Building Information Modeling for Masonry: Defining and Modeling Masonry Walls

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ABSTRACT: This paper reports on the North American initiative to develop digital tools and processes for Building Information Modeling of masonry. Specifically, this paper describes a project to develop the data infrastructure for the modeling of masonry wall systems. In the first part the paper discusses the requirements for an underlying data model for masonry wall systems. Second, the paper discusses various views into this model, from the perspectives of architects, structural engineers, and mason contractors. Finally, the paper reviews and analyses three notable contemporary masonry buildings, and discusses the specific digital representations required to support the design, detailing and analyses of these buildings.

Keywords: masonry design, building information modeling, BIM

1 INTRODUCTION

In 2013, the masonry industry in North America committed to the development of software and business processes to bring Building Information Modeling (BIM) to masonry design and construction [1]. The BIM for Masonry Initiative (BIM-M) includes leading industry trade associations and stakeholders from throughout the masonry industry in North America. The roadmap for the development of BIM-M, written by the authors of this paper, outlines three phases of research and implementation (Figure 1) [2]. The current Development Phase (Phase II) focuses on documenting the workflows and elucidating software requirements for BIM for masonry through a series of projects involving masonry units, masonry walls, and a benchmark of the software tools currently used in masonry design and construction. This paper reports on the early stages of the project to develop the data model for implementing masonry walls in BIM.

2 BACKGROUND

The representation of components and their connectivity within CAD systems began with solid modeling and progressed with the development of feature-based modeling, where the relationship between components is formally expressed within the model [3, 4]. Early theoretical developments led to the commercialization of parametrically-driven 3D modeling software in the mechanical and aerospace engineering domains, as exemplified by software like CATIA, Solidworks, and Inventor. In the architecture and structural engineering domains, software platforms such as Revit, Digital Project,

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and Tekla Structures are at their core parametric solid modelers, which are imbued with specific objects that describe buildings.

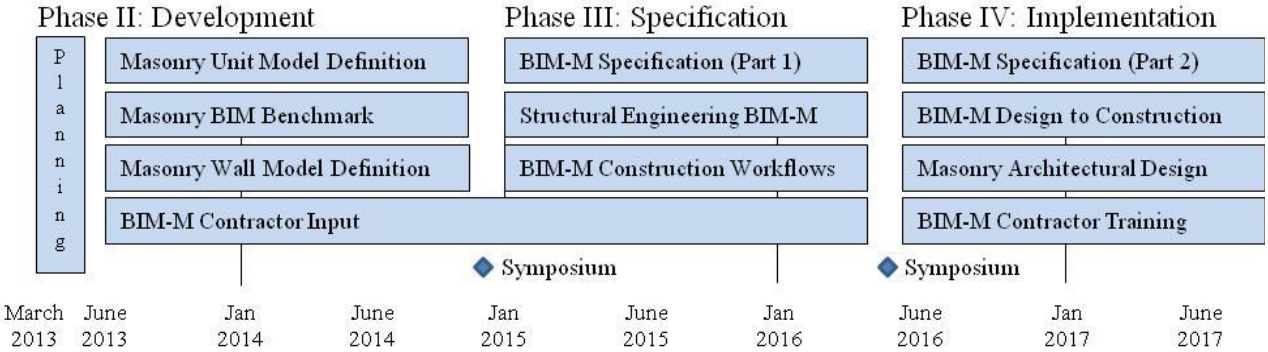

Figure 1. Timeline and Tasks for the Building Information Modeling for Masonry Initiative.

BIM is an acronym that stands for an object, a “building information model” or just “building model” and also a process for creating and using that object “building information modeling”. According to the National Institute for Building Sciences of the United States, a building information model *“is a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward”* [5, 6]. In this context, the proposed parallel definition for masonry BIM is a digital representation of the physical and functional characteristics of masonry materials and systems.

The development of BIM data for structural systems was led by the structural steel industry in the United Kingdom and later in the United States, with the development of the CIS/2 data model for structural steel members and assemblies [7, 8]. CIS/2 formed the basis for early design automation in the structural steel industry, and led to the development of structural steel design and detailing software that demonstrated the level of interoperability possible through BIM. The International Alliance for Interoperability – now known as buildingSmart – developed a more general specification for the representation and exchange of building product models [9]. These models are known as Industry Foundation Classes or IFCs – where the term “classes” comes from object-oriented computer programming and represents the templates of the building components defined in IFC. IFCs are being developed to describe all of the major structural systems in buildings – with major efforts ongoing in the precast concrete and cast-in-place concrete industry segments [10, 11]. IFCs are being used as the basis for automated workflows between structural engineering modeling tools and analysis software [12].

