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BIM schema for masonry units and walls

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ABSTRACT: This paper reports on the North American initiative to develop technical specifications for the implementation of Building Information Modelling (BIM) for masonry buildings. The paper proposes two data modeling frameworks required to represent masonry units and walls in BIM. The formalization of these representations is described as schema that map the tangible characteristics of masonry systems into data structures that can be stored and manipulated computationally. The schema support queries which can be used to generate stakeholder-specific masonry models that facilitate architectural design, structural engineering, material take-off and cost estimating, and construction.

Two distinct but complementary schema are proposed. The schema for masonry units is based on a relational database containing geometric, aesthetic, physical property and manufacturing data. There are five main stages in the development of the masonry unit data: mapping of masonry building project workflows, data requirement identification, design of database structure, provision for data import, and finally design and implementation of data export. The proposed schema for masonry walls is based on a concept known as "regions", where a masonry region is an area of a wall with common characteristics intended to support the description of various levels of development (LOD) pertaining to a masonry wall assembly, capturing the evolution and complexity of design information from early conceptual stages down to construction and operation. The "region" can be thought of a model view of the masonry wall that takes into account the stakeholder perspective as well as the desired LOD of the wall.

1 INTRODUCTION

Building design and construction processes are supported by consensus data models that facilitate the exchange of information between stakeholders. These data models encapsulate and codify industry standard product descriptions, and enable queries across software platforms and from heterogeneous stakeholder viewpoints. In the AEC industry, data models, the software that employ them, and the business processes that rely on them are commonly described as Building Information Modeling or BIM.

In the context of a building material system such as masonry, a data model is a high level abstraction of the system that can be implemented in software. The data model must be crafted so meaningful queries can be applied to a given instance of the data. The data model represents not only the geometry of the system, and the collection of geometries that make up building objects, but also the relationships between objects in the model. These relationships can be spatial or temporal, refer to cost, ownership, production status, etc. When a given stakeholder viewpoint—which includes the role of the stakeholder and the activity in question, for example, structural engineer performing a lateral load analysis—is applied to the data model, a specific "submodel" or abstracted model view can extracted to facilitate the activity (Lee et al., 2016).

Currently, the most mature material-specific BIM models are for structural steel—with the early standardization of steel shapes forming the basis for the steel components used in buildings today (Standard Specification for Structural Steel, 1896). Almost a century after the shapes were standardized, the first computational data model for structural steel was released as the "Logical Product Model" by CIMSteel (Crowley and Watson, 1997). Since then, material-specific models for precast concrete (Eastman et al., 2003) and cast-in-place concrete (Barak et al., 2009) systems have been developed.

The Building Information Modeling for Masonry Initiative (BIM-M), organized in 2013 in North America, has developed a roadmap for establishing the requirements for masonry data models for masonry design, procurement and construction (Gentry et al., 2013). The second phase of the roadmap, recently completed, focused on the development of data requirements for masonry units and walls. In addition, the initiative has completed an extensive set of masonry-building case studies, focusing on the information needs of architects, engineers, material suppliers, and mason contractors (Lee et al., 2015) and has recently released a report on the modelling of masonry buildings in Autodesk Revit (Gentry and Collins, 2016).

This paper reports on the development of BIM data models for masonry material systems. The focus is on two separate but related model development efforts. The first is the development of a model for masonry units. This is parallel to the databases of hot rolled steel shapes promulgated by AISC and the BSI (Structural steel sections. Specification for hot-rolled sections, 2005), for example. Unlike structural steel however, the masonry unit database or MUD is extended to include material property, color, and texture, in addition to geometry. The second effort is development of a data model for masonry walls. The complexity of masonry walls, with high piece count of masonry units and the requirement to relate both overall and local building geometries with the bonding and coursing patterns of masonry units, dictates that an intermediate geometric solution is needed. We have developed the concept of a masonry region which in its simplest form is a subdivision of a wall within which the masonry can be described using simple parametric rules. This paper focuses on continued development of the two data models for masonry units and walls. Additional detail on each effort can be found in our earlier works (Cavieres and Gentry, 2015, Sharif et al., 2015).

