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PARAMETRIC DESIGN, DETAILING AND STRUCTURAL ANALYSIS OF DOUBLY-CURVED LOAD-BEARING BLOCK WALLS

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ABSTRACT
This paper, explores the extent to which concepts of parametric modeling can be applied to support the design process of load-bearing masonry buildings. The research uses the concepts of building information modeling and parametric representation to capture and execute relevant constructive knowledge for the design of doubly-curved masonry walls. Prototype software has been developed to translate this knowledge into a set of explicit parametric rules and geometric constraints which "bound" the curvatures of the masonry walls to those with admissible construction and structural solutions. Rules for calculation of vertical and horizontal reinforcement placement of rebar in grouted cells and bond beams have been developed to allow for preliminary design of doubly-curved walls. The software operates within a CAD environment and provides real-time feedback on wall configuration and reinforcement as the model is built. The paper reviews the rules necessary for block wall description, including door and window openings, and focuses on the calculations necessary for preliminary structural design of doubly-curved load-bearing masonry walls.

KEYWORDS: building information modeling, parametric modeling, concrete masonry units

INTRODUCTION
Masonry buildings and structures are often associated with conservative solutions and traditional architectural designs. Architects and engineers usually avoid innovative configurations or non-conventional building shapes because they are considered risky, difficult and expensive to solve. This perception clearly affects a more widespread adoption of block masonry, as well as its competitiveness with other construction systems. There are two related causes that complicate this situation: first the increasing lack of specialized knowledge about masonry requirements, limitations and possibilities and second, the lack of computational tools to effectively represent, explore and manipulate a masonry design model.

Despite the fact that the masonry industry and the research community have continuously moved forward with advances in new masonry unit types, structural analysis methods and more efficient construction processes there is a perception that the limits of masonry are not being challenged by architects [1], [2]. Current technical innovations are not being extensively transferred into design practice, and in most cases new masonry buildings continue to adopt conventional and rather conservative solutions. A number of misconceptions and prejudices among architects, such as the high cost of masonry construction and its limited formal possibilities threaten the competitiveness of masonry in relation to other structural systems.

There are few digital tools available for designers to represent and explore innovated masonry configurations. In the absence of such tools what becomes costly is the amount of effort architects have to put on modeling and detailing a building with hundreds or probably thousands of masonry units. New Building Information Modeling technologies have been developed in recent years to handle similar complexities inherent to architectural design. They are already being used within the AEC industry for advanced design exploration, sophisticated engineering analysis and precise specification of building assemblies for fabrication. The parametric modeling capabilities of these technologies have facilitated the incorporation of technical knowledge about material behavior, fabrication and construction processes on early design stages, increasing architect's understanding of design implications and promoting successful innovations [3].

This research addresses this issue by focusing on the development of similar capabilities to promote the adoption of concrete masonry systems in contemporary design practice. For that purpose we explore methodologies to incorporate masonry construction knowledge into the design process by using state-of-art computational technologies. The goal is to improve the design and construction processes by supporting the creation, testing and evaluation of a higher number of design alternatives from the beginning. In this scenario an important emphasis will be put on formal variability and geometric complexity of building envelopes. Masonry units allow a wide and rich scope of configurations, and several types of formal results, whether in load-bearing mode or as cladding. This feature can be intensively explored by means of parametric modeling, making the representation of complex geometries and assemblies an easier and more realistic approach towards innovation in the design of masonry buildings.

PARAMETRIC CONSTRUCTION OF CONCRETE BLOCK WALLS

Object behavior in a parametric modeling environment is seen as the ability of a building component or assembly to respond to an internal or external stimulus preserving the original design intent. According to Sacks et al., this response occurs when the system is capable of taking automatic actions in order to “maintain the topological and geometrical consistency of the relationships within and between model objects” [4]. In this manner objects have to be modeled not only as they look but most importantly, as semantic relationships within a specific domain. However a major issue for the implementation of domain-specific BIM parametric solutions relates to the problem of how to specify and embed relevant design and engineering knowledge in a parametric modeling system. One of the main difficulties arises from the fact that much of this knowledge is tacit and difficult to represent.

