Digital Tools for Masonry Design and Construction

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ABSTRACT: One view of conceptual design in architecture is as a negotiation between materials and forms. The process of configuring materials: organizing them, ordering them, arraying them emerges in the creative nature of design practice and the underpinnings of this process are embodied in the tools of architectural inquiry, traditionally: sketching, diagramming, modeling and drawing, and now in the digital age: another form of modeling, in design scripting, and in simulation. Two paradigms dominate digital design tools – surface modeling tools that provide few formal boundaries and no feedback on material realities – and material-aware building information modeling tools that are pre-coded with material and assembly logics. This paper focuses on the difficult middle ground, on design tools, envisioned by architects and technologists, that seek to preserve design flexibility, while embedding design reasoning and material logics. The focus is on masonry materials and systems. Masonry has come late to BIM because of its many forms, types and patterns and because its ability to adapt to complex shapes, make it difficult to instantiate in current BIM platforms. This paper reviews and analyzes four notable masonry buildings, and envisions the computational tools that would support the design, detailing and analysis of these buildings. It represents one component of a comprehensive project, funded by the masonry industry, to develop a software specification and workflows for integrated computational tools to support masonry design and construction.

KEYWORDS: parametric modeling, building information modeling, BIM, masonry

1.0. INTRODUCTION

Contemporary architectural practices engage a wide range of digital tools for the exploration of complex forms. The use of surface and solid modeling allows for the rapid generation of formal propositions – but with few clear strategies for assessing the structural or constructional implications of these propositions. CAD systems that are based on parametric modeling and design scripting facilitate the process of geometric generation, but do not host the semantics necessary to assess the implications of complex geometry. In sophisticated practices, architects embed their knowledge into the models implicitly, and argue that the means of architectural production map in some way onto the means of building production – thus making the implicit explicit (Schön 1992). Other design practices rely on specialized architectural consultants such as Front and Gehry Technologies to help “rationalize” their forms, via the creation of sophisticated parametric models imbued with the consultancy’s fabrication knowledge (Derix 2009). This material agnostic or *amaterial* approach to conceptual design is generally supported by surface modeling tools such as Rhino, form-Z and Maya.

A second approach in the development of building propositions lies in the use of building information modeling or BIM tools, in which the geometric descriptions of architectural elements such as walls, columns and beams are instantiated within a parametric model, and geometric elements are linked to functional descriptions of the objects. This geometric-functional linkage, embedded in the software by its developers, allows the BIM software to assist the architect by negotiating between building objects as they are placed and refined in the building model (Lee, Sacks et al. 2006). A potential limitation of the BIM approach is that the geometric-functional linkage is supported primarily for normative construction assemblies, and generative ideas beyond these norms are not supported. In addition, early-stage conceptual design is not easily accomplished in BIM environments, as the geometric-functional linkage cannot be asserted early in a design process where floor plates, column grids, and elevations are as yet undefined.

The amaterial and the BIM approach are not mutually exclusive, and in many design practices it has become the norm to start with a surface model and transition to BIM at the later stages of design. This transition leads us to consider the role and integration of material knowledge into the models in both phases: do the early surface models require a consideration of materiality and structure or can such considerations be delayed until later stages of design when BIM tools become more relevant? At what point in the building design process does the architect wish to consider materiality and constructed systems? At this earliest consideration, how should the materials be modeled? What material feedback is desired by the architect? In this paper, these questions are asked specifically for buildings constructed with masonry materials. The project reported on in this paper is funded by a wide range of masonry industry participants including material suppliers in clay and concrete masonry, professional societies, mason contractors, and labor unions. The goals of the project are to identify the masonry materials and systems that should be represented in building models, develop the data schema for their computational representation, and interfaces through which architects will interact with this masonry knowledge.

Prior work by the author and his colleagues has focused on embedding masonry knowledge in early-stage design tools, which are useful for formal explorations of load bearing masonry prior to BIM (Cavieres, Gentry et al. 2011). The work has also considered the structural implications of complex masonry configurations, and means to model and analyze non-planar masonry structures (Gentry, Al-Haddad et al. 2011) and has demonstrated the parametric modeling and structural principles developed through the research in a small-scale constructed demonstration (Al-Haddad, Gentry et al. 2012). A forthcoming work describes the requirements for masonry BIM as a function of stakeholder viewpoint and project phase (Gentry, Eastman et al. 2013).

