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HoloMasonry: Complex Brick Assemblies Constructed with HoloLens

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Abstract

Bricks are ancient and essential in human civilization history, whose success in the built environment lies in easy fabrication and simple assembly logic. However, they are almost forgotten in industrialized contexts due to expensive on-site and craft-dependent assemblies, especially those with complex curved geometries. The HoloMasonry project explores the innovative uses of clay bricks to achieve "unlimited possibilities" by embracing modern building technology with Microsoft HoloLens. Empowered by mixed reality through a developed workflow coded in Rhino and Unity, the beauty of equilibrium and the art of construction is achieved through the intrinsic integration of designing and constructing unbonded masonry structures with complex geometries. The gaps between bricks with various dimensions facilitate the smooth changes of curvatures formed by bricks, which may result in exciting light and shading patterns in the space. The paper discusses the design and construction of a primary unbonded masonry wall and two minor masonry structures with complex curved geometries using HoloLens. The computing power augmented designers' and builders' capacities in confirming the structural stability of the unbonded complex masonry structures and improving construction efficiency.

Keywords: Masonry, Complex Geometry, Mixed Reality

1. Introduction

Bricks are ancient, with the oldest found in southeast Anatolia around 7500 BC. They are essential in human civilization history, and their success lies in easy fabrication and simple assembly logic. Bricks have high mechanical resistance, good thermal and acoustic performances, passive regulation of environmental humidity, and excellent fireproof characteristics at a comparatively low cost. Elegant masonry structures including walls, arches, vaults, and shells have been built since the third millennium BC (Joffroy et al. [1]). Historically, the leaning bricks technique and corbelled vaulting require minimum temporary shoring and guidelines to achieve masonry structures with complex geometries (Wendland [2]; Fitchen [3]). The leaning brick technique introduces the first course of bricks leaning against the wall or a previous masonry course using mortar, and other courses laid one after another, leaning against the previous one with angles ranging from 20º to 90º (Figure 1) (Neupane [4]). The structures are built in the shape of a catenary to increase their structural stability (Gargiulo, et al, [5]; Ponce, et al, [6]; Van Beek, G., [7]). The corbelled vaulting projects overhanging bricks from either both sides or one side, which can meet at the apex to form the corbel arch. Extrusion of corbel arches to construct a corbel vault (Figure 2) (Wendland [2], DeLaine, J, [8], Liu et al. [9]).

However, designers and engineers almost forget them in industrialized contexts due to expensive on-site and craft-dependent assemblies, especially those with complex curved geometry. With rational design, curvature yields structural stability and integrity and helps orient surface area towards or away from environmental impact to gain thermal energy or to self-shade. The curved surfaces could accelerate or break airflow and increase or decrease light and visual penetration.