2 DATA MODELS AND SCHEMA

This paper describes both overall data models and where relevant, detailed schema for masonry units and masonry walls. The conceptual description of the masonry data and the ways it interfaces with software applications such as BIM authoring tools is considered the data model. The schema represents the specification or implementation of the data model. For the masonry unit model database (MUD), the schema is described as an entity/relationship diagram and the resulting database is a relational database composed of property tables for geometry, material, color, etc. For the masonry walls, the schema is represented using an object-oriented database model, which is better suited to complex hierarchical structures with nested relationships (Smith and Zdonik, 1987). The conventional tabular database model is insufficient to capture the hierarchy of masonry walls.

3 MASONRY UNIT SCHEMA

The masonry units are represented in a relational database known as the MUD which provides generic masonry BIM objects for concrete, clay and cast stone shapes. By generic, we mean that the unit configurations are widely available from multiple suppliers—and are appropriate for use in early-stage architectural and structural design, generally completed before specific materials are selected for the project. These masonry objects are extracted from the geometry table of the MUD and the 3D geometry is generated on-the-fly from these parameters. This makes it easy to add masonry units to the database—but it limits the shapes that can be represented to those which can be generated through conventional solid modeling operations (extrusion, fillet, Boolean subtraction, etc.). The MUD extends beyond simple geometry, and includes tables for material properties, color and texture (see Fig. 1). For this reason, the MUD cannot be represented as single flattened table in the way that the steel shapes database from AISC is provided (Steel Construction Manual Shapes Database, Version 14.1, 2013).

The proposed implementation of the MUD is described below and is shown conceptually in Fig. 2. Generic shapes are input into the database using an Excel template. The template contains the overall geometry of the unit as well as the parameter set needed to generate the features of the unit.

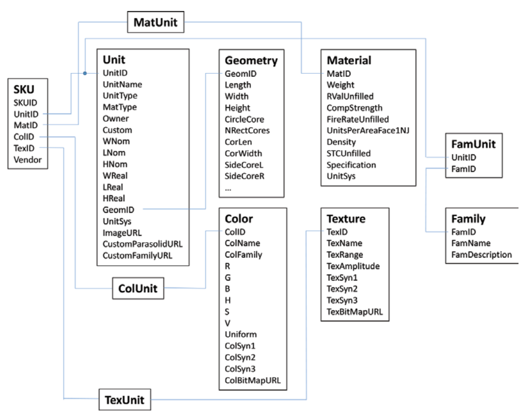

Figure 1. Relational database tables in the Masonry Unit Database.

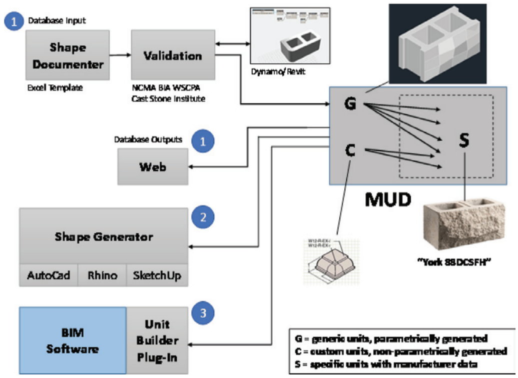

Figure 2. Access to the Masonry Unit Database.

The geometric parameters are validated using a Python script in Dynamo/Revit, as described in our prior work (Sharif and Gentry, 2015).

In addition, because the units are considered generic and thus industry standard, the geometry of the units are validated and approved by the relevant industry trade association for concrete masonry, clay masonry, or cast stone masonry. The resulting geometries are tied to the unit, material, property, color and texture tables in the MUD. In the future, it is anticipated that the generic units will tie to one or more "specific" units in an extended version of the MUD—an example of a textured concrete masonry unit is shown in Fig. 2. In this way the MUD acts as a bridge to the materials procurement project phase and the generic units in the BIM model will be replaced with specific units so that information on cost, lead time, shipping, part ID etc. can become part of the construction-phase BIM model. There are a number of specialized masonry units that cannot be generated parametrically (these units will thus have no entry in the Geometry table). These custom units and their properties will need to be input into the database using a manual procedure. It is likely that the custom unit geometry will be stored in multiple formats in the database (DXF, Parasolid, Revit family). At this time the functionality of the custom unit is envisioned, but not implemented.