This paper looks briefly at four buildings to consider a series of questions about architectural design, material feedback, and the role that masonry plays in contemporary practice. Through each example, the functional considerations regarding masonry design and the scripting and building modeling that could have been brought to bear in support of the case-study designs are described. These considerations are speculative, as the masonry software envisioned by the research does not yet exist. Therefore the process is one of inferring the knowledge of the architect, speculating about intentions and design process, and then envisioning the software functionality required to support the architectural endeavor. Where possible, the viewpoints of the architects – and their position on masonry and the resulting building is considered in light of the technical challenges faced by their choice of masonry.

2.0. PERSPECTIVES ON MASONRY DESIGN AND CONSTRUCTION

The motivation for and trajectory of this paper is based on a number of observations regarding masonry design and construction in the United States. From the author's perspective, they are objectively true, but some are difficult to establish by citation. First, architectural knowledge regarding masonry design, detailing and construction, and especially the use of load-bearing masonry structures, is waning. The same is true of structural engineering knowledge regarding masonry – especially in non-planar forms of load-bearing masonry (Heyman 1997). At one time masonry was the pre-eminent architectural and even structural material, but the development of new load-bearing orders and lightweight facade systems, coupled with the desire to construct faster and with fewer workers on-site have reduced the perceived competitiveness of masonry systems (Sweis, Sweis et al. 2008).

In addition, modern architecture has had an ambivalent relationship with masonry: the rigid frame of steel or cast-in-place concrete and the curtain wall skin led to the dematerialization of design ideas, and masonry construction is at the heart of materiality (Collins 1998). In his *Pathos of Masonry*, Moravánszky documents Alvar Aalto's struggles to create a an architectural setting for materiality in a modern masonry proposition: Baker House on the MIT campus (Moravansky 2002). In the end, it seems that Aaltos's decision was one of texture, and the brick he chose for Baker House was a wood-molded, sun-dried brick, and the variation in the brick's surface and color was inherently linked to Aalto's view of the building proposition (Charrington and Nava 2011). Compare this to Wright's choice of brick for the Johnson Wax building, and his search for brick companies that could produce bricks in a wide range of custom sizes, to exacting tolerances, all while holding the brick color constant (Lipman 1986).

This example reinforces the obvious conclusion that masonry is selected for a wide variety of reasons, from the pragmatic, e.g., to meet municipal or campus architectural guidelines, to the sublime, as in Piano's IRCAM Extension in Paris (Davies 1989) – where bricks in stack bond are locked into steel grids, but are not mortared. It is difficult therefore to imagine a set of digital tools that support the full range of architectural speculation on masonry. Nevertheless, a series of guiding principles can be established. First, modern examples of masonry design envision the cladding of complex forms, and the computational environment for brick design must support and manage this complexity (Mitchell 2005). Second, the early stages of architectural masonry design focus on masonry rationalization – defined here as understanding the relationships between architectural objects, and their dimensions and placement; masonry patterning; and masonry unit dimensions. Third, to understand these relationships, and permute them during design, the objects and patterns must be represented parametrically, so that variations in pattern and geometry and can adjusted without the need to continuously remesh and remodel. To this end the work of Schumacher (from the theoretical perspective) and Aish (from the implementation perspective) are particularly relevant (Shea, Aish et al. 2005, Schumacher 2009). And finally, any computational environment developed for early-stage masonry speculation must be linked to later-stage structural analysis, detailing, and contract document production.

3.0. MASONRY BUILDING CASE STUDIES

In this section, four building case studies are presented and briefly discussed to consider the interaction between architect and elements of design specific to masonry, and to illustrate the software tools needed to support this interaction (essentially a process of reverse engineering). The interaction is between architect and the conception of masonry – the design idea of masonry, abstracted at first and then clarified through the design process. Ponce de Leon and Tehrani describe these conceptual tenets as the “geometric and syntactic laws permitted by particular units of construction” (Ponce de Leon and Tehrani 2002b). The case studies do not provide a complete description or analysis of the buildings, but focus only on those decisions that impact the design and construction of the masonry. These buildings are: the Johnson Wax Building by Frank Lloyd Wright, the Tongxian Gatehouse by Office dA, Yale University Health Services by Mack Scogin Merrill Elam Architects, and the SPSU Design Studio II building by Cooper Carry Architects.

