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An innovative modular block system for rammed earth construction

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Abstract

Rammed earth (RE) construction is gaining increasing attention as a sustainable alternative to concrete in architectural applications. Despite the resurgence of interest in RE, its application has been predominantly constrained to structures with flat or slightly curved forms. Currently, the cost benefits of RE are often offset by its traditional on-site, labor-intensive, and weather-dependent construction process. To address these challenges, this study proposes an innovative modular RE block system, allowing modular design, off-site prefabrication, and on-site assembly. Interconnecting and staggering configurations are implemented in the system to enhance structural performance and stability for the modular RE block system. Additionally, an advanced computational design strategy is incorporated to enable the creation of free-form surface designs while maintaining geometric continuity between modular blocks. To demonstrate the feasibility of the innovative system, small-scale prototyping is employed. The study further presents the design of a single-story building using the modular RE block system, to demonstrate its potential. Compared with traditional RE construction methods, the modular block system developed in this study offers improved productivity, customizability, and sustainability. It holds the promise of standardizing RE construction processes and propelling RE construction forward in modern architectural applications.

Keywords: rammed earth, modular construction, free-form, advanced fabrication, sustainability

1. Introduction

Rammed earth (RE), a traditional construction technique that uses natural materials such as gravel, sand, silt, and clay, has recently gained renewed interest as a sustainable alternative to conventional concrete in architectural applications [1, 2] (see Figure 1). RE construction offers a series of advantages, including sustainability, energy efficiency, durability, and aesthetic appeal, while using locally sourced materials with low embodied energy and high recyclability [3, 4]. However, despite the growing interest, RE construction faces several challenges in the modern construction context. Its application has been limited to structures with simple, flat, or slightly curved forms. Meanwhile, its traditional on-site construction process is labor-intensive and susceptible to weather, which requires skilled labor and is time-consuming, leading to higher costs compared to conventional building methods [4]. Additionally, the maximum achievable structural height of RE is relatively low [5, 6], restricted by the inherent mechanical limitations of earth material [7]. To address the aforementioned limitations, this study proposes an innovative modular RE block system that combines the sustainability of RE with the efficiency and flexibility of modular construction. The proposed system offers a feasible solution to the challenges presented by traditional RE, enabling the creation of complex geometries and free-form structures with earth materials.

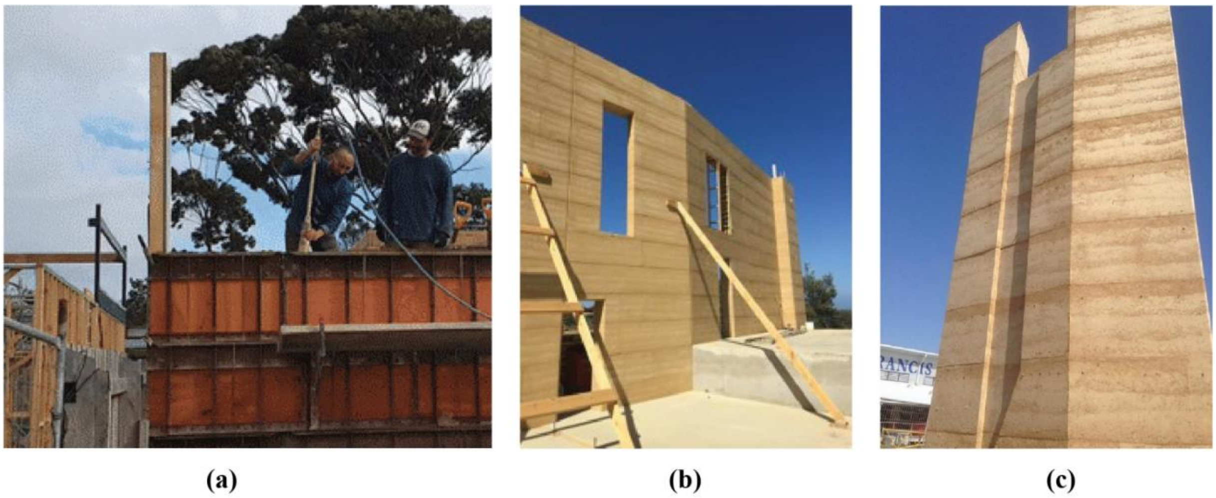


Figure 1: RE construction: (a) ramming process for a RE wall by the author in 2023, (b) curing and lateral support for a RE wall after demolding, and (c) a build RE wall. (Image (b) and (c) provided by and reproduced from [17])