In earlier work by our team, we developed a series of parametric geometric relationships describing the placement of typical 200 mm (8 in.) concrete block in running bond [5]. This work was based on a framework established by Eastman [6] and Lee [7] known as Building Object Behavior or BOB. For the concrete block wall, BOB implies a set of rules for preserving the masonry coursework and vertical reinforcing cells, while providing actors that can morph the shape of the wall, and insert openings within the wall. Figure 1 shows the sequence of geometric and declarative constraints that defines the behavior of a single masonry unit. The unit itself is treated as a hierarchical assembly of points, lines and surfaces. Upon these basic elements higher level geometric entities are built.

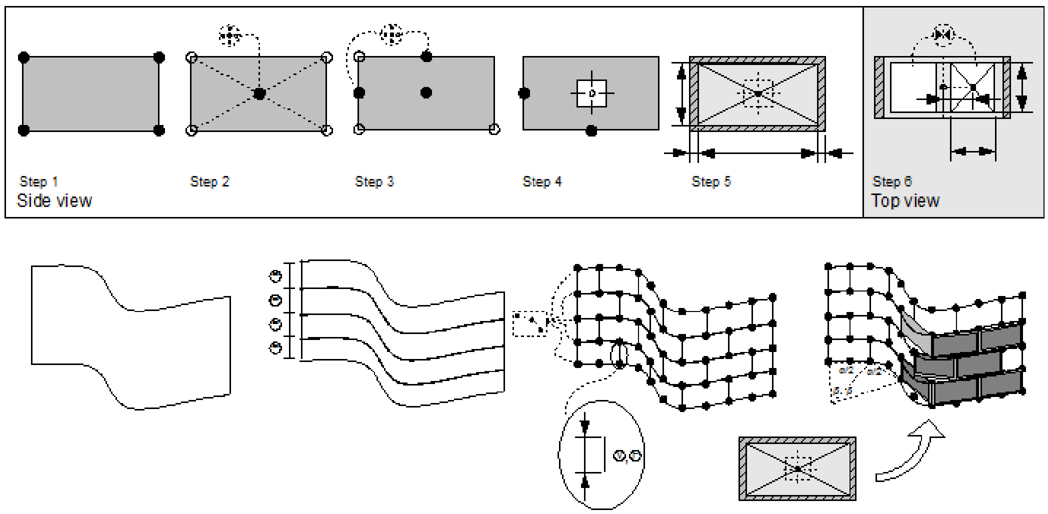

Figure 1: Building Object Behaviors for Curved Block Walls.

At a higher level within the model, the wall assembly is defined following a top-down modeling approach. The overall skeleton or control rig is created before the propagation of the blocks. The initial input is a surface that describes that wall geometry. This surface is tied to overall building geometry and works as supporting element for the wall assembly and at this level the bonding patterns and the spacing between courses, headers and mortar thickness is defined. At this point in the research, only running bond is considered.

The running bond pattern algorithms were defined and then implemented as an iteration to create the woven sequence. For the generation of rebar in vertical cells and bond beams, additional functions are required. Functions for placing door and window openings in the walls, and the adjustment of these opening to accommodate wall curvature and wall reinforcement are needed as well. The specifications for these geometric and structural algorithms are discussed in detail in what follows. The implementation of early versions of these rules, and the feedback provided, are depicted in Figure 2 and described in detail in by Cavieres et al. [8]. In Figure 2a, blocks which exceed pre-set corbelling limits are highlighted. In Figure 2b, blocks which will require cutting to meet the desired curvature in the horizontal courses are highlighted. The generative nature of these scripts allows the designer to freely change the dimensions and shape of the supporting surface while keeping the regularity of the running bond pattern – and while observing the feedback from the geometric and structural calculations in real time.