In masonry construction, the development of BIM tools has lagged that of other material systems, due to a large degree to the complexity and variety of masonry systems, and the diverse nature of the masonry industry. Early work by our research team demonstrated the potential for linked parametric modeling and structural analysis of masonry structures [13]. Knight and Sass developed parametric modeling techniques for CNC-produced block systems and a grammar to describe their order of assembly [14]. Monteiro et al. discussed the potential for modeling architectural aspects of masonry in AutoDesk Revit, and highlighted the lack of an underlying data model for masonry components and assemblies [15]. Nawari developed an initial concept for representing masonry walls in IFCs and identified the basic data requirements for structural masonry [16]. More recent work by our team has introduced the concept of an object-oriented representation for masonry walls [17].

The difficulty of representing masonry in current BIM tools comes from many sources. First, in most cases a wall is represented within BIM software as a series of layers, from the outside of the building to the inside; but without knowledge of the geometry of the materials within the layers (Figure 2). Certain layers, such as the air cavity with veneer ties, is not represented at all – it has thickness but no definition. The relationships between the components within the layers (the intra-layer relationships), or the relationships between the components in the various layer (the inter-layer relationships) are not modeled. Materials which bridge the layers, or appear in more than one layer break the layer paradigm. The surface of the outer layer may be represented with a 2D pattern or “hatch” that depicts the masonry units, but this pattern does not inherently relate to the masonry coursing; it does not adjust at openings, and does not negotiate the corners of the building.

Thus the motivation for this aspect of the research in BIM-M arises because current BIM tools do not represent the architectural layout of masonry walls, that is the interaction between the masonry units, the bonding patterns in which the units are laid, and the other aspects of the wall, such as openings and parapets. And so, for example, during architectural design, the placement of an opening within a multi-leaf wall in a BIM tool takes place without knowledge of the modularity of the wall and will not necessarily integrate with the coursing or the vertical repeat of the masonry.

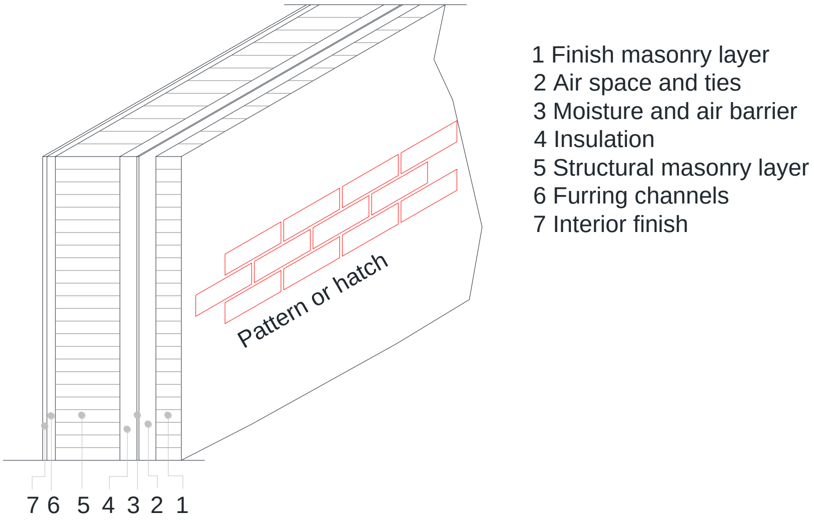

Figure 2. Layer model used in current wall definitions in BIM.

3 MASONRY WALL MODEL DEFINITION

The BIM-M project described in this paper is known as the “Masonry Wall Model Definition” project and is at the core of masonry BIM – this because masonry BIM is to be a computational model of masonry construction, and masonry walls are the fundamental assembly in masonry construction. In this section of the paper, the tasks of the project will be described and the initial description of the masonry wall definition will be presented.

3.1 Project Tasks

The tasks associated with defining the masonry wall within BIM are as follows:

1. Define high-level classes that must be required to be defined in masonry BIM: veneers, bonding patterns, masonry backup systems, openings, pilaster, etc. and methods for generating objects based on these classes.
2. Formalize the concept of a masonry family, which is a complete set of objects needed to define the veneer masonry and its backup system within a given bounded region in the BIM system.
3. Identify rules that define the relationships between objects. These will be the parametric rules that control bonding patterns and the relationship between veneer and backup bonding. These rules will determine how bonding patterns react to the placement of door and window openings,

to the placement of floors and roof systems, and how the bonding systems will react to the region boundaries in which a given masonry family is mapped.