Modular integrated construction (MiC) [8] has gained significant attention recently in the construction industry (see Figure 2), offering benefits such as reduced construction time, improved safety, lower costs, and minimized waste generation [9–11]. Modular RE construction combines the sustainable advantages of RE with the efficiency of MiC by pre-fabricating RE wall sections in a controlled environment [2]. Recent studies have highlighted the potential of leveraging digital manufacturing technologies to harness the sustainability benefits of earth construction while providing an alternative to modern concrete construction [18-19]. It can enhance the RE construction through higher accuracy, better quality control, reduced waste, and shorter construction timeframes, compared to traditional on-site methods. Several studies have investigated the prefabrication for RE structures, such as an example shown in Figure 3, demonstrating the feasibility and potential of modular RE systems in architecture applications [12–14]. Various advanced technologies, such as computer numerical control (CNC), laser cutting and robotic hot-wire cutting, are utilized in the studies to create delicate formworks for RE modules.

Figure 2: The construction of a residential apartment using the MiC concept. (Image provided by and reproduced from [15])

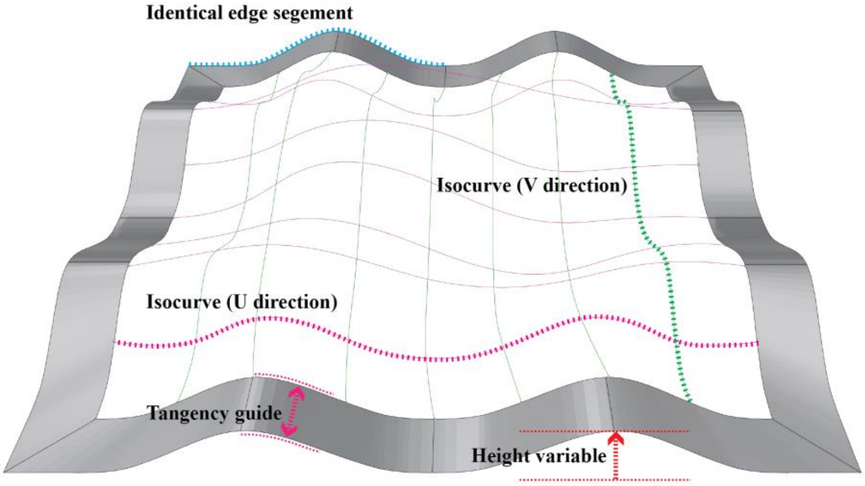
Figure 3: A RE modular block rammed on site by the author in a previous study. (Image provided by and reproduced from [16])

This study proposes a novel prefabricated modular RE block system that can enhance structural performance and assembly mechanism beyond current modular RE construction techniques. While the proposed system shares similarities with conventional reinforced brick masonry [20], it introduces unique features such as interconnecting and staggering configurations while fostering the ability to maintain surface continuity between customizable block surfaces. These features not only improve the overall integrity of the structure but also enhance its aesthetic appeal. The system incorporates the flexibility of modular design strategies, enabling the creation of RE walls with smooth, doubly curved surfaces in various configurations.

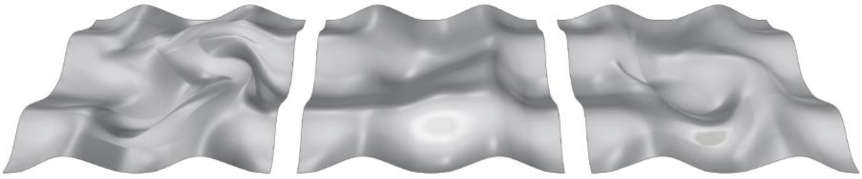
2. Modular RE block system

2.1. Computational design strategy

The design process of the proposed modular RE block system incorporates geometric continuity constraint and geometry form finding. In the first step, an inner boundary is created through offsetting the outer boundary with a uniform prescribed distance. A tangency guide is then formed between the inner and outer boundaries shown in grey color in Figure 4. The tangency guide facilitates a smooth tangential transition between blocks, accommodating various forms of curvature within the inner edge. The geometric conditions for the surface texture are defined by the symmetric boundary shared by all blocks, with the tangency guide and height parameters determining the scope of variation. The distribution of various block types along the wall is guided by both aesthetic and structural considerations. In the second step, the UV curves can be manipulated via their control points to generate different curvature shapes on the block surface, enabling the generation of complex and customized geometries on the RE block by designers.



(a) Block design parameters and constraints



(b) Block design varaities

Figure 4: Design guideline for customizing the block surface geometry.