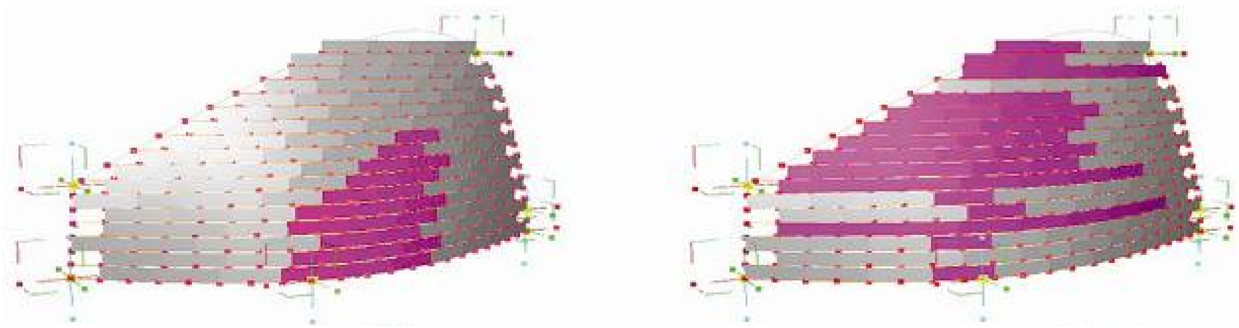

Figure 2: Parametric Model: a) Cut Block Feedback Selected, and b) Corbelling Feedback Selected.

CONSTRUCTION AND STRUCTURAL REQUIREMENTS

In the following text, the geometric, structural and detailing issues raised by the doubly-curved block walls, and the parametric approach to dealing with the issues are discussed. The generic wall in question is shown in Figure 3. The specific issues addressed are curvature in plan (which can be seen in Section P-P), curvature in section (which can be seen in Section S-S), accommodating internal reinforcement, insertion of door and window openings, and calculation of out-of-plane flexural capacity. In all cases we are dealing with a masonry wall, without intersections or pilasters. The wall can be curved in plan or section, but it cannot accommodate sloped bed joints.

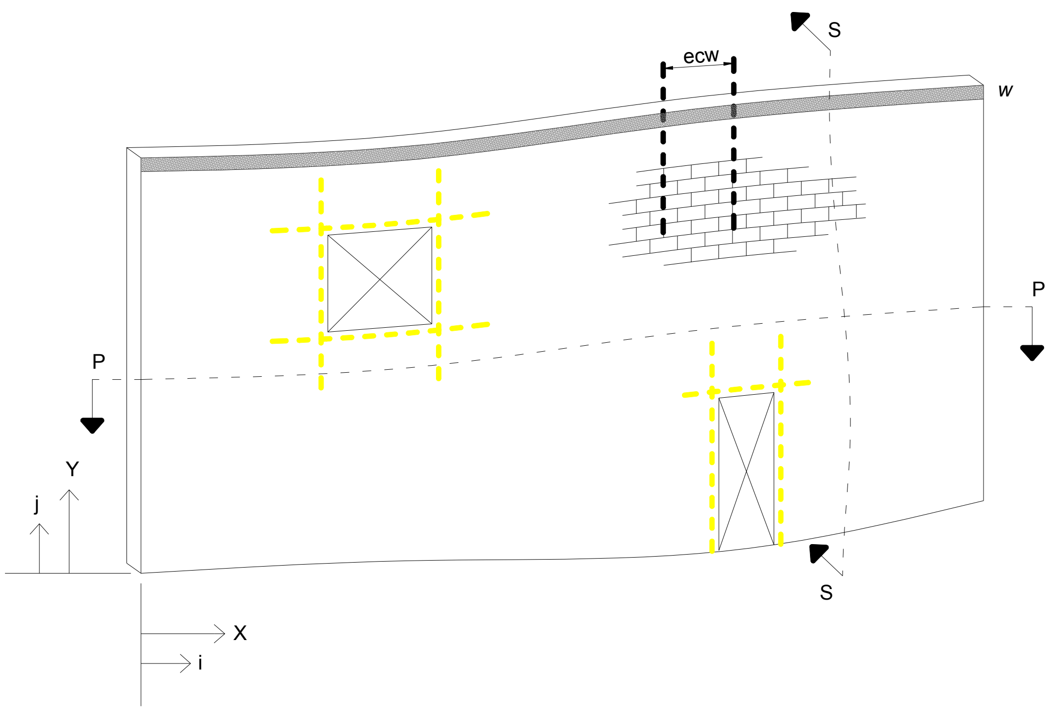

Figure 3: Doubly-Curved Block Wall.