4. Define strategies for regions to adapt to modularity of the masonry systems embedded in them.
5. Define a set of views of the masonry system, from lightweight views that should be computationally tolerable to detailed view suitable for photorealistic rending and virtual construction.
6. Develop an interface that allows for the importing of masonry units (from a masonry unit database) into a wall definition.
7. Develop user interface requirements for the input of wall types (denoted a “wall definition module”) to be implemented in BIM.

3.2 Parametric Masonry Wall Definition

The masonry wall must be defined as a formal proposition within the parametric modeling environment that underlies the BIM model. In order to support a wide range of architectural expression and the full range of masonry construction, both load-bearing and non load-bearing, the wall should be defined in a manner that supports building geometric flexibility and variation in wall types while also conforming to our shared idea of what is, and is not, a masonry wall. Therefore, the surfaces of masonry domes can be considered to be outside the scope of a “wall definition”, whereas an inclined surface or curved surface that contains bricks laid in horizontal coursing can be considered within the scope of the definition. The range of types and variation is considered in more detail in the short case studies in Section 5 of the paper. Table 1 and Figure 3 present a formal definition of concepts used in the wall definition model. These are discussed in more detail in the text that follows.

The masonry wall is considered to be a region defined by four sides. The wall is not required to be planar, and is therefore defined by a NURBS (non-uniform rational b-spline) surface at the exterior surface of the wall. The curvature of the wall must be modest so that the wall can be smoothly tiled by the masonry units in the horizontal and vertical directions. The limits for this curvature have been discussed in our previous work [18]. Constant thickness layers of masonry and non-masonry materials are offset inward from the defining surface. The masonry is laid in courses, where a course is defined as a path parallel to and offset from the bottom side of the wall. Masonry units within the course may be offset in the positive or negative direction perpendicular to the coursing plane, allowing for the modeling of ashlar patterns. Random or rubble masonry cannot be represented.

The masonry units are described by the size of the units and the pattern in which they are placed in each layer. Because multiple unit types can exist in each layer, the pattern describes the position of each unit relative to the anchor in each unit. Individual units can also project out of or recede into the surface defining the layer, allowing for the modeling of corbeling or other textures on the surface. It is also possible to describe a local rule for selecting the unit, based on a global condition of the wall. And so, a curved unit could automatically be selected from a table based an assessment of the local curvature of the wall at the location of the masonry unit. The mortar joint is specified as part of the pattern and is given as a range. In this way, the spacing of the units can be negotiated based on variations in the geometry, meaning that the computational model of the wall behaves in the same way that real masonry walls do – in the way that masons adjust the bed joints and head joints as the masonry is laid, to preserve the overall appearance of the masonry relative to the features of the wall.

Masonry layers in multi-leaf walls are generated according to the rules described above, with each layer distinct from the adjacent layers. The pattern and anchor of the individual layers are defined so that opportunities exist both vertically and horizontally to bond the layers. Bonding can be accomplished by masonry units that exist within two layers, such as in Flemish bond brickwork, or it can be accomplished by non-masonry means by ties (typically but not limited to metal ties).

Table 1. Formal concepts used in masonry wall definition

Concept	**Description**
Wall	Region of masonry bounded by four sides. Top and bottom sides are defined by masonry coursing.
Surface	Four sided NURBs surface at the exterior face of the wall.
Layer	Masonry and non-masonry layers offset from the outside surface of the wall.
Units	Set of masonry units used to defined a given layer of the masonry in the wall.
Pattern	Arrangement of units within a masonry layer.
Repeat	Dimensional increment of the pattern used to generate the field condition. Layers of masonry in a wall may have different patterns, but must have the same repeat.
Anchor	Insert point of the key unit masonry within a pattern repeat where the units are inserted into the wall.
End Boundary	Plane representing the end condition of a wall, typically vertical.
Course Boundary	Plane representing the top or bottom condition of a wall, required to be parallel to the masonry coursing.
Inset	Region within the wall in which the field condition definition for the masonry does not apply.
Opening	Specific type of inset within a wall in which masonry is omitted and another enclosure system in inserted.
Wythes	Layers of masonry through the thickness of the wall.
Courses	Nominally horizontal planes used to define the incremental layout of masonry vertically.
Bonding Units	Masonry units that exist in more than one layer and are used to bond layers together.
Bonding Ties	Non-masonry system used to bridge across layers of masonry.
Field Condition	Region of the wall where no special conditions apply and the masonry is applied according to the basic generative rules.