3.1. Johnson Wax Building

Frank Lloyd Wright’s Johnson Wax Building was constructed in two phases, with the administration building completed in 1936 and the research tower completed 8 years later in 1944 (Fig. 1A). The buildings are constructed with reinforced concrete interior columns and cores, and a load bearing reinforced masonry exterior. The masonry exterior, with a curved geometry inspired by the streamlined moderne, is a two-wythe brick wall, laid in running bond, and bounding an interior layer of cork insulation, with copper ties bridging the cork and joining the two reinforced wythes (Lipman 1986). One layer of brick acts as the exterior finish, and the other as the interior finish. The brick-clad forms include straight walls, radiused walls, and walls with transition from straight to round. Over 200 types of custom brick were made for the building by the Streator Brick Company, all in Wright’s signature Cherokee Red color. To accentuate the horizontality of the building, the vertical masonry joints were struck flush, and painted or mortared red. The horizontal joints were deeply raked. Many of the wall segments float above the ground over openings, and are supported by steel lintels integral to the reinforced masonry structure.

The archival record does not identify the mason contractor for the building, or whether masonry shop drawings were completed for the project (though this is unlikely). Regardless, a team of detailers in Wright’s office or in the mason contractor’s office was required to rationalize Wright’s design, in terms of the number of types and design of the custom brick. Photographs of the construction indicate that tight control of the vertical running bond joints was achieved, meaning that straight-sided, radiused and transition bricks (bricks that start straight and initiate the radius) were required for the project – as the radius in many of the curved walls was too small for these curves to be created with cut straight-sided brick (Perlman 1993). Because the project contained brick in the interior as well, a matching set of bricks with offset radii were required for the interior walls. In addition, Wright’s bricks for Johnson Wax were specially textured on the back side, to ensure that they would bond with the concrete cast behind them.

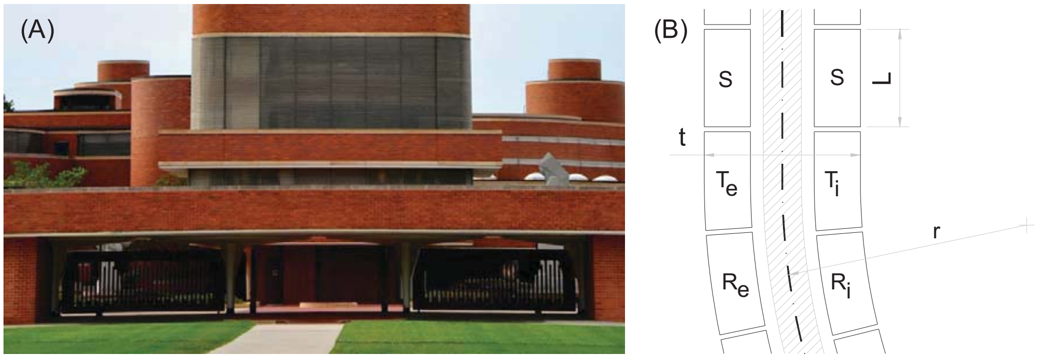

Figure 1: (A) Johnson Wax Building, Frank Lloyd Wright, base of research tower (image credit: Wei Ping Teoh), (B) Five .brick types needed to achieve straight wall transitioning to curved wall of a given radius (r).

What computational approaches could be taken to rationalize Wright's masonry design – and to support the design, analysis and detailing required in contemporary practice? First, all wall plan and elevation dimensions could be checked and adjusted to verify that they were integral to the brick modular length and height. Second, bricks could be defined parametrically as straight (S), radiused (R) or transitioning (T) and the dimensions for these bricks could be calculated automatically from the centerline geometry of the walls. In the example shown in Fig. 1B, it is shown that five unique bricks are required to achieve a straight wall section that transitions to a section with a circular radius. In addition, if bricks of a given modular stretcher dimension L were desired, then the masonry computational model could adjust the radius (r) or overall thickness (t) of the wall in order to ensure that the radiused portion of the wall could be constructed with an even incremental number of bricks. A computational model of the desired geometry could be used established whether the desired geometry could have been achieved with few custom bricks, by using cut bricks or a small number of radiused brick.

