Representation + Fabrication: Connecting descriptions and artifacts in the digital age

T. Al-Haddad, R. Gentry, A. Cavieres, M. Carpo, J. Cho, L. Wagner & A. Zaitsev
Georgia Institute of Technology, Atlanta, Georgia, USA

This paper broadly considers the question of new modes of linking the representation of a thing to the actual process of physical making through advanced parametric CAD and digital construction technologies to reformulate existing construction logics; in other words considering parts, relationships, and actions. This approach implies the refinement of the traditionally understood idea of CAD/CAM, or digital manufacturing, and begins to formulate a new intellectual direction of *Digitally Augmented Making* [DAM] paradigms where anthropological design and fabrication activities are enhanced through digital means. An important aspect of this research deals with broadly applying the *digital promise* to real world AEC industry constraints in order to have a meaningful impact on well established construction protocols. The particular case study presented in this paper is framed through the lens of rethinking complexity and potentiality in variable concrete masonry systems and processes.

1 INTRODUCTION

1.1 *Descriptions and artifacts*

The gap between the description of a thing and the thing itself has been the subject of inquiry dating back at least as far as the Platonic construct of the Ideal. In today's AEC industry this gap could also be understood in terms of the relationship between the design representations of the architect and the material constructs of the builder in the act of Becoming, or the act of translation from drawing to building. The traditional process of interpreting design intent into constructible form has long been established through the system of shop drawings, submittals and specifications. This process of interpretation and translation from the design representation to material construct is a contested space riddled with perceived limitations, miscommunications, and ambiguities. It also represents a vast territory for architectural research in light of the computational tools and technologies that have emerged both in practice and academia. These tools represent an opportunity to bring the representation and the artifact into closer direct contact in the many actualization phases of a project.

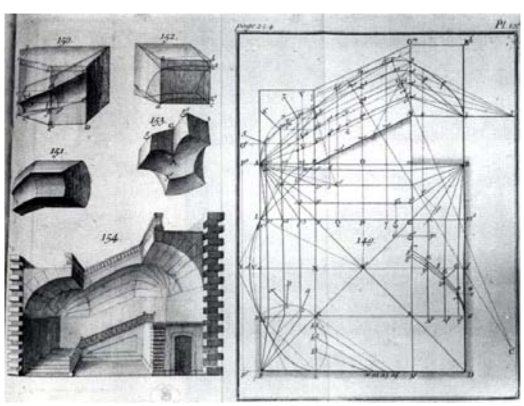


Figure 1. A.F. Frezier – La Theorie et la pratique de la coupe des pierres (Evans, 1995)

Digital technologies, both representational and fabricational [CAD/CAM] have been said to allow for a new form of digital craft and user specification through CNC fabrication. This type of purely digital making has been widely researched, practiced, and written about in the last decade however it is becoming more and more clear that the notion of the purely digital is incongruent with the realities, traditions and possibilities of current construction practices at the scale of buildings. As was the case in computer science the concept of the purely virtual gave way to the hybrid, the blended, the bastardized. The research moved from the concept of Virtual Reality to Augmented Reality, a form of both/and. Digital making is at a similar intellectual bifurcation. In order to push the possibilities of the digital into the practicalities of the physical a new hybrid approach of Digitally Augmented Making [DAM] must be developed which asks first how can the space of potentiality offered by digital technologies begin to learn from, react to, and ultimately transform existing design and making processes that have long historical threads and broad cultural implications.

Today the question of non-standard construction and formal complexity often implies the use of sophisticated CNC fabrication equipment to manufacture unique parts in order to construct a complex whole. While this approach remains to be a valid and rich territory for exploration the inverse approach of using standard parts within a complex whole offers another trajectory for designers and constructors to explore within the larger question of complexity, emergence, and construction. Through the systematic deconstruction and codification of the rules, or logics, that regulate various material/construction systems we are now beginning to close the gap between the representation and the artifact. This extracted construction knowledge can now be made explicit and can be embedded within intelligent design environments [Parametric Models/BIM] in order to give designers the ability to interactively test high level formal or programmatic ideas against low level material construction possibilities so as to tune design intentions with material realities. BIM systems [Building Information Modeling] are beginning to allow architects to develop constructible complex geometries from both standard and non-standard construction systems while giving engineers and contractors a means by which to calculate, verify, and construct the design. Again, this emphasizes the ability of digital technologies to begin to close the gap between the representation and the artifact; working both as top-down and bottom-up design systems simultaneously.

1.2 *Historical Traces*

In the beginning, buildings were conceived and made by those who needed them. In time, as constructions grew bigger and more complex, actors and agencies intervening in the process of building became increasingly estranged from one another. Buildings, or parts of them, started to be designed by specialists working off-site, who sent documents of various kinds to workers that were expected to understand or interpret the instructions they received, and build accordingly. The degree of separation between design and construction (hence the degree of precision of design notations) ebbed and flowed in the course of time, but it is at the beginning of the Renaissance that Leon Battista Alberti, the humanist, first claimed that architects should stop making things, and should design them instead.