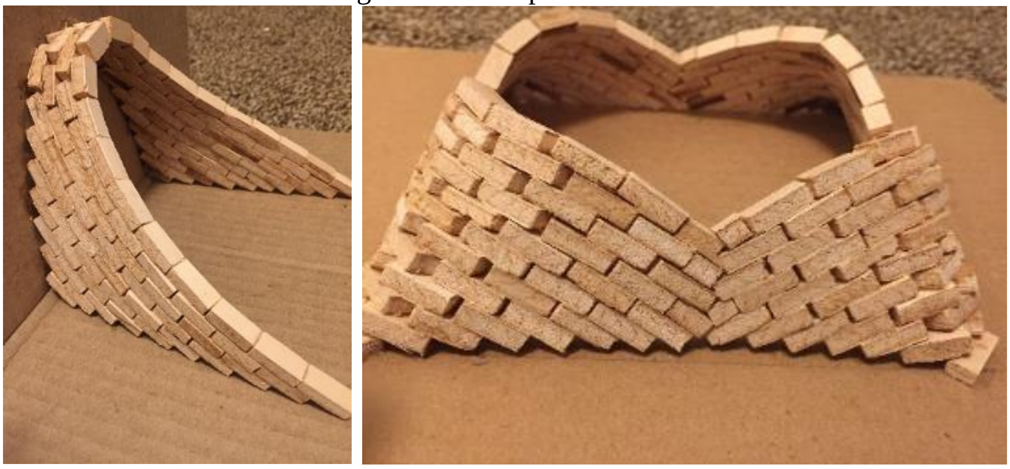
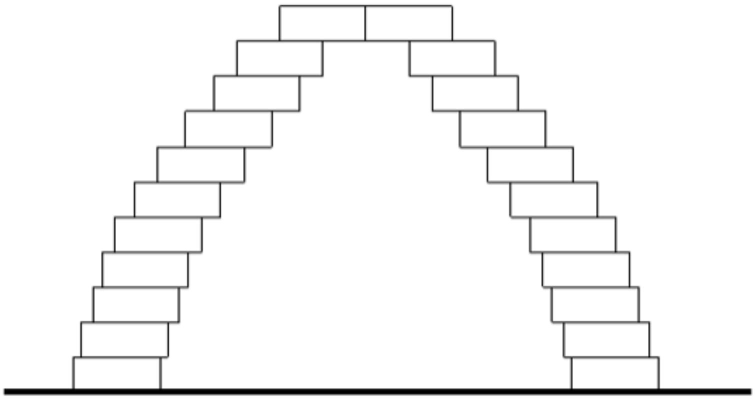
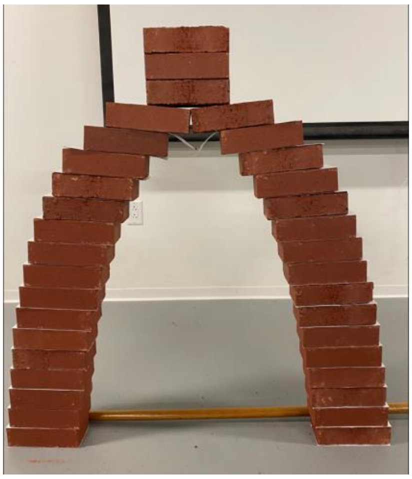


Figure 1: Leaning Brick Technique (Neupane [4]), reprint with permission.



(a) Diagram (Neupane [4])



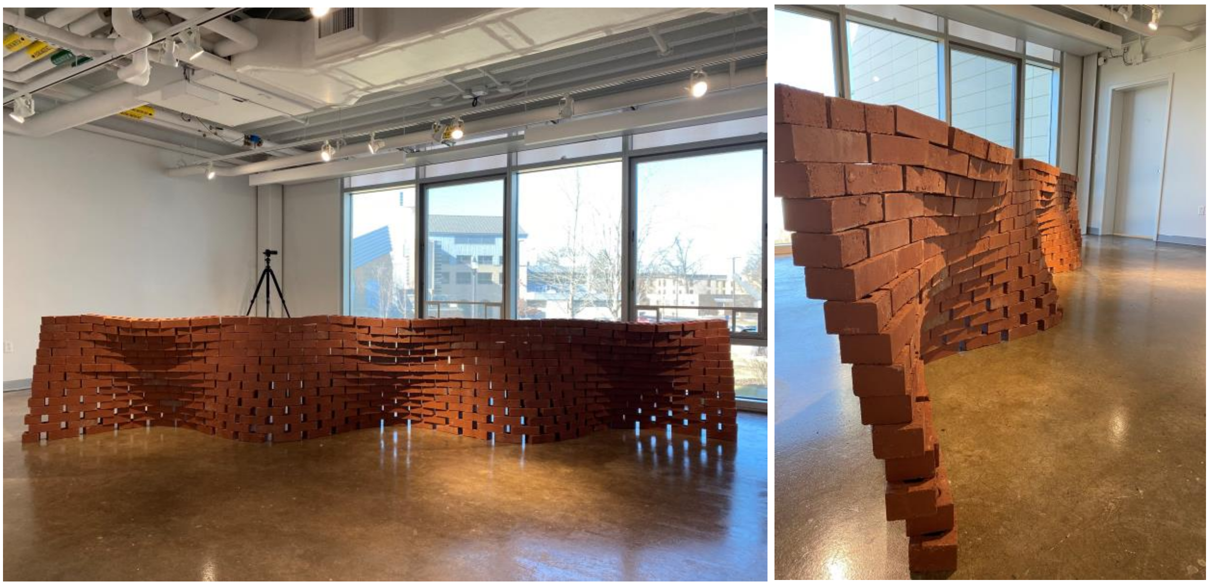
(b) Corbel arch (Liu, et al [9])