3.2. Tongxian Gatehouse

Office dA designed the Tongxian gatehouse as the first of multiple planned structures for an artist colony in Tongzhou, Beijing, China (Ponce de Leon and Tehrani 2002a). The architects describe their motivation in the design of the gatehouse (Ponce de Leon and Tehrani 2002b) as follows:

> ... the visible deformations of the body of the building are, at once, the result of programmatic pressures that guide the form, and also the result of geometric and syntactic laws permitted by particular units of construction ... in this project we have used brick as both formwork and finish, thereby securing an unmediated relationship between the bonding, its layout, and the ultimate effect.

In this case, the unit of construction is brick masonry, laid in Flemish bond, with many of the brick headers corbelling out from the surface mean. The masonry walls share some aspects of the Johnson Wax building, as they are mortared in place from behind, becoming molds for the reinforced concrete walls that support them. In many locations the walls are two-sided – with an interior and an exterior brick condition. The reinforced concrete walls that support the brick allow for a significant cantilevered condition on the front of the building, and some of the walls are non-planar and non-plumb.

In the Tongxian gatehouse, as compared to Johnson Wax, the parametric modeling of the brick façade is not dependent on rationalizing the number of types and configuration of the bricks, but rather on the rules that govern the texture created by the block headers (Fig. 2). The patterning required is envisioned to occur in two steps. First, the brick coursework in Flemish bond must be mapped onto the NURBS surface. This task is simple if the surface is planar, but is complex if the surface has single curvature and even more so as the surface becomes doubly curved. Algorithms for locating the bricks on a doubly-curved surface, and meeting the bonding requirements to the greatest degree possible, have been discussed by Cavieres et al (2011). As the curvature of the walls increase, individual mason units must be cut, and mortar joint thickness must be adjusted meet the masonry bonding pattern. The algorithms can provide feedback to the designer as to whether the curvature envisioned can be met without wholesale cutting of masonry units, or result in the general dissolution of the desired bonding pattern. In the Tongxian gatehouse, most of the walls are essentially planar, and the modest curvature is easily accommodated within the mortar joints, without apparent cutting of masonry units. This seems to support the architects' intentions to adhere to the systems geometric and syntactic laws. The second task in modeling the brick façade on Tongxian is to establish rules for describing the corbelling of the brick from the mean surface. This is relatively simple to imagine, with one NURBS surface representing the mean plane of the wall, and a second offset NURBS surface representing the extrusion of the headers out from this mean surface.

Figure 2: Tongxian gatehouse by Office dA (image credit: Nader Tehrani, NADAAA).

The presence of non-planar walls in the Tongxian gatehouse leads to significant structural questions in this reinforced masonry – reinforced concrete hybrid. An important requirement for architectural modelling in this example is the linkage between the architectural model and the structural analysis of non-planar eccentric walls. To facilitate this interaction, the mid-surface of the structural portions of the walls, whether of reinforced concrete or masonry, needs to be tracked in software, and the boundaries of the walls, with openings, needs to be translated into a finite element model for analysis of gravity and lateral loads. The basic functionality for the structural analysis (for planar walls) is available in commercial software (Lashway and Troop 2008), but the facilitated exchange of information between architectural and structural masonry models does not yet exist.

3.3. Yale University Health Services Building

The Yale University Health Services Building was designed by Mack Scogin and Merrill Elam architects with construction completed in 2010 (Fig. 3(A)). The building features a non-planar brick facade, with some walls more than 2 meters [6 feet] out of plumb. A custom bull-nose brick was designed to serve both architectural and engineering requirements: to add visual depth to the facade and to engage the mortar bed joints for the transfer of eccentric loads to the masonry backup system (Fig 3(B)). The design and engineering of the building facade is extensively described in a recent paper by the design team (Filloramo, Scogin et al. 2011).

The complex brick facade led to many design challenges – most of which were addressed through the use of surface modeling and design scripting tools and are documented by the team in their recent paper. The first is the situation of rectangular plan door and window openings in a warped (non-planar) facade. In this case, the magnitude of the warping was mild enough to allow for a planar jamb and proper flashing of the windows. The second is the documentation of wall out of plumb-ness, which was necessary for the construction of the planar steel stud backup system. Horizontal slicing of the surface model was used to determine the number of bricks in each course, and to establish the elevations for window and curtain wall rough openings.