All of the parameters previously described work together to describe the “field condition”, that is, the masonry wall as it exists away from building features that perturb the layout of the masonry. We recognize that there are a number of conditions that necessitate a change in the masonry pattern. Some of these conditions represent the change in appearance of the masonry due to an architectural consideration and others describe how a masonry wall starts, stops, or is interrupted. Together, these conditions can be denoted as “wall behaviors” and are described here using the language developed by Lee et al. for precast concrete [19].

3.3 Wall Behavior: Case of Inserting an Opening

The wall opening is a special case of an inset (a region within a wall within which the field condition is over-ridden). The opening is defined by a rectangular patch that fits into the horizontal and vertical modularity of the wall, but its effect propagates into the field condition, beyond this boundary (Figure 3). When the opening is inserted into the wall, the parametric model wall takes the following actions:

- the user is warned if the opening does not fit within the wall modularity and is given the option to redefine the opening or select a different opening;
- the masonry within each layer of the wall is removed at the opening;
- special elements associated with the opening feature are inserted into the wall, in both architectural and structural masonry layers;

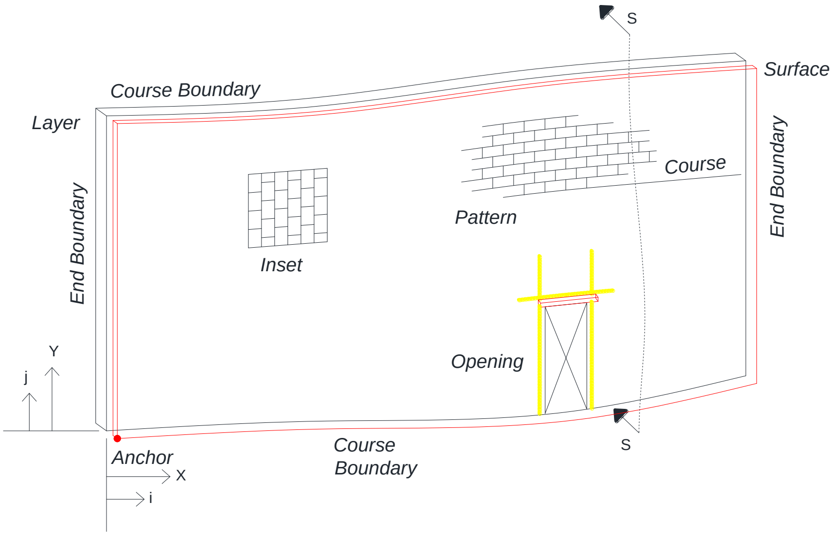

Figure 3. Key concepts used for defining masonry walls in BIM

- masonry units in the surrounding field condition are cut to accommodate the surrounding elements.

4 VIEWS INTO THE MASONRY WALL

An important aspect of the masonry wall definition is the ability to support a view of the wall tailored to the “need to know” of the stakeholder. In BIM systems based on IFCs, the support of a given view is often achieved through a model view definition or MVD [20, 21]. In this paper, these views are not presented as requirements for a formal IFC exchange, but rather as a description of the attributes that the given stakeholder is likely to need to complete their design, analysis, or construction task. The three primary views are generically described as architecture, structural engineering, and mason contractor (Figure 4).

4.1 Architecture Viewpoint

The architect desires tools to quickly map masonry units and systems onto building forms, and to be able to manipulate these forms without having to re-generate the masonry. Architects want BIM systems to recognize the module on which a given masonry system acts and to guide in the dimensioning of walls and the placement of openings to conform to the masonry system. They want access to preliminary quantity and cost-estimates to understand the practical implications of their design decisions. Architects are concerned with building enclosure and waterproofing, and desire that details regarding masonry reinforcing, support, ties, and sealing are included in the BIM families published by the masonry industry for their materials and systems. For novel and complex buildings, architects wants a BIM system that supports flexible parametric modeling that allow for representing novel forms of masonry.