Since then, the "Albertian paradigm" has defined the architectural profession in the West, and to this day still underpins the global practice of architecture, including in its legal aspects. In the modern, humanist tradition architects are expected to design objects without making them, and builders are expected to carry out the design notations they received without changing them. The consequences of this cultural and technical paradigm have been determinant for many aspects of early-modern, modern, and contemporary architecture. The separation between design and building limits the realm of buildable forms to those forms that can be geometrically notated, and measured in drawing. In turn, the architect's authorial role depends on the identical translation of architectural notations into building: as Alberti first stated, all changes in design that are not "authorized" by the designer should be considered as errors. The industrial revolution, and the mechanization of construction technologies that ensued, further validated and corroborated the importance and extent of this notational and authorial way of building.

But for the last twenty years or so, the digital turn (the shift from mechanical to digital technologies) has drastically reversed this trend. As digital tools can be used to design and fabricate at the same time, CAD/CAM technologies have already started to bridge the gap between conceivers and makers; digital notations have conspicuously reduced the formal limitations of traditional, Mongian based architectural drawings; digital fabrications technologies are mostly indifferent to economies of scale, which derived from the technical logic of mechanical matrixes, molds, or imprints; and the interactivity and reversibility which is inherent in all digital processes are alien or averse to the traditional and modern definitions of authorship (Carpo, 2008).

Bricks, or in this case blocks, are a technology of choice to test this new covenant between digitally enhanced machinofacturing and pre-mechanical hand-making, because bricks have always been a hybrid technology, at the frontier between industrial mass-production and manual artisanship. From the start, bricks were made to measure for hand manipulation, as their sizes and weights are determined by the shape of the hand, and the strength of the arm. But from Roman times, baked bricks (unlike the sun-dried bricks still described by Vitruvius) started to be industrially mass-produced, in standard sizes and with standard mechanical resistances. Until recently (before, that is, the digital turn) bricks have been, paradoxically, highly standardized items of mass-productions in a technological chain of which the last and determinant step is still entirely and exclusively dependent on the old, ancestral gesture of the bricklayer--a gesture which has not changed from prehistoric times. Mass-produced and machine-made, bricks must still be laid one by one by the hand of a craftsman: a craftsman who is in turn expected to repeat the same gesture identically and ad infinitum, as a machine would, and possibly as fast.

Unlike asphalt, steel, or reinforced concrete, which can be machine-made from start to end, bricks were never a good ideological fit for modernist, mechanized building technologies, due to their ultimate and apparently inevitable dependence on the human factor. The filmmaker Andrzej Wajda immortalized in a famous movie of the pre-Solidarnosc age (Man of Marble, 1977) the true story of the bricklayer Birkut, the man that could lay 30,000 bricks in a single shift, and of his rise and fall from grace in communist Poland in the 1950s. But today's digital technologies, unlike the mechanical technologies of the twentieth century, can reproduce, imitate, and emulate the organic adaptivity of the human gesture. And digital technologies can deliver the same amount of customized variations at a lesser cost, both human and economic--as individual variations are now calculated, designed and produced by machines, not by hand in many cases.