Once the database is populated, three methods of database access are anticipated. First the database can be used as a repository for a simple web portal into the data. The portal allows for the user to select and view masonry units according to unit type, size range, color, texture, or family relationship. The second mode of database access is a download of the masonry unit in one of a number of standard CAD/BIM formats. At this time we have selected three such formats: (1) AutoCad DXF, (2) SketchUp Component, and (3) Rhino Block. We expect that the application will generate these files as needed in run-time, directly from the parametric data, without the need to store the files.

The final mode of access for the MUD will be through a BIM plug-in. A plug-in is a custom software tool that runs within existing software, in this case a BIM authoring platform (e.g., Revit), and adds functionality to that software. The role of the plug-in is to bring masonry information into the BIM model, and allow the placement of single masonry unit relative to the wall. The plug-in assists the user in placing the units by allowing the unit to be hosted at the face or centreline of the wall. In addition, the plug-in generates 2D view information where necessary to create vertical and horizontal section views. Finally, the plug-in carries with it associated type parameters so that the masonry unit can be counted, scheduled, and managed parametrically, as is common for other elements such as doors, windows, and furniture within BIM applications.

4 MASONRY WALL SCHEMA

The problem of masonry walls is considerably different from that of masonry units. The MUD is internally-focused to provide comprehensive information about units, but little information about the context in which the units are applied. Masonry walls on the other hand are defined wholly by their context—the functional, engineering and aesthetic requirements dictate the geometry of the walls and the masonry schema is configured to fulfil these requirements. The overall geometry of a given masonry wall includes the base plane, top of wall, start and end points, and door and window openings. The architect/engineer also specifies the sizes and bonding patterns for the masonry, so that the masonry units can be fit within this overall geometry. In the past, masonry bonding and coursing has been represented by a 2D pattern or "hatch" which is applied to the wall surface, to imply that the wall is composed of masonry, but not in reality to establish the exact location of masonry units. The capabilities of BIM and the goal of the masonry wall schema is to establish the location of every masonry unit in the wall, computationally. This raises a number of problems.

First, in the early stages of design, architects are concerned with the overall geometry of the building and less concerned about the location of individual building elements. During the design process, objects such as walls, doors and windows are added, moved and deleted from the model and the designer has little interest in tracking the location of masonry units. As the design is refined, the issue of wall construction comes into play. The concept of Level of Development (LOD) in BIM is a useful construct that guides the increasing fidelity of information that is encoded into a building model as design decisions are made (BIM Forum, 2015). According to the LOD Specification, model elements are represented with a range of information complexity, from the most schematic representation (LOD 100) to the most detailed representation, which contains complete 3D geometry, specifications, and as-built information (LOD 500). At the early stages of design wall elements are represented at LOD 100 and wall thickness and materials may not been identified. At some later stage in the design process, the wall is identified as masonry, and the masonry units are propagated into the wall and three-dimensional details and reinforcement are added. We recommend that this occur at LOD 400 (Cavieres and Gentry, 2015). At this point, the global geometry of the wall and the local geometry of masonry units has to be resolved, and masonry units populated into the wall. This likely involves the cutting of masonry units, adjustments in coursing and bonding, and in reinforced masonry, the propagation of vertical and horizontal reinforcement (Cavieres et al., 2011).

This leads to the second problem. BIM applications are known to be computationally-intensive, and the performance of any parametric-modeling software like BIM degrades as the number of elements in the model increases. Most BIM applications are memory based: all of the objects in the building model, and the hierarchical relationships that manage the placement of objects are held in memory, not in separate files on disk or in the cloud (Eastman et al., 2011). It is likely that a masonry building will have tens or even hundreds of thousands of masonry units—and it is simply not possible with current computer limitations to model each masonry unit in BIM.

We have therefore developed an intermediate construct that is somewhere between an entire wall and a single masonry unit. This intermediate unit is defined as a "region". The region is both a subdivision and a functional abstraction of the masonry wall. In our prior work we have introduced a definition of regions that includes stakeholder viewpoint and a model abstraction commensurate with the concept of a Model View Definition or MVD. The MVD concept was developed to formalize the extraction and exchange of information from a building model according to the specific actors and analysis context (East et al., 2013, Venugopal et al., 2012). For masonry walls and buildings the analysis context might be structural analysis, energy simulation, rebar detailing, quantity take-off, lift and scaffold placement, etc.