2.2. Staggering and interconnecting features

The proposed modular RE block system is designed with staggering and interconnecting features which can enhance stability, simplify assembly, and improve structural performance. To enable the staggering feature, each block boundary is constrained to form by two identical and symmetrical sections. In such a way, the smooth transition between blocks can be maintained in the staggering assembly. To facilitate and enhance interconnection, embedded tubes are incorporated through the RE modular blocks in the vertical direction, which allow incorporation of reinforcement bars for assembly.

Here, we demonstrate the staggering and interconnecting features using five distinct block types as shown in Figure 5: A00, B00, C00, D00, and E00. Blocks A00 and B00 each come in two variants—A01, A02 for the former and B01, B02 for the latter—distinguished by the different orientations of their embedded tubes. Subtypes A01 and B01 are designed with tubes oriented in the U direction, while A02 and B02 align their tubes in the V direction during the ramming process. Importantly, these variants, despite their orientation differences, share the same mold and base design, ensuring minimized increase on material costs and construction time. The embedded tubes are shown in grey color.

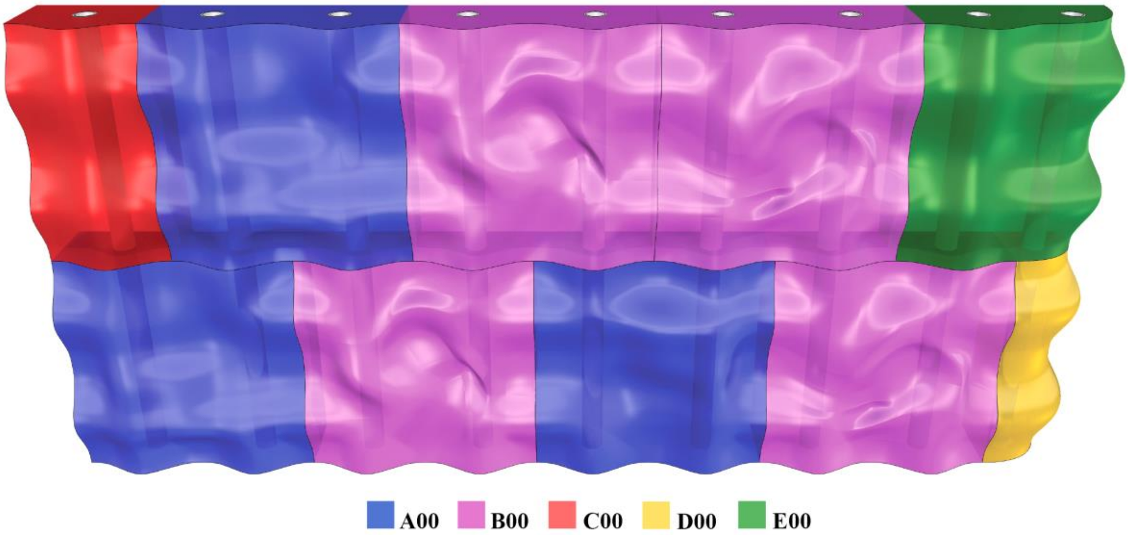


Figure 5: The assembly of five different types of modular RE blocks with staggering and interconnecting features.

2.3. Small-scale prototyping and validation

Small-scale prototyping is implemented for concept validation. Physical prototypes of block types A01, A02, B01, and B02 from Figure 5 are 3D printed in a 1: 10 scale to validate the interconnecting and staggering features, as well as to evaluate the continuity between the block surfaces after assembly. Each block is 3D printed using a high-resolution FDM printer with poly-lactic acid filament. The assembled prototype is shown in Figure 6. Note that to facilitate lifting of the heavy RE blocks in full-scale construction scenarios, notches are incorporated on the bottom surface of each block. These notches are designed to accommodate lifting slings, simplifying the assembly process.