Figure 2: Corbel arch built from one side with equilibrium balances. (Figures reprint with permission).

Empowered by augmented and mixed reality, the beauty of equilibrium and the art of construction could be achieved by designers and builders. Numerous masonry projects were completed using Fologram (https://fologram.com/), a commercially available software package. In addition, Mitterberger et al. explored the construction of intricate brickwork through object-aware augmented reality in 2019 [10]. Designers and researchers from Skidmore, Owings & Merrill and Princeton University built the Angelus Novus Vault, a self-balancing brick arch, using augmented reality goggles in 2023 [11]. The design and research team at Kent State University integrated the design and construction of unbonded masonry structures with complex geometry into the HoloMasonry project, considering structural equilibrium and self-balancing of masonry bricks. The paper discusses the design and construction of a primary unbonded masonry wall and two minor masonry structures with complex curved geometries using HoloLens. The gaps between bricks with various dimensions facilitate the smooth changes of curvatures formed by bricks, which may result in exciting light and shading patterns in the space. The paper details how computing power augmented designers' and builders' capacities in confirming the structural stability of the unbonded complex masonry structures and improving construction efficiency.

2. HoloMasonry

The HoloMasonry project explores the innovative uses of clay bricks to achieve "unlimited possibilities" by embracing modern building technology with Microsoft HoloLens (Figure 3). It demonstrates the intrinsic integration of design and construction and shows the beauty of equilibrium and the art of construction employing mixed reality. The section discusses an innovative integrated design process for masonry structures with complex geometries, considering the equilibrium conditions of individual bricks during erections. The research team developed HoloLens apps using Microsoft's Mixed Reality Toolkit 2.0 (MRTK 2.0) to deploy full-scale three-dimensional structural models into HoloLens.



(a) Front view (Photo © R. Liu) (b) Side view (Photo © R. Liu)

Figure 3 HoloMasonry wall

2.1. Workflow with Rhino/GH and Unity

As illustrated in Figure 4, the research team developed a linear workflow for the HoloMasonry project. Inspired by precedents and arts, designers proposed unique complex geometries in Rhino, a 3D modeling CAD software, with their structural stability checked using a developed algorithm in Grasshopper, a plug-in in Rhino for computational design. The team created HoloLens apps from scratch in Unity using Microsoft’s MRTK 2.0 to deploy the 3D structural models from Rhino to HoloLens. Commercial packages are available for masonry applications e.g., Fologram, but the research team developed our apps using MRTK2.0 with C# to have full control over the interface and interactions. MRTK2.0 provided the HoloLens features of input options of hand gestures and tracking for using buttons, sliders, along with voice commands. Although it was possible to create hand interactions with buttons or sliders, the research team implemented voice commands to allow the hands to stay focused on the task of laying the masonry components and used raycasting and spatial awareness options in conjunction with placed targets to identify the ground for positioning and alignment of the wall.