WALL CURVATURE IN PLAN

Concrete masonry in standard running bond construction accommodates curvature in plan quite well. Thomas Jefferson's curved walls at the University of Virginia offer the prime example of the strength of curved walls, being only one brick wythe thick. In concrete block moderate radius can be achieved by allowing the ears of the blocks on one side of the wall to come into contact (head joint thickness equal zero) while allowing the joint thickness on the opposite ear to be double thickness (Figure 4a). For a standard 8 in. concrete stretcher block, this equates to a radius of around 4 m (13.3 ft.) or an allowable rotation of 5.6 degrees of any one block in a course relative to the next. A higher degree of curvature in plan can be achieved by cutting the ears off the block on the inside of the curve. In this case, a radius of around 1.7 m (5.7 ft.) can be achieved (equating to an incremental radius of 13.4 degrees between blocks). In this case the head joints on both sides of the wall will flush and there will be no mortared head joint (Figure 4b).

This rather simplistic geometric example is used to indicate how curvature rules can be embedded into the system. A block to block rotation of less than 5.6 degrees can be achieved within the head joint. A block to block rotation of up to 13.4 degrees can be achieved by cutting the ears off the stretcher. Curvature of more than 13.4 degrees is probably not advisable. In the parametric CAD system, if the feedback for "horizontal curvature" is turned on, the system will color-code the blocks in real time to indicate whether they are not cut, have cut ears, or are beyond the limits recommended by the system. These curvatures are well within the limits for bending small-diameter rebar, so accommodating bond beams within the curved coursing will not be an issue.

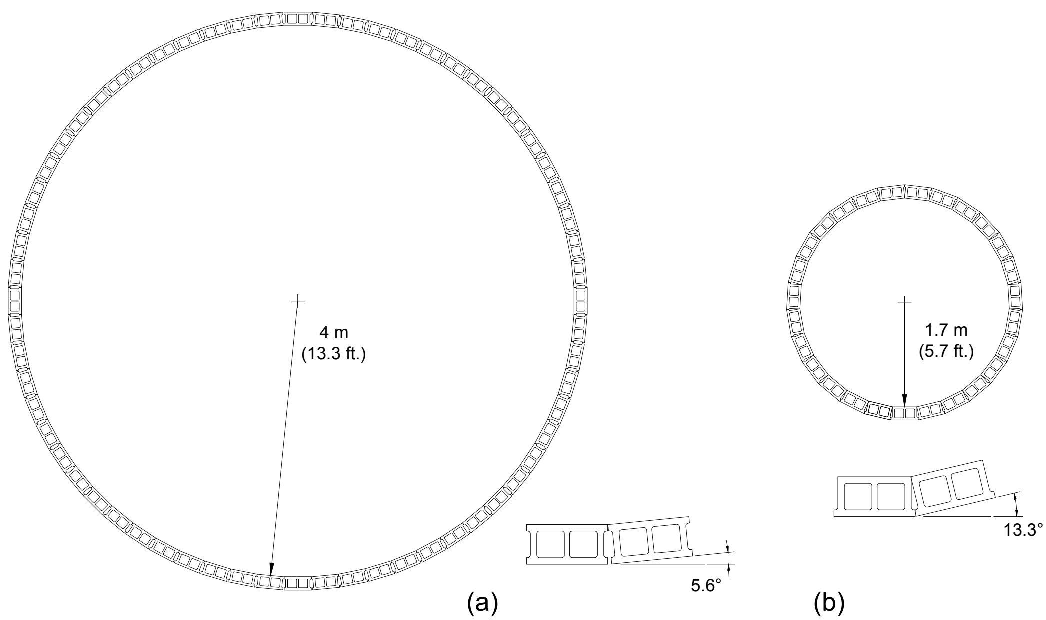

Figure 4: Limits for Plan Wall Curvature: (a) Standard Stretchers without Cutting, (b) Ear Removed from Stretcher