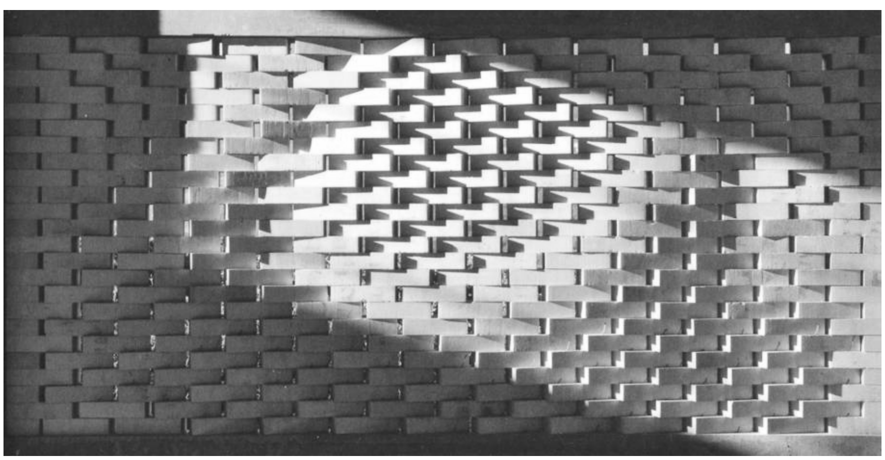


Figure 2. Gramazio + Kohler - Gantenbein Vineyard Façade

Robotic, non-standard bricklaying has been the object of recent research at the ETH in Zurich (see the recent work of Gramazio and Kohler [G+K]; the winery Gantenbein, Fläsch, a collaboration with the office of Bearth and Deplazers, Chur, has recently garnered much critical and public praise) (Figure 2). This work is widely known and may be one of the best recent examples of digital masonry. The project described in this paper reflects a similar approach in many regards but also tackles many other issues not addresses in the work of G+K. The construction of structural masonry at the scale of buildings is still problematic with the fully digital approach. There are two significant problems with the robotic approach and two significant differences between our project and the work of G+K which deal with the interpretation and implementation of construction conventions and structural behavior in masonry. The robotically laid bricks of G+K are essentially glued together, are unreinforced, and deal with relatively small, single story walls. All of these aspects present significant limitations of the G+K system to be deployed as a primary structural system within buildings of any significant size and which must comply with contemporary building codes. Our project begins to deal with these issues by developing a hybrid making system between conventional analog construction methods and digital technology, the DAM approach. Additionally, structural calculations, constructability feedback and detailed construction data is all embedded directly into the parametric model for a more holistic representation.

1.3 *Workshop Explorations in Concrete Masonry*

This question of Digitally Augmented Making is being interrogated through a series of graduate research workshops entitled Parametric Modulations in Masonry [PMiM] in the College of Architecture [CoA] at Georgia Tech [GT]. These workshops investigate the potential of parametric representations in relationship to existing construction conventions within today's masonry industry in order to develop tools and techniques for creating robust constructible masonry systems as parametric design tools. The research explores both the possibilities and the limits of a standard masonry unit as seen through a computational lens. The spring 2009 workshop developed the computational, structural, and constructional logic which allowed for a fully parameterized wall design using standard concrete masonry units [CMU]. A simplified structural calculation was imbedded within the parametric model to calculate for structural compliance in real-time with each parametric permutation in the overall design scheme. Additionally, construction data such as quantity takeoffs, block positioning and rebar placement have been explicitly parameterized within the system. This parametric masonry tool/system allows us to quickly work through a series of formal iterations in the design of a double masonry wall which will be built in the Georgia Tech College of Architecture courtyard in the spring of 2010 (Figure 3).

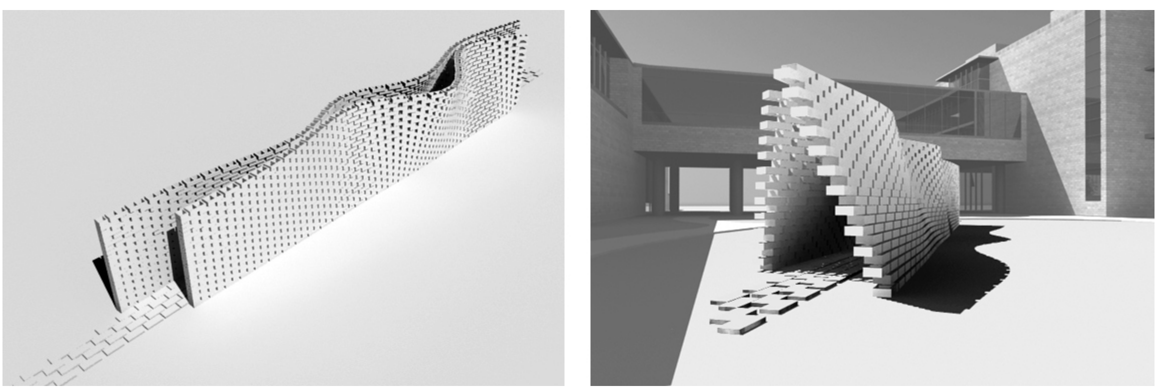


Figure 3. Parametric Modulations in Masonry Wall | Georgia Tech

2 CONCRETE MASONRY

2.1 *Unpacking the parametric potential of the unit*

Masonry is a system of assembling units into a whole through the use of a mortar joint. The logic of masonry as a system of standardized parts aggregated within a larger configurational whole offers many possibilities to explore formal complexity at the level of both the local [masonry unit] and the global [wall/building]. In this case study a standard 4 hour rated half-high CMU was selected as the module for exploration. This unit was selected due to its 'half-high' 3-5/8 inch tall face and 2 inch thick face shells. The half-high dimension allows for an increase in the resolution of the overall geometry and a 'smoother' doubly curved surface through the use of smaller masonry units, or conceptual pixels. The thicker face shell of the 4 hour block allows for a larger amount of sectional 'slippage' between units in regular running bond coursings;

therefore allowing for a greater amount of resultant curvature and geometric complexity within the overall system while still maintaining structural stability and configurational limits for proper block-to-block bearing and steel reinforcing placement (Figure 4).