Figure 4 Workflow of HoloMasonry project

2.2. Structural Design of Complex Masonry Assemblies

The research team adopted corbel masonry construction to design and build unbonded complex masonry assemblies. Neupane and Liu ([12]) explored the equilibrium conditions of overhanging bricks with or without bonding. The HoloMasonry team adopted the same principle in the project to design complex masonry assemblies without bonding. Figure 5 shows three conditions of a single brick lying on the top of a firm base, i.e., stable, balanced, and unstable. If the center of mass is supported by the base, the brick is in either stable or balanced condition. Otherwise, the brick loses its stability and starts to topple.

The same concept applies to calculating the overlanding length of each brick by adding one above another for *n* courses shown in Figure 6.

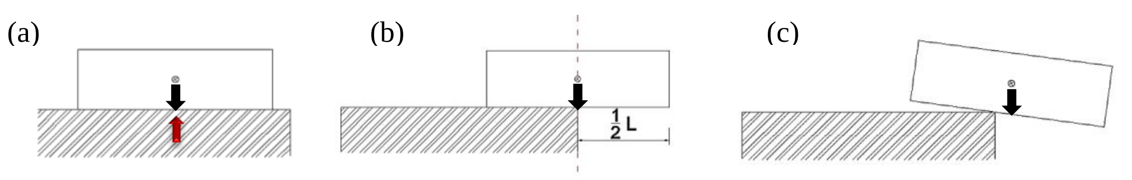


Figure 5 Stability of a brick (Neupane and Liu, [9]), reprint with permission

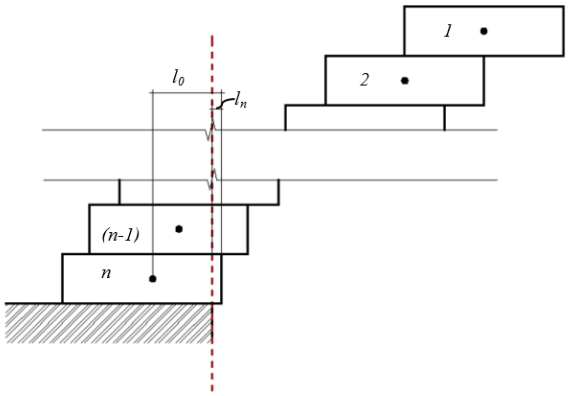


Figure 6 Overhanging distance of unbonded individual bricks with n courses (Neupane and Liu, [9]), reprint with permission

Eq. (1) was established by Neupane and Liu [10] to determine the maximum overhanging distance of a structure without bonding. The top course of the brick structure is labeled as "1" and the bottom course is labeled as "n". Theoretically, the mass center of the total top (*n-1*) courses should be located at the edge of the support, which is the right edge of the n^{th} bottom course, and the mass center of all *n* courses should be located at the edge of the base. Assuming the maximum overhanding distance of the n^{th} bottom is l_n, the moment of all *n* courses about the right edge of the bottom brick is equal to the summation of the moment of the top (*n-1*) courses, and the moment of the bottom brick about the right edge of the bottom brick.

$$(nw) \times l_n = (n-1)w \times 0 + w \times l_0 \qquad \text{Eq. (1)}$$

Where *n* = number of brick courses
w = weight of each brick
l_n = overhanging distance of the bottom course
l_0 = distance from the mass center of the bottom brick to its edge (half of the dimension L)

Table 1 summarizes the maximum overhanging distances of brick courses, shown below:

Table 1 Maximum overhanging distances

No. Brick Courses	Overhanging Distance
1	*1/2 L*
2	*1/4 L*
3	*1/6 L*
4	*1/8 L*
n	*1/(2n) L*
Total	$(\sum_{i=1}^{i=n} \frac{1}{2i})L$

All masonry assemblies in the HoloMasonry project projected from one side with the corbelled construction. Ninety percent of the calculated values using the equations from Table 1 were used to check any cross section of the masonry structure with complex geometries. A Rhino python script was developed by the research team and integrated with the parametric design of the complex masonry assemblies to check their structural stability.