WALL CURVATURE IN SECTION

In section, wall curvature will be more difficult to accommodate, as both geometric and structural limitations come into play. This will lead to less radical levels of wall curvature than will be possible in plan. Sectional curvature could be achieved by cutting the block parallel to the bed joint, but this will violate the principle of retaining the horizontal mortar joint. Sectional curvature could also be achieved by varying the mortar thickness between the inside and outside faces of the wall, but this too will lead to non-horizontal bed joints. Therefore, we have elected to achieve sectional curvature through corbelling of the block wall. Corbelling of the wall in this manner will lead to the violation of the traditional corbelling requirements found in ACI 530 /ASCE 5 /TMS 402, Section 1.12, as the back face of the wall will not remain within 25 mm (1 in.) of plane [9]. Furthermore, the definition of plane as used in the standard is not clear for doubly-curved walls.

Generally, prescriptive corbelling limits per course are on the order of 25 mm (1 in.) per course with a total degree of corbelling up the height of the wall not to exceed one-half the wall thickness. What is proposed here is a tighter restriction on course-to-course corbelling, and no arbitrary geometric limit on the degree of offset over the height of the wall. The overall offset will instead be established using flexural calculations up the height of the wall

The typical concrete block has a face shell thickness between 15 and 35 mm (0.75 to 1.5 in.). An arbitrary inter-course corbelling distance of some fraction of this face shell thickness, e.g., one-fourth, has been set as an initial limit within the parametric rule set. This prevents radical local change in sectional curvature and provides for a mortar bed joint that can still be filled and raked clean even when the blocks are corbelled.

For a typical 4 m (12 ft.) high block wall, this leads to a maximum offset of approximately 135 mm (5.3 in.) for the height of the wall. The corbelling of a typical block, and the maximum "tilted" and "belly" wall are shown in Figure 5. As the diagram portrays, these are moderate levels of out-of-plumbness. Higher leveling of corbelling is possible and thus higher levels of section curvature are possible, but this might lead to weathering problems in the bed joints, and P-Δ effects in the walls, as discussed in what follows. In any case, the selection of a limit on corbelling of one-fourth the face shell thickness is arbitrary, and limits of one-third and one-half are being explored as well.

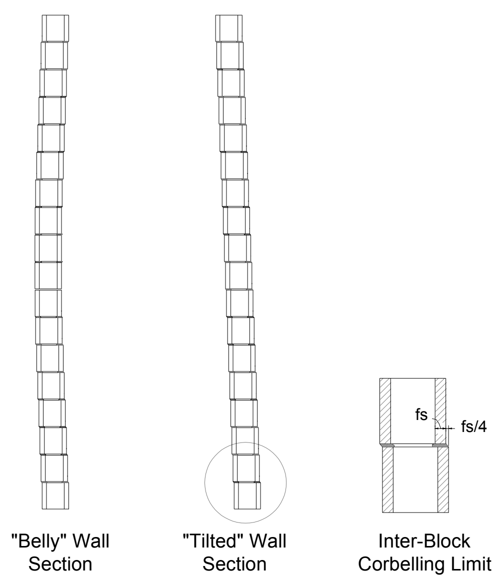

Figure 5: Limitations on Curved Walls in Section.

WALL REINFORCEMENT REQUIREMENTS

The parametric approach must provide feedback not only on geometric limitations, but also on structural limitations. The structural feedback described below should not be considered a complete structural design, but is intended to indicate whether a given wall configuration is reasonable, and if so, what level of vertical reinforcement is required. The focus is on in-plane compression and out-of-plane flexural forces caused by wall curvature and eccentric loads. In-plane shear and bending, usually generated by lateral loads and present in shear walls, are not considered.