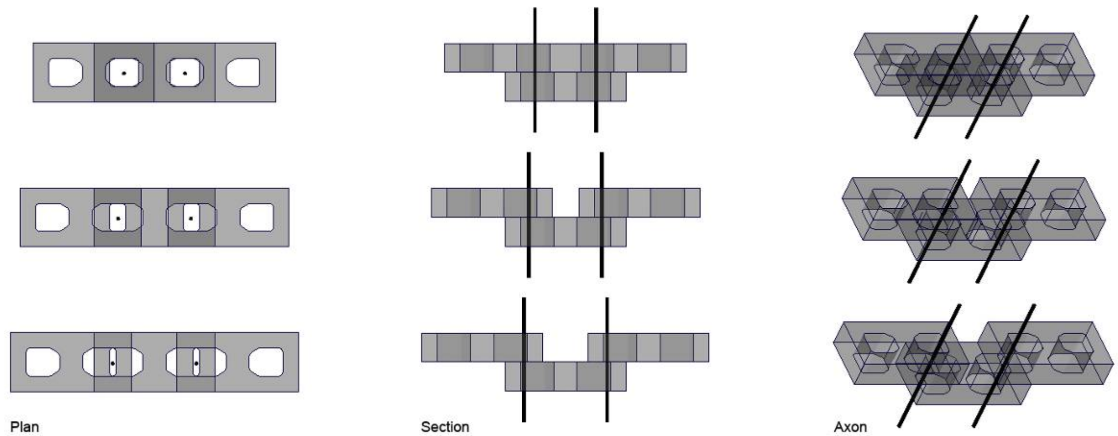


Figure 4. System logic - possibilities and constraints of block adjacencies | 'Slippage'

3 PARAMETRIC DESCRIPTIONS

3.1 *Building Object Behavior [BOB]*

In general the process of embedding design intent and knowledge into parametric models remains an art. As in computer programming, there are always several different ways of implementing a solution within a design. This depends basically on the designer's expertise, goals and constraints. In any scenario a good solution will be a trade-off among design requirements, model performance and flexibility as well as model re-usability.

Indeed one of the major challenges for the development of rich-knowledge parametric models is to find a general and formal method to facilitate the translation of design intent and expertise into a proper set of parametric behaviors. This approach is required because it emphasizes the principle that parametric objects have to be modeled not only as they look but most importantly, as semantic relationships within a specific domain (Sack et al, 2003).

To solve this issue we adopted the Building Object Behavior (BOB) description method and notation developed by Lee, Eastman and Sacks (Lee et al, 2003). In our project we adapted this methodology to guide the implementation of parametric behaviors of components and assemblies within the domain of concrete masonry construction (Cavieres et al, 2008). The graphic and abstract nature of BOB representation facilitated the process of collaborative elucidation of structural and constructive constraints. In this manner we were able to pre-tune and guide the parametric definition prior to any software implementation or modeling activity. Such processes allowed us to reduce ambiguity and unnecessary complexity, while providing a graphic specification that can be further re-used and up-dated.

3.2 *Parametric Implementation*

Generative Components was selected as the parametric CAD environment for its ease of use, extensibility, and flexibility. Given the specification of parametric behaviors required by concrete masonry construction the implementation was set according to the main design intent and system constraints (Figure 4). In this case that blocks in a course would be separated from each other based on the curvature of the wall, generating a screen effect. This result was defined as a function of the gradient of the horizontal coursing curves (as seen from top view). The mechanism used was the projection of equal-spaced (16 inch) vertical cross-section lines on the wall surface. The vertical spacing for the joint beds (4 inch) was achieved by propagation of equal-spaced points along the projected vertical cross-sections. In this way the specification of both vertical and horizontal spacing for the masonry running bond grid was satisfied while producing the gaps needed for the screen effect (Figure 5a and 5b).