2.3. Computational Parametric Design of Complex Masonry Assemblies

The research team developed a Grasshopper (GH) script to design the masonry wall with complex geometries. Figure 7 shows one design using the script. Masonry brick was first created in Rhino as a block. Designers controlled the geometry of the curves on the x-y plane, by interpolating points into two curves. One curve was moved to a certain height along the z-axis, considering the thickness of the brick and the number of courses. A surface with a complex curvature was generated by lofting with the two curves. The script created contour lines spaced with a vertical distance of the brick thickness and aligned horizontal frames along these contour lines. Finally, the script oriented the brick blocks along the horizontal frames with controlled gaps between these bricks. The research team checked the structural stability of the walls using the method presented in Section 2.2 by selecting the cross section with the large overhanging distances from the bottom course. One of the final designs is illustrated in Figure 8, as well as two minor structures.

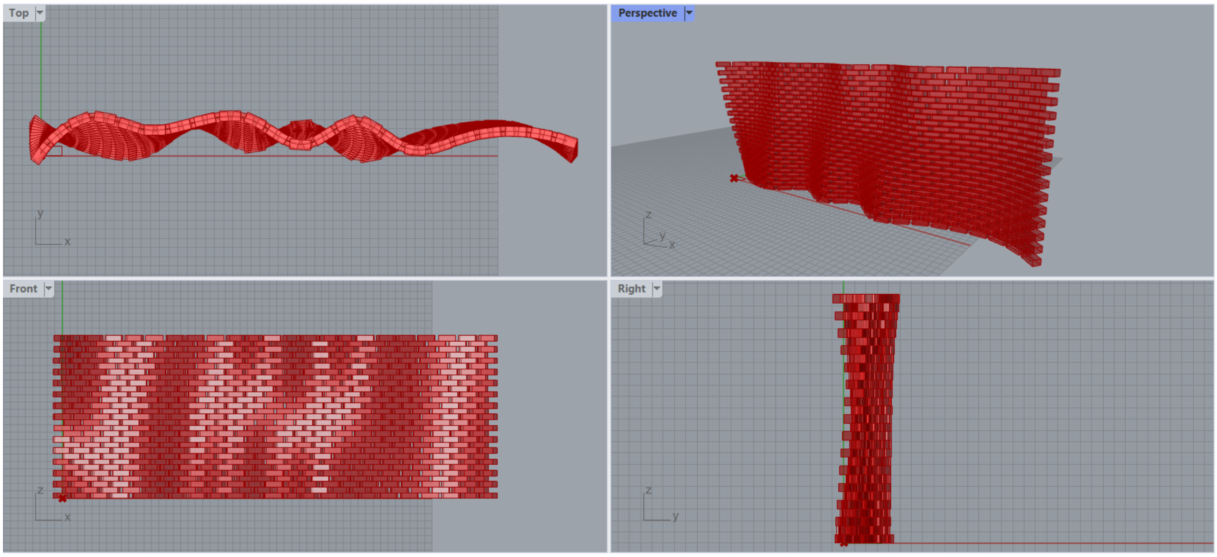
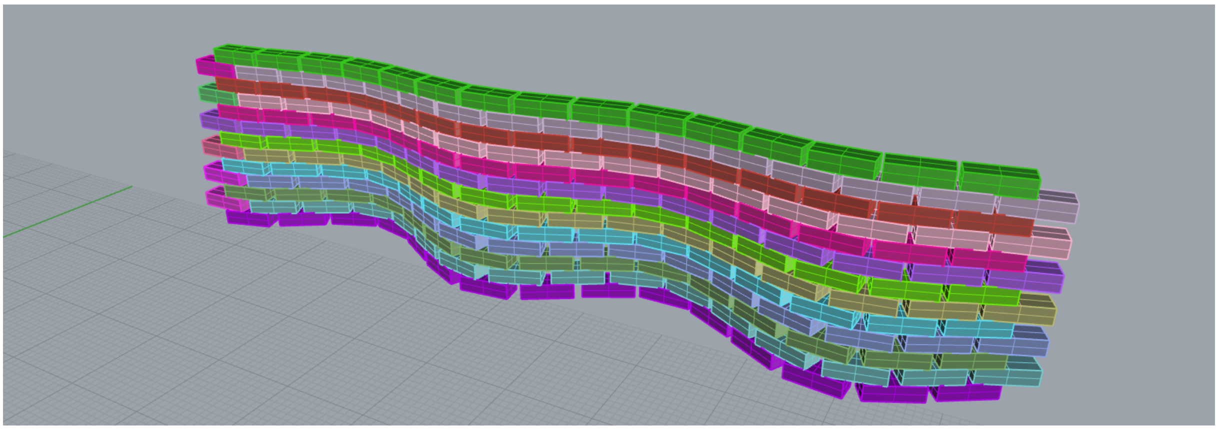
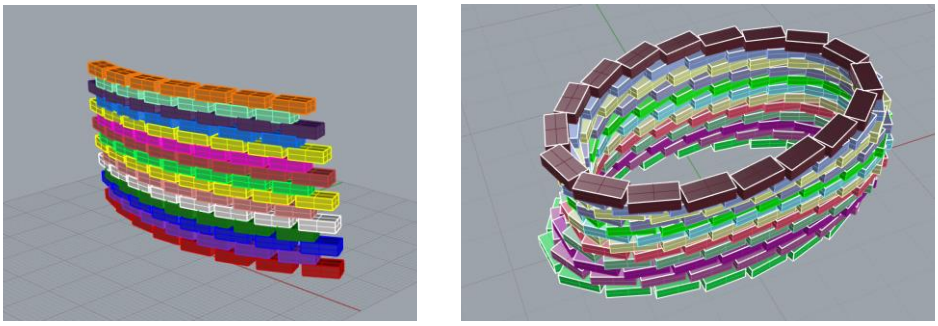