The Yale design team made extensive use of physical mock-ups to understand the detailing and construction aspects of the canted masonry system – including window openings and masonry coursework. It is unlikely however that they were able to generate a computational solid model of all of the brickwork on the facade, to assess the termination of the brickwork coursing at the non-orthogonal curved boundaries of the NURBS surfaces (Fig 3(C)). Software for propagation of individual masonry units in non-planar arrays, within a solid modeling environment does not exist at this time, and is an ongoing focus of the research initiative supporting this research.

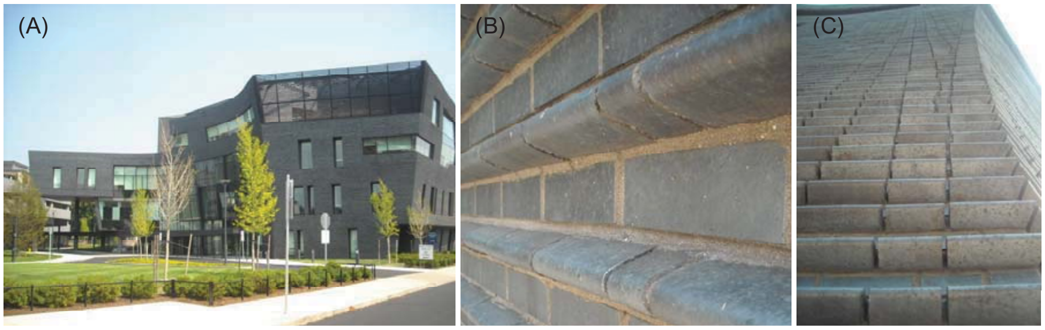

Figure 3: (A) Yale University Health Services building by Mack Scogin Merrill Elam Architects, (B) detail of bullnose brick, (C) brick coursing at non-orthogonal corner (image credit: Tristan Al-Haddad).

3.4. SPSU Design Studio II

The Southern Polytechnic and State University, Design Studio II building was designed by Cooper Carry Architects. The reinforced concrete building features four brick facades with a rotating brick that is indexed along the facades (Fig 4(A). Every other brick course is a typical stretcher course, which bonds the units together in a continuum. The architects developed the idea of the masonry patterning in discussion with Jollay Mason Contractors, who mocked up the generative idea during early conceptual design (Fig. 4(B)). The project was delivered using a conventional CAD/BIM process, and the architects provided detailing of the brick coursework that allowed for the templating of the masonry wall during construction. Details specific to the installation included the use of stainless steel ties and heavy gage adjustable anchors between the brick wall and the concrete backup wall.