In this paper we focus solely on the underlying fundamental region concept, which is the geometric subdivision of the wall according to overall wall parameters including wall geometry and masonry wall coursing and bonding. This definition forms the basis for the masonry wall data model. The requirements for representation of regions within the wall are enumerated below. We provide specific, and somewhat limiting, requirements at this time so that the region concept can be prototyped in a BIM plug-in.

An example of a brick wall with region subdivision is shown conceptually in Fig. 3 and the definitions and behaviors of the regions are as follows:

1. A masonry region is bond by horizontal lines defining the courses of masonry. The first and last courses are the outermost horizontal boundaries.
2. A masonry region is bound by vertical lines in coordination with the masonry bond and head joints. Thus, the region contains only full and half masonry units. When a wall in running bond is represented at LOD 400 or higher, the vertical region definition is a staggered line that follows the bond.
3. The masonry within a given region must all be laid within a given bonding pattern, but, it is possible to create a sub-region within a given region which can have a different bonding pattern.
4. For this initial implementation, it is assumed that regions may be rectangular, trapezoidal or triangular (so that gables can be defined). A sloped region boundary may only occur at the top of a wall.
5. Regions may be defined also through the thickness of the wall, to accommodate walls with multiple wythes of masonry.
6. A subdivision of a wall into regions is required and is driven by door and window openings, movement joints, wall corners, etc. Once these

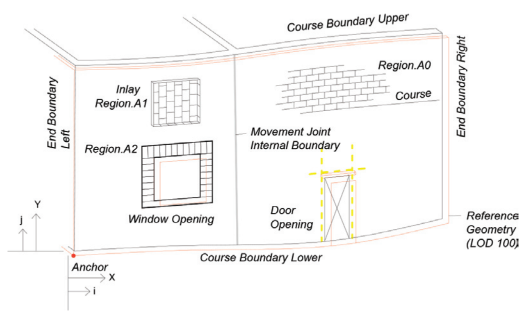

Figure 3. Definition of regions in masonry walls in BIM.

sub-regions are established, masonry patterns can be propagated.

7. Within a given region, a set of rules are established that control the placement of masonry-specific components such as vertical reinforcement, bond beams, grout, wall ties, weeps, etc.
8. The smallest region is the size of one masonry unit—but it would be unlikely that such detailed subdivision is necessary. If a single masonry unit were unique, for example a unique glazed or molded brick, then in our proposed schema that brick would be part of its own region.
9. Rules will define the behaviour of the regions at the horizontal, vertical, and sloped boundaries. The boundary rule interacts with both regions that meet the boundary.
10. The region concept enforces that the wall be "in-coursing" and "in-bond". Rules adjust the vertical and horizontal mortar joint thickness to fit the masonry units into the regions where possible.
11. Masonry wall corners at L—and T-shaped intersections form their own special region type. Therefore a complex set of walls can all be controlled geometrically from a single "anchor point", from which the masonry pattern is established. Fig. 4 shows an example of L-type masonry corner definitions.

4.1 *Relationship between regions and LOD*

At LOD 100, masonry regions are not defined, but the overall geometry of the wall and the openings has been established. As a masonry wall model is promoted to LOD 200, regions may first be defined. The division of a given wall into maximal regions occurs at this moment and it is anticipated that this subdivision can be automated in the BIM wall plug-in. The maximal regions might then be further subdivided by architectural wall features such as such as a stone water table at the base of a wall or soldier brick coursing over the top of window openings.

It should now be possible define masonry unit coursing and bonding patterns and to apply these bonding patterns to the regions. In most BIM applications, this involves the definition of the masonry unit, mortar joint spacing, and other properties through the thickness of the masonry wall. Also as part of this process, the behavior of the masonry at the region boundaries must be established. Typical examples for vertical boundaries include: "preserve running bond with adjacent regions" and "insert half bricks and establish control joint" (see Fig. 4).

At this point it is possible to generate a custom hatch (2D surface pattern) for each region on the masonry wall. These patterns can be used for manual verification that the masonry wall bonding and coursing is correct. The hatch representation is computationally lightweight—and might well be sufficient for much of the early-stage architectural design process.