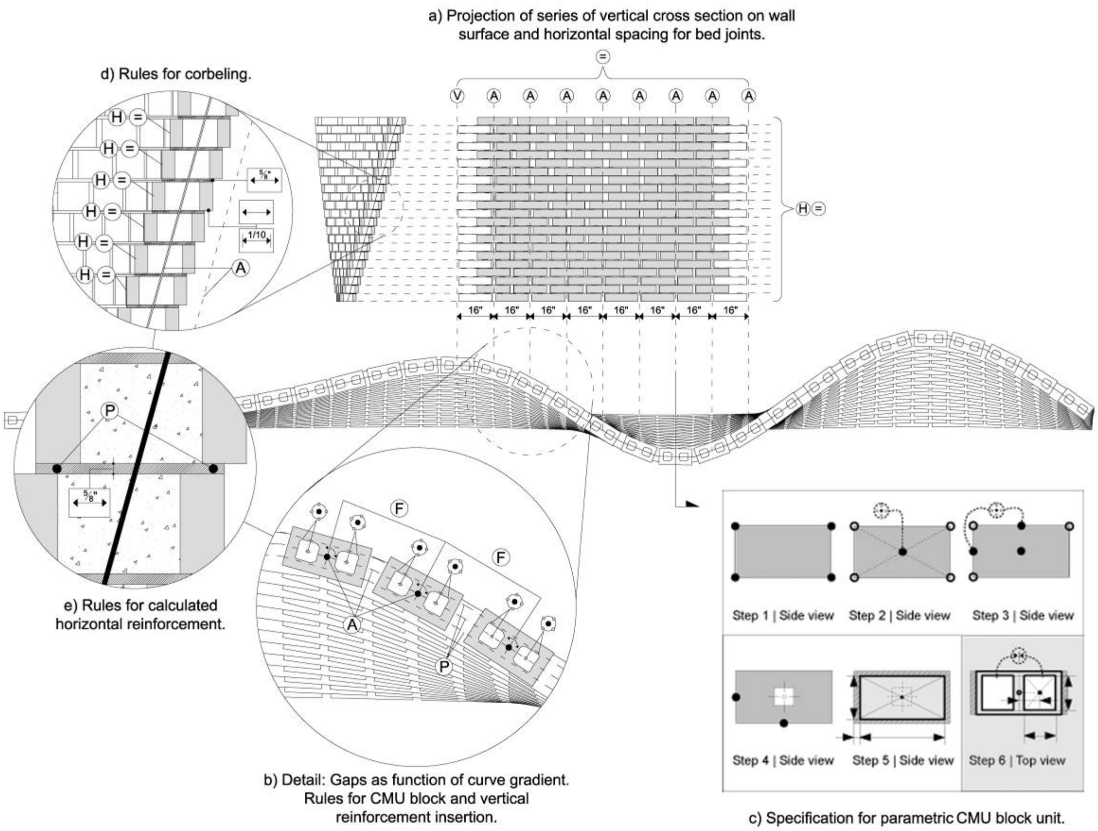
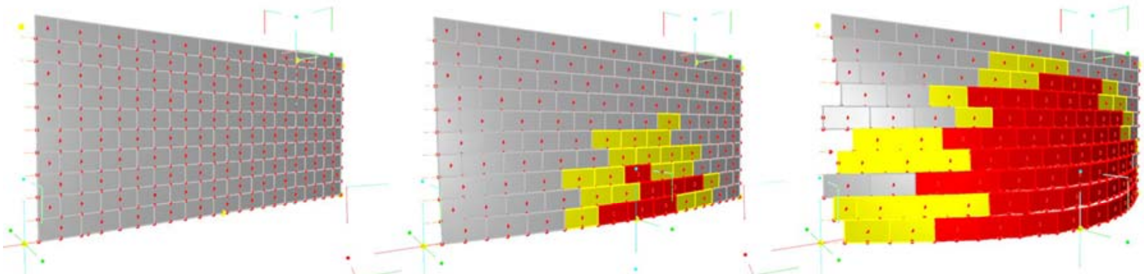


Figure 5. Parametric relationships of local objects within global configuration [B.O.B.]

The parametric implementation for the blocks themselves follows the specification of the BOB diagram (Figure 5c). In this case, rather than explicitly modeling the block solid with cells, a lightweight data structure was chosen for memory efficiency. This data structure encapsulates the coordinates for the each cell centroid, guiding the insertion of vertical reinforcement (rebar and concrete grout) if needed based on the procedure described in the previous section (Figure 5b and 5d). A similar approach is used for horizontal reinforcement when horizontal tying is required by excessive traverse wall displacement (Figure 5e). Additionally, the model gives designers real-time feedback of constructability by analyzing local relationships between units and color-coding conditions that do not meet the predefined criteria. As a final process the model generates a list of coordinates for block and rebar placement by the mason during the physical construction of the wall. This data represents the handoff from the digital to the physical realm.



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course03	179	179	178	177	177	177	178	178	179	
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course05	179	178	176	175	174	175	176	177	178	179
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course08	179	177	176	174	172	170	172	174	176	177
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course10	179	177	176	173	170	168	169	172	175	177

	column01	column02	column03
ecc01	0.00	1.12	2.17
ecc02	0.55	1.62	2.60
ecc03	0.00	1.06	2.07
ecc04	0.51	1.51	2.44
ecc05	0.00	0.95	1.88
ecc06	0.45	1.33	2.20
ecc07	0.00	0.83	1.65
ecc08	0.38	1.14	1.91
ecc09	0.00	0.69	1.40

	column01	column02	column03
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course03	366.25	366.25	366.25
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course06	486.25	486.25	486.25
course07	526.25	526.25	526.25
course08	566.25	566.25	566.25
course09	606.25	606.25	606.25

	column01	column02	column03
course01	7.15625	7.15625	7.15625
course02	7.231367	5.40928	3.670329
course03	9.15625	5.045189	1.054585
course04	6.755317	0.049048	-6.36895
course05	11.15625	1.344295	-8.20291
course06	5.546491	-7.50564	-20.0501
course07	13.15625	-3.682	-20.1179
course08	3.749832	-16.8342	-36.7195
course09	15.15625	-9.73739	-34.1217

Figure 6. Example of feedback function to check angles between adjacent CMU blocks in a curving wall. Grey block means angle values above 179 degrees, so that no cut is necessary. Yellow means that flanges of flanged blocks have to be removed. Red means cuts beyond flanges. A spreadsheet version of angle values is automatically generated (top), as well as spreadsheets containing eccentricities between adjacent rows (bottom left) and automatic load and stresses calculations for vertical reinforcement.