Figure 7 Masonry wall with a complex geometry



(a) 3D model of HoloMasonry wall in Rhino



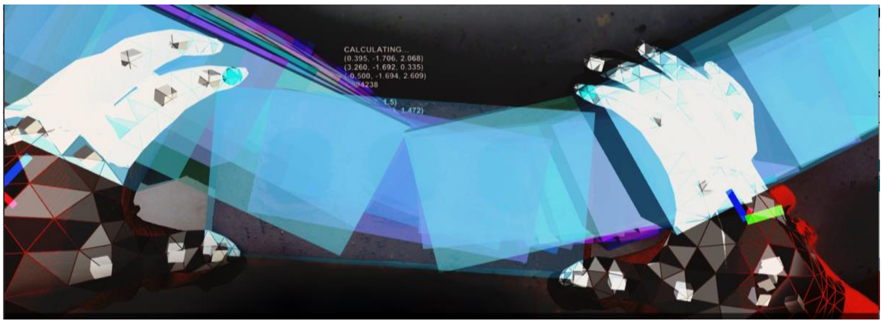
(b) Minor complex masonry assemblies

Figure 8 HoloMasonry with complex geometry for exhibition

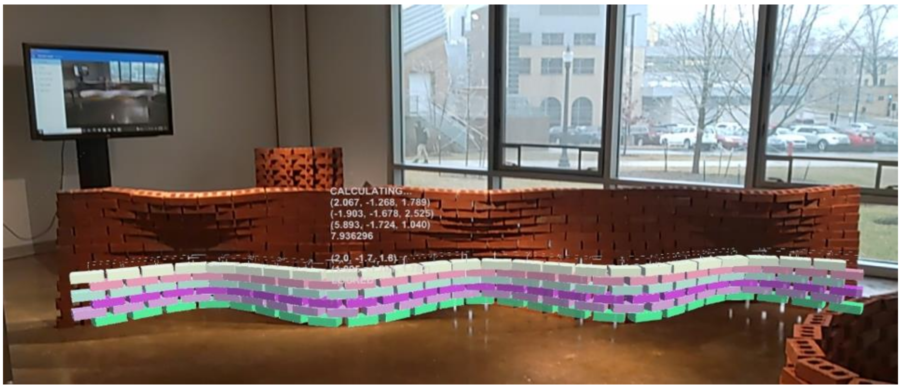
2.4. Construction

Due to the complex geometry of the unbonded masonry wall, the team needs to know the exact location of each brick. Augmented by the mixed reality provided by HoloLens, the team was able to visualize the accurate locations of bricks in an environment mixed with real and virtual. Figure 9(a) shows the view from HoloLens to lay the bricks at the exact location. Figure 9(b) illustrates a mixed real and virtual environment with physical and digital models overlayed.

Instead of building buttons and sliders in the HoloLens apps for the project, the research team developed and implemented voice commands to allow the hands to stay focused on the task of laying bricks. The HoloLens app uses spatial mapping to identify the existing context and create a mesh of the ground plane. Targets were used with raycasting to establish the positioning and alignment of the masonry assemblies. The positioning was then locked, and the mesh was hidden to begin the construction with incremental displaying of each course (Figure 10).



(a) HoloLens view showing the exact location of each brick.