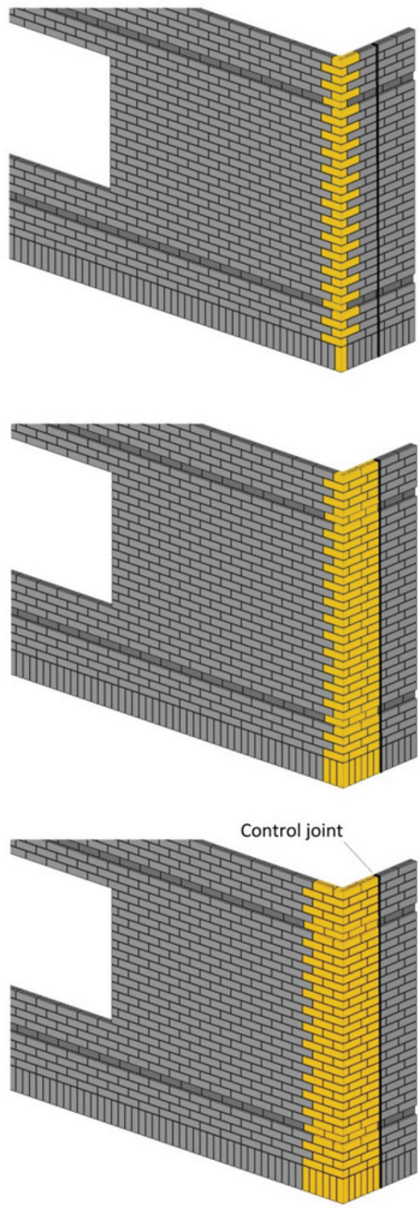

Figure 4. Possible masonry wall L-type corner definitions.

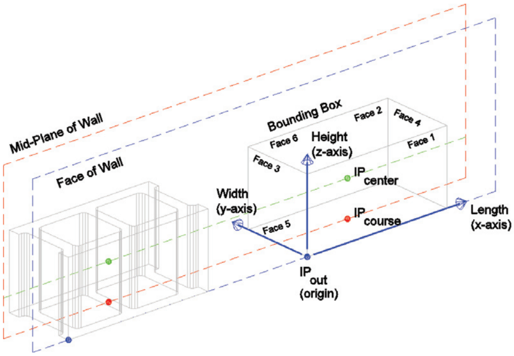

Figure 5. Insertion of masonry units into masonry walls.

The act of placing and correcting the architectural hatch on walls is not trivial. This may mean that overall building dimensions need to be adjusted, or that the size and location of doors and windows need to be changed. Or it may be that alternative masonry units will be specified to meet the overall building geometry. In some situations it may be possible to adjust the width of the head and bed joints—or allocate the dimension mismatch to vertical and horizontal control joints. Once the masonry patterning has been established, and the patterns accepted, the masonry wall can be considered to be at LOD 300.

For structural masonry, LOD 350 has a specific definition as outlined in the 2015 BIM Forum Specification. In the structural layer of the walls, the following elements should be included in the model: bond beam and lintels, reinforcing and embedments, and jambs sections. These are key elements included in automated clash detection and trade coordination.

Finally, the propagation of individual masonry units into the BIM model, if required, occurs at LOD 400. The region concept supports the selective placement of masonry units into the model on a region by region basis. Therefore, if certain regions are complex or of specific interest due to detailing, then only those regions can be promoted to LOD 400. The masonry units in the MUD are parametrically generated within a specified local coordinate system (Fig. 5), allowing the masonry units to be merged with the hatch pattern at either the wall face or wall centreline, as appropriate.

An LOD 500 masonry wall model might be useful for condition assessment of existing wall facades, but the schema for such models has not been considered in these models at this point.

5 SUMMARY AND CONCLUSIONS

The semantics of masonry walls are largely missing from current BIM applications. To integrate masonry into BIM, definitions for masonry units and masonry walls, which are relevant in the physical world, as well as in the computational world, are needed. The data models for masonry units and walls, as described in this paper, form the basis for the computational representation of masonry in BIM.

The geometry of most clay and concrete masonry units can be represented parametrically in relational database. The geometric data can be joined relationally with data regarding engineering properties, color and texture so that masonry units can be populated into architectural, structural, and construction BIM models. The implementation of the masonry unit database is underway, and we expect it to be commercialized within the next year.

The computational representation of masonry walls is much more complex. This paper outlines our underlying philosophy for a compact but extensible representation of masonry walls in BIM platforms. We believe that the schema as described here can be overlain on existing BIM / 3-D modeling platforms (e.g. Revit, Sketch-Up) as well as work with the proprietary wall representations used in masonry-specific software packages.

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