4 STRUCTURAL FEEDBACK

4.1 *Background*

From a structural perspective, masonry is well-suited for horizontal curvature – witness Jefferson's horizontally curved walls at the University of Virginia. To achieve horizontal curvature, each masonry unit can rotate in its coursework a moderate amount from the prior unit while still maintaining its horizontal coursing.

Vertical curvature is more difficult to achieve. The traditional method, and the one employed in this project, is through corbelling – that is, the offset of one block relative to the one below it by some limited amount, all while keeping the horizontal coursework flat and level. Tilted masonry coursework has been achieved by Brunelleschi and Dieste, and is a key component in masonry vaults, but generally only works with completely centered or self-stabilizing forms (Dieste, 1992). Another example of this type of masonry construction can be seen in the vaulted work of Rafael Guastavino Moreno as documented by John Ochsendorf of M.I.T. (http://web.mit.edu/masonry/).

4.2 *Structural strategy*

In our project, double curvature is achieved through a combination of rotating each block in plan and through corbelling in section. Structural strength and stability are achieved through a combination of vertical and horizontal reinforcement in the wall – conventional strategies in concrete masonry. These are made more complex in this project by the rotation of the units and by the sliding of units along the courses – and the subsequent gaps cause by the sliding.

The structural design algorithm is detailed in what follows. For more details see Parametric Design, Detailing, and Structural Analysis of Doubly-Curved Load-Bearing Block Walls (Gentry et al, 2009). As a first-order approach, the walls are treated as individual cantilevered wall segments. The wall is divided into to a set of vertical slices, at 16 inch increments (Figure 7). The vertical bending moments are calculated based on the self-weight of the wall, along with a 200 lb/foot uniform load applied at the top. The vertical reinforcement is sized based on the typical reinforced masonry wall assumption that the masonry takes all of the compressive stresses and that vertical steel reinforcement takes all of the tensile stresses. The 16 inch increment represents two cells in the block wall, the range of reinforcement required ranges from no vertical steel (for a completely vertical wall) to one number three bar (in one cell) to two number five bars (in both cells).

The transverse displacement at the top of the wall is also calculated for each segment, to allow for a determination of the relative deformation between segments. For a given segment, if adjacent segments show significant differential displacements, this indicates the need for horizontal joint reinforcement, to allow for sharing of bending forces between segments. In conventional walls, this horizontal tying would be achieved through the use of bond beams. Here, that is not possible due to the use of half-height masonry units and due to the sliding of blocks relative to one another in highly curved sections of the wall.

This iterative process uses the well-understood idealization of the way that masonry works in vertical and horizontal bending. The use of linear-elastic finite elements, while possible, does not lead to the direct determination of wall reinforcement. This embedded structural feedback allows the designer of the wall to have a real-time "check" of the structural requirements and validity of each design iteration.