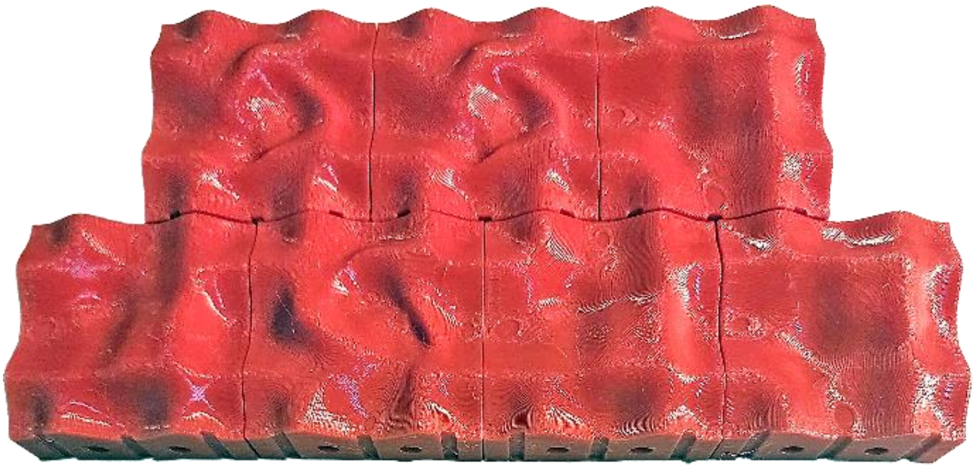


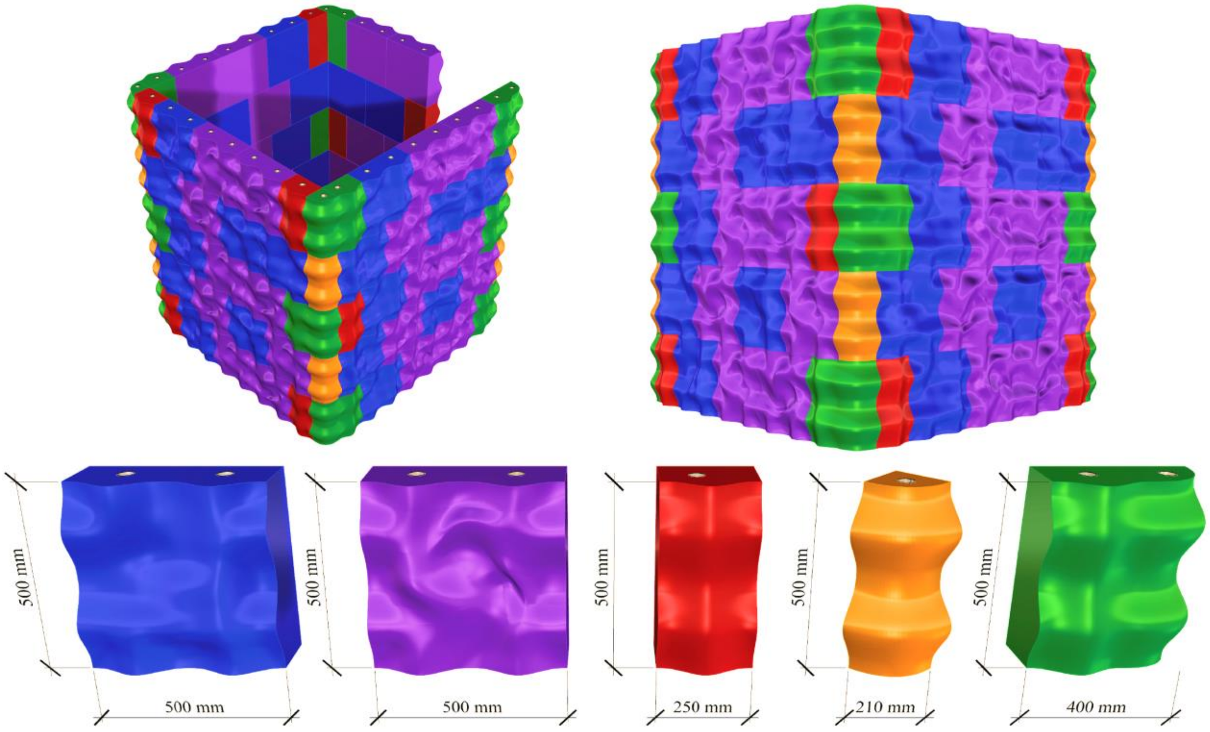
Figure 6: Small-scale prototyping to validate the assembly process with staggering and interconnecting features.

3. Design and construction of a single-story building

The RE block system offers flexibility in creating different wall configurations, such as single walls, perpendicular walls, and complete enclosures for a whole building. Here, we design a single-story building utilizing the proposed modular RE block system with various RE block types.

3.1. Design configurations and block dimensions

The design of the single-story building features a height of 2.5 meters and covers an area of 6.25 square meters. It includes three enclosed walls and one wall with an opening, as depicted in Figure 7. To construct the single-story building, the five block types in Figure 5 are utilized, with their specific configurations and dimensions given in Figure 7. The specific composition of the building employs 17 units of A01 and 10 units of A02 from the A00 block series, 16 units of B01 and 20 units of B02 for the B00 series, along with 11 units of the C00 block, eight units of the D00 block, and 12 units of the E00 block.



A00 **B00** **C00** **D00** **E00**

Figure 7: A single-story building constructed using five different types of modular RE blocks.