4.2 Structural Engineering Viewpoint

The structural engineer desires to closer integration with the digital tools that architects use, including the ability to share digital information bi-directionally with architects using BIM tools. The structural engineer needs to identify walls that are load-bearing and non load-bearing, and to further identify walls that are acting as part of the lateral load resisting system. The structural engineer desires to have these wall identification steps operate within BIM, to preserve the dialog with the architect during early stage structural design. In addition, structural BIM should be linked with structural analysis software, to provide feedback on the efficacy of structural configurations. Finally, as designs mature,

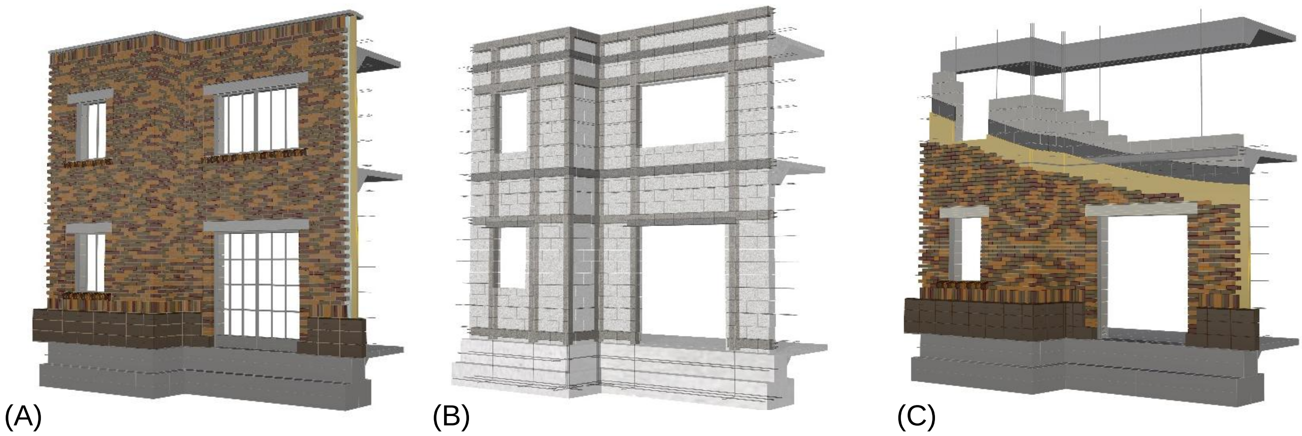
(A) (B) (C)

Figure 4. Architectural (A), structural engineering (B), and mason contractor (C) views of the masonry wall model.

the structural engineer needs to have BIM-enabled tools for generating reinforcing plans for reinforced masonry walls, as well as coordinating masonry details in the structural BIM model.

4.3 Mason Contractor Viewpoint

The mason contractor is interested in processes involved in planning, procuring, scheduling and executing masonry construction. In the surveys completed as part of this our Phase I research, both general and masonry contractors identified project scheduling and clash detection as two of the highest priorities for masonry BIM. In addition to these two activities, mason contractors identified quantity take-off, cost estimating, scaffolding design, and wall bracing design as high priorities for masonry BIM. The contractor views therefore need to include views often described as 4D (3D geometry + time) and 5D (3D geometry + time and cost).

5 MASONRY BUILDING CASE STUDIES

In this section, three case studies are presented to consider the interaction between architecture 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, abstracted at first and then clarified and made solid 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” [22]. 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, and the Yale University Health Services by Mack Scogin Merrill Elam Architects.

5.1 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 (Figure 5A). 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-leaf 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 leafs [23]. 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 bricks 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. 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 [24]. 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.

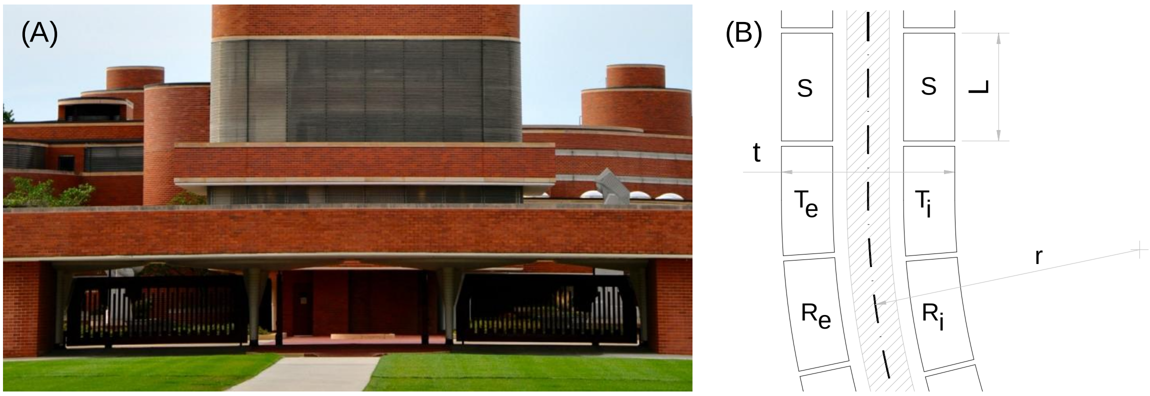

Figure 5. (A) Johnson Wax Building, Frank Lloyd Wright, research tower (image credit: Wei Ping Teoh), (B) Five brick types needed to achieve straight wall transitioning to curved wall of a given radius (r).