(b) HoloLens view with mixed reality

Figure 9 Construction of the HoloMasonry with HoloLens

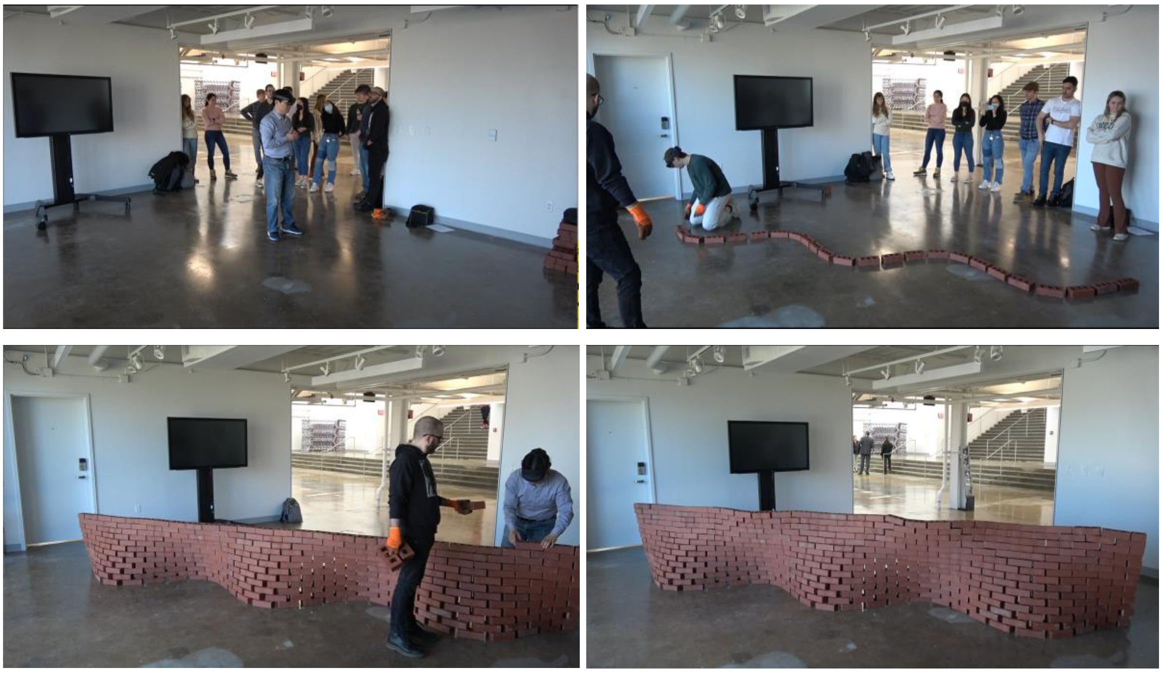


Figure 10 HoloMasonry wall construction

It took about two hours for two team members to fabricate the wall in a gallery with approximately eight hundred bricks. As shown in Figure 9 (b), the full-scale digital model in HoloLens did not include the half-size bricks at both ends of the wall to support the bricks above. These half bricks were prepared and installed in the gallery for structural stability and aesthetics. HoloLens views are sensitive to light. The indoor gallery installation went smoothly without interruptions, but special consideration should be given to outdoor construction. The digital model assumes that bricks are perfect blocks with same dimensions and smooth surfaces. However, these assumptions do not hold with small variations of brick sizes and bumps on all sides. These errors could accumulate and affect the upper courses of the masonry assembly with complex geometry.

4. Conclusion

The HoloMasonry project explored the innovative uses of clay bricks to achieve "unlimited possibilities" by embracing modern building technology with Microsoft HoloLens. It demonstrated the intrinsic integration of design and construction and shows the beauty of equilibrium and the art of construction employing Mixed Reality. Computing power augmented designers' and builders' capacities in confirming the structural stability of the unbonded masonry structures with complex architectural geometry and improving construction efficiency.

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References

[1] Joffroy, Thierry, and Hubert Guillaud. "The basics of building with arches, vaults and cupolas." (1994).

[2] Wendland, David. "Traditional vault construction without formwork: Masonry pattern and vault shape in the historical technical literature and in experimental studies." International Journal of Architectural Heritage 1, no. 4 (2007): 311-365.