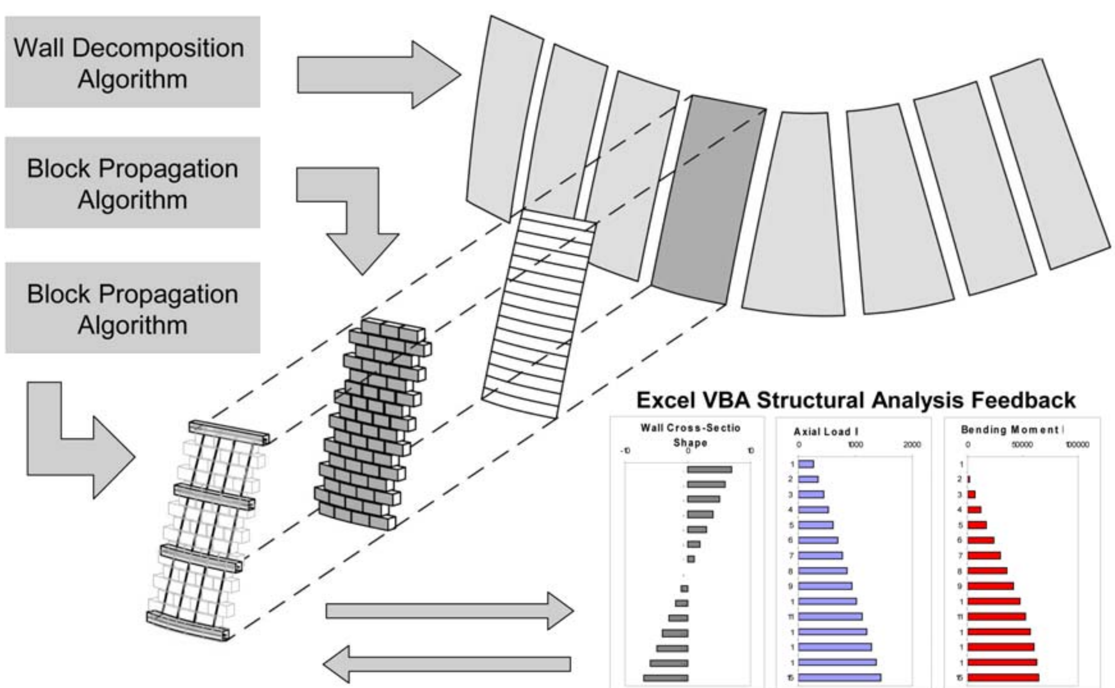

Figure 7. Top-down decomposition of a wall for simplified structural analysis. Feedback function checks cross section eccentricity of blocks and loads to verify allowable stresses and the recommends back values for positioning and diameter of steel rebar.

5 CONSTRUCTION

5.1 *The digital mason’s line*

The use of robotic positioning systems in construction is well known, with the best examples coming from the automobile manufacturing sector. The robotic masonry work of Gramazio and Kohler, referenced above, along with others is both exciting and relevant, and it represents a vast terrain for future research. However, contemporary use of robotically placed load-bearing masonry assemblies for onsite construction has proven to be a difficult task for many logistical reasons at the scale of actual buildings. Additionally, our research has not shown the use of robotically placed reinforced masonry for onsite construction due to complexities of applying mortar and placing rebar inside grouted cells. For this reason, along with some of the larger conceptual goals of the DAM paradigm, our research is developing alternative construction protocols which can quickly and intuitively be integrated within current construction practices.

As an initial experiment into physical construction of the system we looked to one of the most fundamental masonry construction technologies, the mason’s line. Using the mason’s line as a low-tech analog to a digital vector we developed an anthropomorphically driven NC [Numeric Control] construction machine. An initial design sketch of the construction machine and staged process model of construction is illustrated below (Figure 8). The basic concept of NC technology is constructed around the idea of automated positioning and action [cutting, placing, joining, etc] in Cartesian coordinate space [X,Y,Z]. Our construction machine establishes a variable XY plane and XY coordinate through the intersection of these two primary axes. These planes then floats up and down along a tracking scaffold to determine the Z coordinate, or course height, of the block configuration. The XY coordinate for the centroid of each block and Z-Axis rotational vector are all queried from the BOB model and stored in a spreadsheet. The mason then uses the spreadsheet block positioning data along with the line intersections to place each block quickly and with a technique that is familiar. Therefore with the construction machine and data on the four degrees of freedom for each block [X,Y,Z,A (Z-axis rotation)] the mason is able to place each block within the overall wall configuration with sufficient accuracy, speed, and conventional hand tools. This familiarity of construction contributes to the overall DAM strategy to be more easily integrated into an industry where radical change is not always welcomed. In this way the construction machine becomes a hybrid system somewhere between conventional masonry construction methods and fully automated robotic block placement.