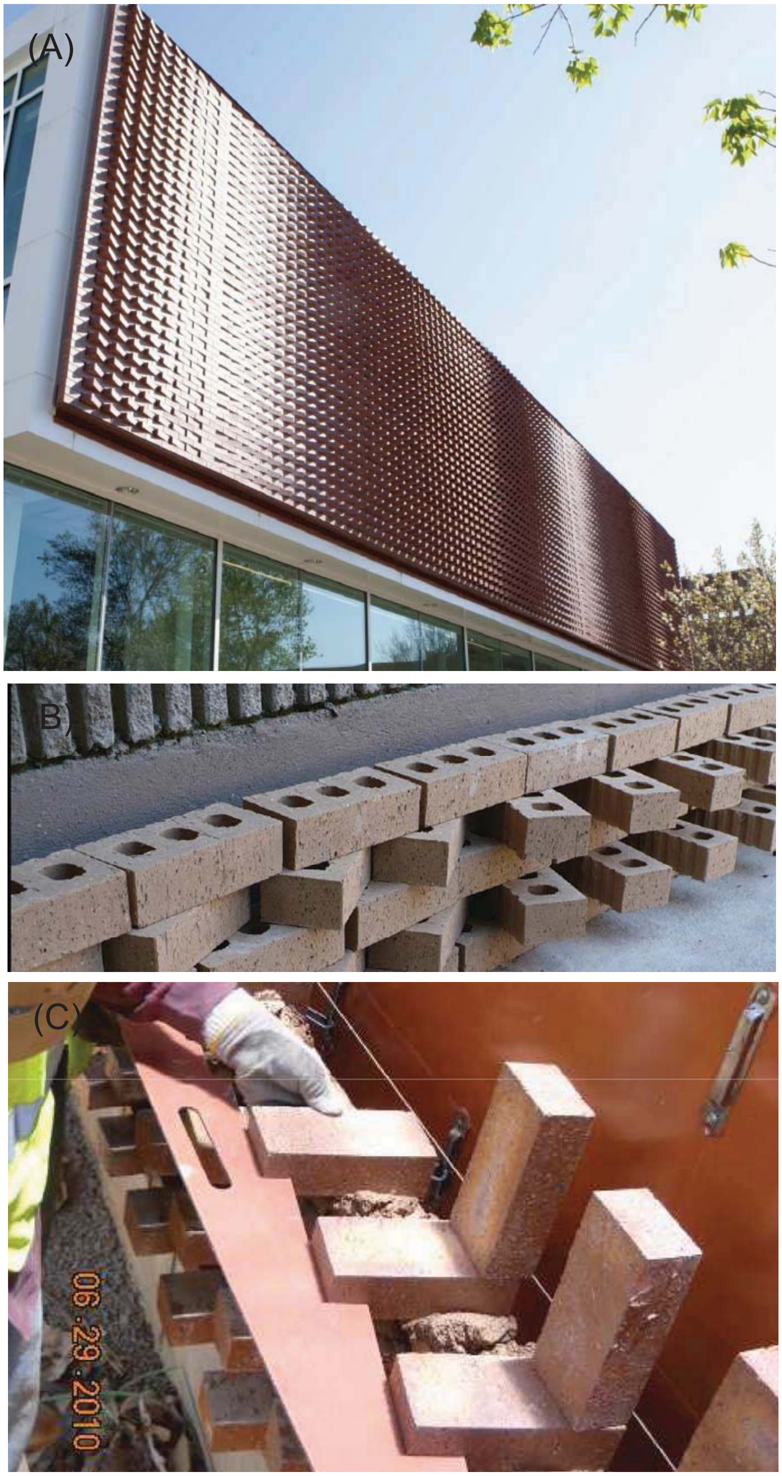

Figure 4: (A) Southern Polytechnic State University, Design Studio II, by Cooper Carry Architects, (B) conceptual strategy of brick coursework, (C) templating of rotating brick during construction (image credit: Cooper Carry Architects).

In this case, the primary use of a computational design tool for masonry would be the automatic instantiation of the brick coursing rule onto the plane of the facade, allowing for parametric variation of the pattern as a function of the various facade dimensions. In discussions with the design architects, it was clear that they desired to assess the visual impact of the moiré pattern of the bricks through visualization, and especially the comparison of the effect on facades of various lengths, before committing to the design idea. In addition, the use of the computational model to drive the CNC fabrication of the templates was made easy due to the modeling completed by the architects.

CONCLUSION

These four case studies demonstrate a wide range of design strategies and the potential for computational modeling in architectural masonry. Though it unlikely that any one closed-form computational tool can represent all of the complexity demonstrated in these four buildings, a few conclusions regarding masonry computation for early-stage generative design in masonry can be made. First, the relationship between the masonry coursing and the underlying NURBS surface must be represented. If the masonry bonding patterning takes precedence, then the boundaries of this surface must be adjusted carefully to adapt to the coursing rules. This seems to have been taken place in the Tongxian gatehouse, for example. In some cases, the bonding pattern rule can be linked to an overall surface dimension (SPSU). If, the bonding pattern must conform to non-orthogonal boundaries, then rules for adapting the pattern must be established and assessed (see Yale Health Services, Fig. 3(C) for example). Second, these patterns are likely to vary from region to region on many masonry buildings, and thus the computational tool will need to provide support for negotiating the coursing at the boundaries. Appropriate responses could be adjusting the size of regions to best accommodate the natural bonding dimensions of the masonry, adjusting mortar joint size to accommodate the bonding pattern within the specified region, or the cutting of masonry units. Finally, the transition from surface modeling to BIM must be accompanied by the ability to represent individual masonry units as solids within a parametric modeling environment – so that the “geometric and syntactic” implications of the masonry systems can be assessed in the context of complex geometry.

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