[3] Fitchen, John. The construction of Gothic cathedrals: a study of medieval vault erection. University of Chicago Press, 1981.

[4] Neupane, B. "Exploring forms of masonry vaults built without centering". M.S. Thesis. Kent State University. U.S.A. 2020.

[5] Gargiulo, Maria Rosaria, and Immacolata Bergamasco. "The Use of Earth in the Architecture of Hassan Fathy and Fabrizio Carola: Typological and Building Innovations, Building Technology and Static Behaviour." In Second International Congress on Construction History, Queens' College, Cambridge University, vol. 29, pp. 03-02. 2006.

[6] Ponce, ALFONSO RAMÍREZ, and RAFAEL RAMÍREZ Meléndez. "Curves of Clay: Bóvedas del Bajío." Nexus V, Architecture and Mathematics., Florence: Kim Williams Books (2004): 143-154.

[7] Van Beek, Gus W. "Arches and vaults in the ancient Near East." Scientific American 257, no. 1 (1987): 96-103.

[8] DeLaine, Janet. "Structural experimentation: The lintel arch, corbel and tie in western Roman architecture." World Archaeology 21, no. 3 (1990): 407-424.

[9] Liu, R., Koliyaee, V., Lucak, F., Guo, Y., and Liu, R. "Changing roles of human in the human-robot interactions in design and construction," *The Research and Design Interface*, Proceedings of Architectural Research Center Consortium, 2023.

[10] Mitterberger, D, Dörfler, K., Sandy, T., Salveridou, F., Hutter, M., Gramazio, F., Kohler, M.. "Augmented Bricklaying." Construction Robotics 4, (2020): 151-161.

[11] Oberhaus, D. "Renaissance algorithm meets augmented reality at Venice Biennale" . Accessed on 6/1/2024 from https://engineering.princeton.edu/news/2023/06/07/renaissance-algorithm-meets-augmented-reality-venice-biennale, 2023.

[12] Neupane, B., Liu, R. "Exploring forms of masonry vaults built without centering." In S.A. Behnejad, G.A.R. Parke and O.A. Samavati (eds). *Inspiring the Next Generation*. Proceedings of the IASS Annual Symposium 2020 and the 7th International Conference on Spatial Structures. 24-28 August 2020, Guilford, U.K.