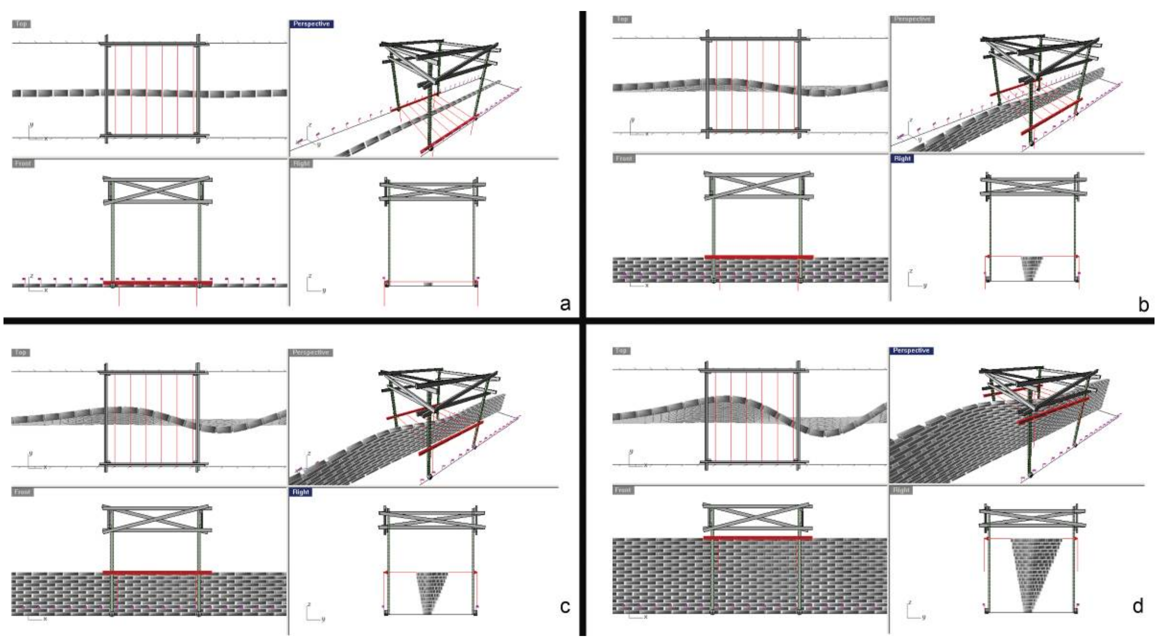

Figure 8. Construction machine for variable masonry assemblies seen in 4 stages from the first ‘straight’ course in X,Y,Z,A space to the top ‘curvy’ course X,Y,Z,A space.

6 CONCLUSION

6.1 *Future research*

Ultimately this research hopes to give architects, engineers, and constructors new tools and methodologies to expand the formal and compositional possibilities of existing construction systems in an intelligent and responsible way. The construction machine described above in Section 5 was an interesting and enlightening first pass at the question of physical construction however current and future research questions are focused on the use of digital positioning systems which could drive floating handheld block positioning devices. There are many existing market-ready technologies which could be adapted to work with DAM masonry systems. The intension is to ‘fit’ the block with a small light-weight device which will be a kind of visual homing mechanism for the mason to place each block and will be driven from coordinate data from the B.O.B. model. One could almost imagine the mason with an on-demand iPhone block positioning system.

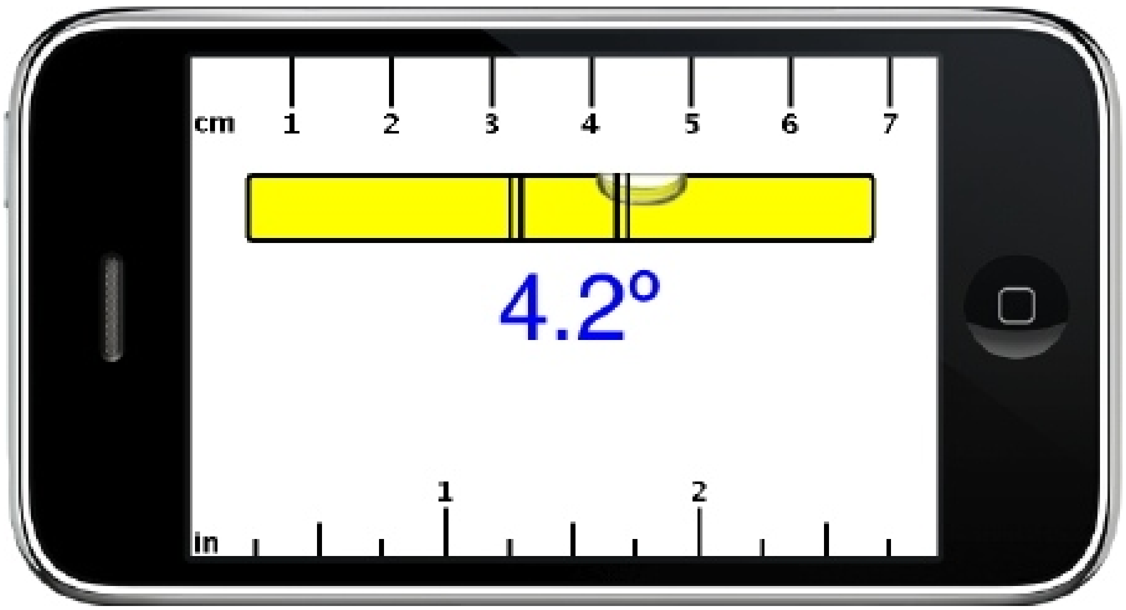

Figure 9. Accelerometer controlled freeware leveling application for Apple iPhone.

Additional future research will focus on the refinement of both the structural analysis method and the B.O.B. implementation in order to create a valid tool which all the players of the design and construction process can easily and intuitively understand and creatively use.

The gap between digital design representations and physical constructs continues to contract as new and novel methods for interrogating the relationship between existing construction industry conventions and new modes of practice continues to develop. Questions of how and where digital tools will fit into an industry as enormous and complex as that of the AEC world are only beginning to be formulated. The promise of fully automated, self constructed buildings may or may not come to fruition but in the meantime hybrid Digitally Augmented Making methods will fill the void of this possible future.

6.2 *Acknowledgement*

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