure and visual openings merge into one single element.

4- Weaved Canopies: according to initial calculations, cement bricks are necessary to support the resulting post-tensioning force. A specially-design branching piece plays an essential role, allowing the conception of compelling structures.
All entities are capable of accommodating sharp curves because the post-tension allows the suppression of the traditional bonding logic (overlapping of 50% between bricks of contiguous courses). The stack bonding becomes structurally resistant and geometrically versatile.

Fig. 4: Architectural entities.

Fig. 5: Digital iterations for continuous facade with smooth light transitions.

4.4. ASSOCIATIVE MODELS

The research aims to develop intuitive-to-use design tools that synthesize computational design and physical results into one continuous process (Gramazio and Kohler, 2008). The correlations and interdependence between the subsystems is what finally triggers the design (Schumacher, 2011). In the context of this investigation, scripting has the objective of envisioning and customizing architectural entities (Fig. 5). Through their combination and superimposition, even more complex formations are attainable up to the creation of architectural spaces as unfolded in the next section.

Within this framework, architects are able to customize their own tools in order to find new applications for the warped bricks to satisfy their requirements.

5. Architectural Spaces: Design speculations

The following designs reveal how the resulting brick system can adapt to a wide range of typologies, expanding the possibilities of traditional brick masonry (Fig. 6). The examples, far from aiming to be evaluated as architectural proposals, intend to prove how the system can be adopted by different design philosophies (from curved to box spaces) and work integrated with common bricks or as an autonomous material system.
6. Fabrication

The formal complexity accomplished through the design procedure is still feasible to fabricate under low-tech conditions with minor modifications in the manufacturing method -Soft Mud- such as the shape of the mould and the introduction of a hole to accommodate a post-tensioning system during the assembly.

Digital fabrication is only required to mill the moulds but they can also be produced using an alternative craft technique. The rest of the process remains unchanged. For prototyping, the moulds were produced by milling recyclable expanded polystyrene (EPS - 10kg/m$^3$) since it is cheap, light to carry and faster to mill. Nonetheless, for mass-production the moulds should be fabricated using hard-wood, offering accuracy and resistance over time.

6.1. FULL SCALE PROTOTYPES

Several prototypes of bricks and assemblies provided material information for the development of this research project. Different toolpath-patterns were tested in order to add texture to the bricks -since the clay copies the roughness of the moulds- increasing its capacity to capture light while expressing surface curvature and material tactility. Also, alternative assembly methods were proven: the creation of an interlocking key to add structural soundness and the use of two post-tension holes.

As a proof of concept, two full-scale ceramic prototypes explored initial feasibility of the system by testing the complete design and fabrication workflow. The first one is a Continuous Façade made of 18 components of 15 bricks. It addresses issues such as the global assembly technique and the combination of patterns to perform diverse effects like gradual accommodation, indirect lighting and attractor openings (Fig 7).

The second prototype is a Turning Supports composed of 64 bricks and 8 branching pieces and it tackles formal and structural performances of branching formations (Fig. 8).

After finishing the assembly of a component it is crucial to add an initial post-tension force to give rigidity to the structure.
7. Structural Performance

The results of preliminary calculations and the construction of several prototypes show initial feasibility to post-tension the helicoidal courses. However, a detailed study is necessary to fully understand the structural behaviour of these innovative brick formations since the position of the section, and thus the inertia, is changing along the span.
8. Production Outlook

Because of their warped geometry, the moulds should consist of two separable parts so the bricks can be removed immediately after pressing and striking the clay. Another fact is that bricks need a support surface to avoid deformations while drying. Similarly to the moulds, this drying surface is CNC milled. Accordingly, it can also be used several times, allowing the initial inversion to be profitable. Under these conditions the production of warped bricks can be perfectly transferred to industrial facilities, extending the contribution of this research.

The system is suitable to be assembled either on-site or pre-assembled off-site, depending on contractors’ preferences and building site conditions. Four different strategies were developed and are illustrated in Figure 9. The last option presents a set of ribs that can even be adjusted or customized on-site since ordinary mason’s bench-saws are used in the process. In this option, no CNC milling is involved. A wooden-box full of sand might be, speculatively, an inexpensive and easy option to be used as a ‘resting bed’ since it can easily be arranged to copy the shape of any component while drying.

9. On-going Research

Further development is required to move forward this investigation into a compelling material system ready for implementation on-site. More extensive structural calculations are needed to determine precisely thresholds and structural capacity. Concerning design aspects, the combinations between different types of bricks would be a compelling next step in the on-going design process. Another crucial aspect is to develop specific construction details that integrate the warped bricks with other building systems such as concrete, glass and timber.

Scripting is an area that can be further developed to create variations in other architectural entities to generate more recombination patterns. Eventually, they can be combined with the constraints and limitations resulting from the structural calculations.
10. Conclusions

This investigation proposes innovative masonry systems as a complement that can coexist with current bricks, thereby simplifying their insertion into architectural practice. The new bricks work as a ‘plug-in’, with the objective of achieving complex geometry in domestic-scale project as a medium to revitalize brick-construction.

The general framework for developing new material systems engages the challenge to bridge between digital design, materiality and the design culture and enhances our understanding of contemporary tectonics, understood as a determinant factor that immanently affects architectural performance.

Though the proposal is about the ‘mutation’ of solid clay bricks, this research aims to develop an efficient procedure that can be followed using diverse types of bricks or even other vernacular construction systems, thereby expanding its contribution.

Finally, the underlying ambition behind this project is to re-thinking brick as a contemporary material, paving the way for putting it back on the agenda of avant-garde architecture.

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References