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 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 Figure 5B, 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.

5.2. Tongxian Gatehouse

Office dA designed the Tongxian gatehouse as the first of multiple planned structures for an artist colony in Tongzhou, Beijing, China [25]. The architects describe their motivation in the design of the gatehouse 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 "* [22].

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 (Figure 6). 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 [17]. 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 cutting the masonry units. This seems to support the architect's 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 the datum.

The presence of non-planar walls leads to significant structural questions in this reinforced masonry – reinforced concrete hybrid. An important requirement for architectural modeling 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 [26], but the facilitated exchange of information between architectural and structural masonry models does not yet exist.

5.3. 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 (Figure 7(A)). The building features a non-planar brick facade, with some walls more than 2 meters 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 (Figure 7(B)). The design and engineering of the building facade is extensively described in a recent paper by the building's design team [27].

Figure 6. Tongxian gatehouse by Office dA (image credit: Nader Tehrani, NADAAA).

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 plumbness, 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. They were unable 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 (Figure 3(C)). Software for propagation of individual masonry units in non-planar arrays, within a solid modeling environment does not exist, and is an ongoing focus of the initiative supporting this research.

6 SUMMARY AND CONCLUSIONS

The case studies demonstrate the potential of and requirements for BIM modeling of masonry. Though it unlikely that any one computational tool can represent all of the complexity demonstrated in these three buildings, a few conclusions regarding masonry computation can be made. First, the relationship between the masonry coursing and the underlying NURBS surface must be represented. The layer metaphor used in current BIM software must be extended to more clearly define the materials that exist within the layers, and the bonding of materials between the layers. As the masonry patterning takes precedence, so then the boundaries of this surface must be adjusted carefully to adapt to the coursing rules. Masonry patterns are likely to vary from region to region on

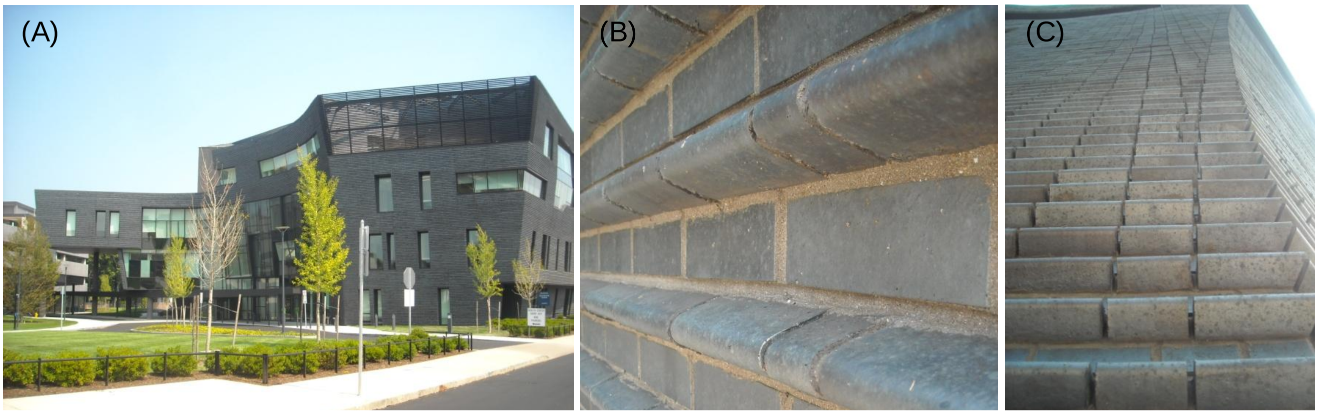

Figure 7. (A) Yale University Health Services building by Mack Scogin Merrill Elam Architects, (B) detail of bullnose brick, (C) brick coursing at non-orthogonal corner (image credit: Tristan Al-Haddad).

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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