It is possible to use a simplified approach to calculate the flexural stresses in individual blocks, like a crude finite element approach. This however will not lead to a clear method for calculating the required vertical reinforcement. Instead our approach is to extract vertical sections out of the wall, at a spacing of some multiple of 200 mm (8 in.) as shown in Figure 6. In the example, the spacing is shown as 1000 mm (40 in.). Since the goal of this analysis is to treat vertical curvature, each section is treated as if it has no curvature in plan, and the system facilitates this by calculating the eccentricity of each block relative to the block above for all the blocks in the section. Since the wall is laid in running bond, each section contains a mixture of full block and sectioned block, but that does not affect the analysis.

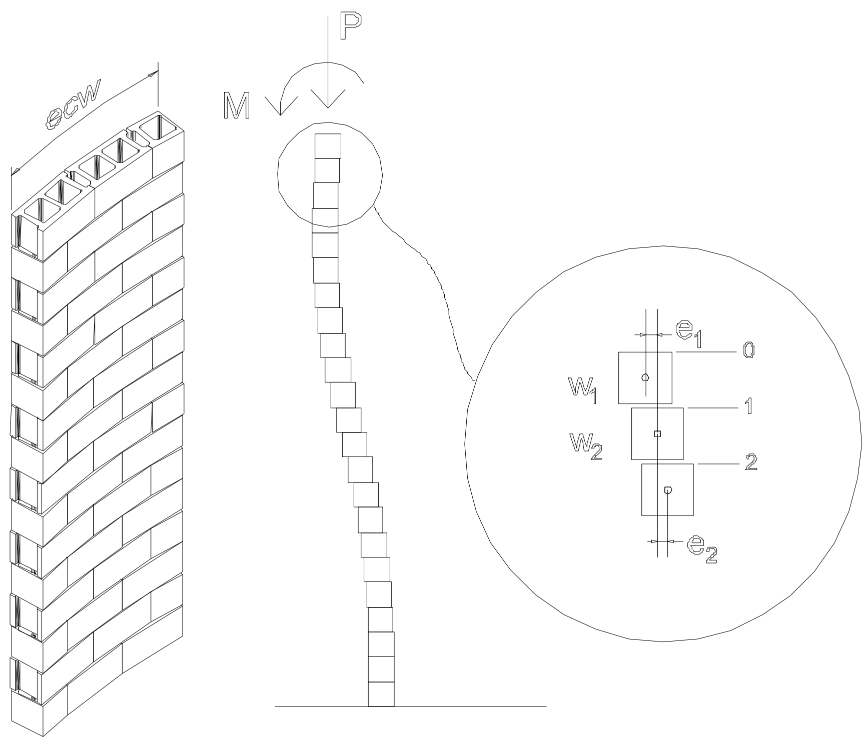

Figure 6: Vertical Section for Wall Flexural Reinforcement Calculation.

The section is preliminarily considered to contain one M13 (No. 4) reinforcing bar. Therefore, the section selection must meet the requirement for the effective compression width for a single bar as provided in Section 1.9.6 of ACI 530 /ASCE 5 /TMS 402. If the wall is considered pinned at the top and the bottom, then the wall section is statically determinant and two vectors P* and M* are easily calculated representing the factored axial force and bending moment for each of the courses down from the top of the wall to the base. These P* and M* are compared to tabulated versions of the axial load bending moment interaction diagrams for a single M13 (No. 4) reinforcing bar at a spacing of between 8 and 120 inches, as found in design guides such as NCMA Tek Note 14-11B [10]. At this point in the research, no method for calculating moment magnification due to wall deflection has been implemented – but these considerations will doubtless be important for tall walls.

The feedback to the user is provided in the form of the number of bars required in each section. If, force and moment demands cannot be satisfied, even with reinforcement in every cell, the entire section turns red to provide feedback that the combination of loads and vertical curvature are too high.

The requirement for horizontal (bond beam) reinforcement is primarily empirical, and is not based on structural calculations. Though not a code requirement, it is probably a reasonable idea to require bond beams at 1200 mm (48 in.) spacing maximum, along with the typical requirements for bond beams at the bottom and top of openings, and at the top of walls.