3.2. Fabrication and assembly process

Off-site fabrication offers advantages of improved quality control, reduced waste, and faster construction speed. The fabrication for the full-scale modular RE blocks is planned to be conducted in an off-site facility. To produce the modular RE blocks, a new customized mold is developed as shown in Figure 8(a), which is improved based on a previous work [16]. The new mold features a CNC milled timber base that incorporates curvature patterns, and a timber frame that forms the four boundary surfaces with pre-set holes for positioning the embedded tubes. Additionally, timber strips can be attached to the frame surface through bolt assembly, in order to create notches at the RE blocks' bottom surface for lifting and assembly. Once the mold is ready, locally sourced soil mixture can be added into the mold for ramming. The initial layer is compacted manually to protect the CNC-milled wood base, while subsequent layers are compacted using pneumatic rammer to ensure uniform density and strength. To maintain environmental sustainability, while enhance the strength and durability of the blocks, bio-binders are planned to be used for stabilization, as an alternative to the commonly used cement.

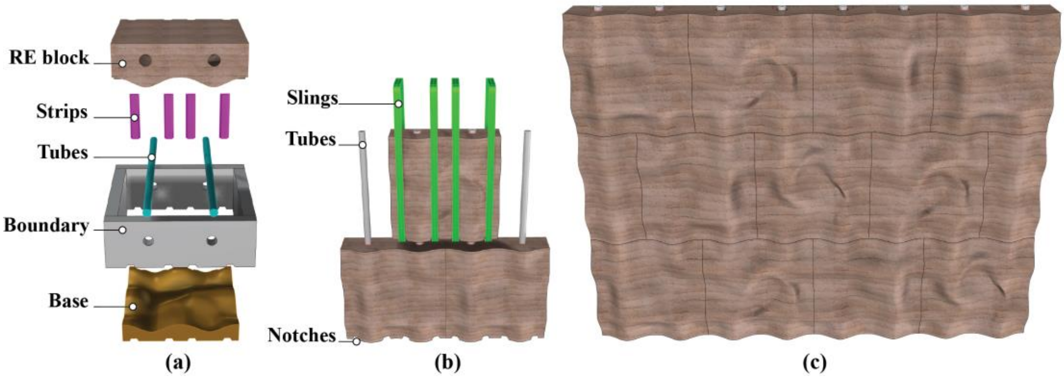


Figure 8: Fabrication process for the full-scale modular RE building: (a) a novel customized mold for producing the modular RE blocks, (b) lifting and assembly process for construction, (c) postprocessing by filling the notches on each RE block and smooth by sanding to obtain a continuous RE wall.

After a curing period of 28 days, the RE block is ready to be demolded and transported to the construction site. The assembly process, illustrated in Figure 8(b), employs slings for lifting the blocks, and arranges them in a staggered configuration. Reinforcement bars are then inserted through the embedded tubes, facilitating precise positioning and fastening of the blocks, thereby enhancing the structure performance of the RE wall.

The final step in the assembly involves filling the notches with soil and smoothing the surface by sanding. The post-processing addresses the impact of notches on the geometry transition of the RE wall surface, ensuring a seamless integration of each block with its neighbors, as illustrated in Figure 8(c). The finally constructed single-story building is anticipated to match the render images in Figure 9.

Figure 9: Render images of the proposed single-story building in the daytime and in the evening.

4. Conclusion

This study introduces an innovative modular rammed earth (RE) block system, integrating the advantages of advanced computational design, modular integrated construction, and the inherent sustainability of RE, to modernize traditional RE construction methods. While the proposed system draws inspiration from conventional reinforced masonry, it introduces unique features such as surface texturing and optimized block configurations to enhance both aesthetic appeal and structural performance. The geometric achievement of the system lies in its ability to create visually complex and continuous surfaces through the strategic arrangement of modular units with varying surface textures. This work can be contextualized within the broader history of construction innovation, particularly in the realm of modular and prefabricated systems that explore the balance between standardization and customization [21]. The proposed system utilized an advanced computational design strategy, enabling designers to create customized free-form modular blocks that can be seamlessly assembled into various configurations with smooth geometry transitions. Interconnection and staggering features are implemented in the developed system, facilitating the inclusion of reinforcement bars to enhance the structural performance and stability of RE walls. Small-scale prototyping is used to demonstrate the feasibility of the developed system. Furthermore, a single-story building is designed utilizing the modular RE block system to demonstrate its potential. Future work will focus on evaluating the structural and performative characteristics of the system, as well as comparing its ecological sustainability across different system configurations, such as the use of cement versus agricultural waste as binders, in terms of carbon footprint and embodied energy [22].

Acknowledgements

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