DOOR AND WINDOW PLACEMENT

The placement of a door or window opening in a load bearing masonry wall requires that the opening be coordinated with the masonry coursework and with the wall reinforcement. Because of the doubly-curved walls, the algorithms must also assist in ameliorating between the flat surfaces of the doors and windows, and the doubly-curved wall surface.

As implemented, the door and window placement rule facilitates the proper sizing and placement of masonry openings. The size of the openings is limited to vertical and horizontal increments of 200 mm (8 in.). In addition, as the openings are placed, they “snap” to masonry coursework and bed joints (and “half” bed joints). The approach eliminates the placement of openings that cut into a course of masonry.

The openings are coordinated with wall vertical reinforcement as follows. If the horizontal dimension of the opening is of the same size or smaller than the clear wall vertical bar spacing, and one vertical reinforcing bar is cut by the placement of the opening, then the closest jamb bar adjacent to the cut bar is converted into a bar up the full height of the wall and the previously cut bar is eliminated. If the wall opening is larger than the clear wall vertical bar spacing, then both jamb bars are converted into bars up the full height of the wall. For openings with even larger horizontal dimensions, both jamb bars will be continuous and vertical bars will be cut both above and below the openings. This process is depicted in Figure 7, below.

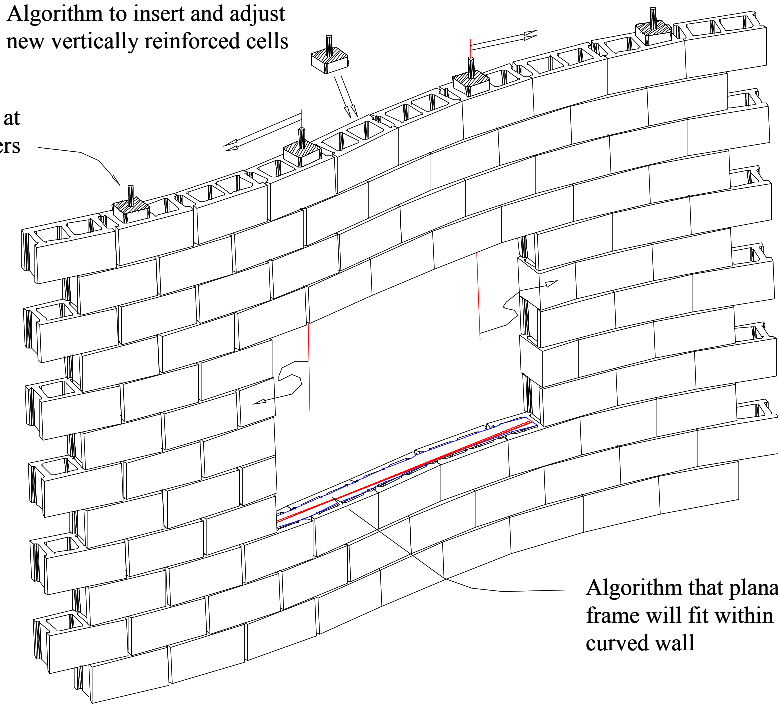

Figure 7: Algorithms for Creating Openings in Walls.

Finally, the system must verify that an opening within the curved wall, is "planar enough" to accommodate a planar door or window frame. The thickness of both the wall and the window frame are known – and the thickness of the window frame is usually 50 to 75 mm (2 to 3 in.) thinner than the wall thickness. Consequently, the parametric relationship between opening and frame can be tracked, so that openings that violate the "plane within a surface" restrictions are coded as the openings are placed, alerting the user to the fact that the door or window will not fit properly in this location – or, that the wall curvature will need to be changed to accommodate the door or window.

CONCLUSION

The methodology presented above is simplified so that all calculations can be updated continuously as the wall is varied with the CAD environment and the Building Information Model is constructed. The purpose of the system as described acts primarily in the early stages of design, before the architect seeks the advice of a structural engineer. The system functions then as a tool to validate, shape and bound architectural decisions. The goal is to provide architects with a tool to design complex masonry walls with confidence to know that the walls are both structurally feasible and constructible.

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