INTEGRATING COMPUTATIONAL DESIGN AND ADDITIVE MANUFACTURING IN CERAMIC-BASED MODULAR SYSTEMS

João Carvalho
Bruno Figueiredo
Paulo J. S. Cruz

The integration of Additive Manufacturing (AM) in modular architectural systems combines the benefits of AM with the principles of circular tectonics. Following previous research here is presented the development of a modular architectural system composed of 3D-printed ceramic components, leveraging digital design tools, computational optimization, and hybrid material integration to enhance structural performance and functionality. The research explores the potential of ceramic materials in AM for architectural applications, emphasizing their compressive strength while addressing inherent brittleness through hybridization with complementary materials.

The study introduces a modular system designed using topological optimization principles to ensure efficient material distribution, integrating ceramics with strategic reinforcements to enhance mechanical properties. The fabrication process employs Paste Extrusion Modelling (PEM) to produce discrete ceramic components, which are then assembled into a structurally coherent system. Additionally, the system adheres to Design for Assembly and Disassembly (DFAD)principles, ensuring ease of repair, reconfiguration, and material reuse. By advancing the knowledge of AM in architecture, this research contributes to the sustainable evolution of ceramic-based structural systems, demonstrating their viability in contemporary construction practices.

INTRODUCTION

Additive Manufacturing (AM) has emerged as a disruptive technology in architecture and construction, offering unprecedented geometric freedom, material efficiency, and customization possibilities. The advent of digital fabrication has enabled the transition from traditional construction methods to highly optimized, computationally driven processes. Among these, AM has gained significant attention for its ability to produce intricate architectural components with minimized material waste and enhanced performance [1, 2].

Within the realm of AM, ceramic materials represent a compelling frontier due to their exceptional compressive strength, durability, and thermal properties. Historically widely used in masonry construction, ceramics have seen a resurgence with digital fabrication, allowing for the creation of complex forms that were previously unattainable through conventional means [3]. However, despite these advantages, ceramics pose inherent challenges, particularly in tensile resistance and brittleness [4]. These limitations have prompted research into hybrid material integration, combining ceramic components with components made of materials such as polymers, wood, metals, and composites to enhance mechanical behaviour [5, 6].

Another critical aspect of AM in architecture is the shift toward modular and prefabricated systems [7]. Unlike monolithic 3D-printed structures, modular fabrication enables the production of discrete, transportable components that can be assembled on-site. This approach aligns with the broader architectural trend of Design for Assembly and Disassembly (DFAD), which prioritizes adaptability, sustainability, and circular material use [8]. By implementing modular strategies, AM facilitates mass customization, allowing to produce bespoke elements while maintaining cost-effectiveness and ease of replacement. Computational design and topological optimization further expand the capabilities of AM by ensuring material placement aligns with structural demands. Through generative algorithms, designers can refine geometries to enhance load-bearing capacity while reducing material consumption. Such advancements have led to significant breakthroughs in lightweight and high-performance structures, contributing to the broader field of digital fabrication in architecture [9, 10].

Despite these advancements, challenges remain in scaling AM for widespread architectural application. Issues such as production scalability, material performance under varying environmental conditions, and integration with existing construction methods continue to be areas of active research [11]. However, as AM technologies advance, the potential for ceramic-based architectural systems to redefine contemporary construction remains substantial.

Building on these advancements in Additive Manufacturing and the integration of ceramics into modular architectural systems, the research presented here seeks to further explore material, structural, and fabrication parameters that define the feasibility and scalability of such approaches. To achieve these objectives, the study employs a methodology structured around three key interrelated elements: (1) analysing the characteristics of ceramic materials and evaluating potential supplementary substances to enhance performance, (2) utilizing topological optimization to strategically allocate material within structural components, and (3) refining component shapes and sizes to align with the capabilities of the production equipment. Through systematic experimentation and prototyping, this study aims to establish a comprehensive framework for the development and application of AM-enabled ceramic systems in contemporary architecture.

MATERIALS

The production of ceramic components for the constructive system relied on fine stoneware paste, chosen for its compatibility with production equipment and its remarkable compressive strength of up to 175 MPa when fired at 1260ºC. The material, free of chamotte and containing 35% water, was used uniformly across all prototypes to streamline the processes of design, production, and assembly. This decision allowed the focus to remain on refining system design and performance rather than managing multiple material compositions. The production method required the discretization of larger components into smaller, manageable pieces due to equipment volume constraints, which highlighted the critical role of effective connection and union between elements. Such connections were fundamental to ensure the structural system's functionality and reliability, distinguishing it as a viable alternative to traditional construction methods.

To address the inherent brittleness of ceramics and optimize its mechanical performance, especially under compression, complementary materials were tested to act as connecting elements between ceramic components. Compression tests were conducted on cylindrical ceramic specimens produced through Paste Extrusion Modelling (PEM), simulating real components. Materials tested included wood (oak), rubber (SBR), mortar (Sika glue), acrylic glue, and concrete (C-30 mixture). The specimens were developed with specific designs, such as three-wall cylindrical configurations, to evaluate the performance of each material in combination with ceramics. A total of 51 test specimens were created (Figure 1), covering various configurations: simple ceramic elements, stacked ceramic elements with and without separating materials, and concrete-filled ceramic components, alongside solid and hollowed concrete cylinders for comparison.

The results of the compression tests highlighted the potential of ceramics for load-bearing structures. Even without separating materials, stacked ceramic components displayed higher resistance values than equivalent concrete specimens. However, separating materials played a significant role in mitigating ceramics' brittleness. While rubber and acrylic glue caused instability and deformation leading to failure, mortar and wood proved more effective, enhancing the structural resistance and compensating for the ceramic fragile behaviour. These findings demonstrate the feasibility of combining ceramics with suitable complementary materials to create functional, durable structural systems with properties comparable to, or even exceeding, those of traditional concrete structures.

TOPOLOGICAL OPTIMIZATION

Although AM enables the creation of highly efficient components by depositing material only where necessary, its full potential is only realized when closely aligned with the design process. To fully leverage AM's advantages, a direct relationship between the production method and the design is essential. Topological optimization serves as a key tool in this context, balancing form, structure, and material. Using advanced computational tools like Rhinoceros® and

Figure 1: Complementary material specimens and concrete reference specimens for load bearing tests.

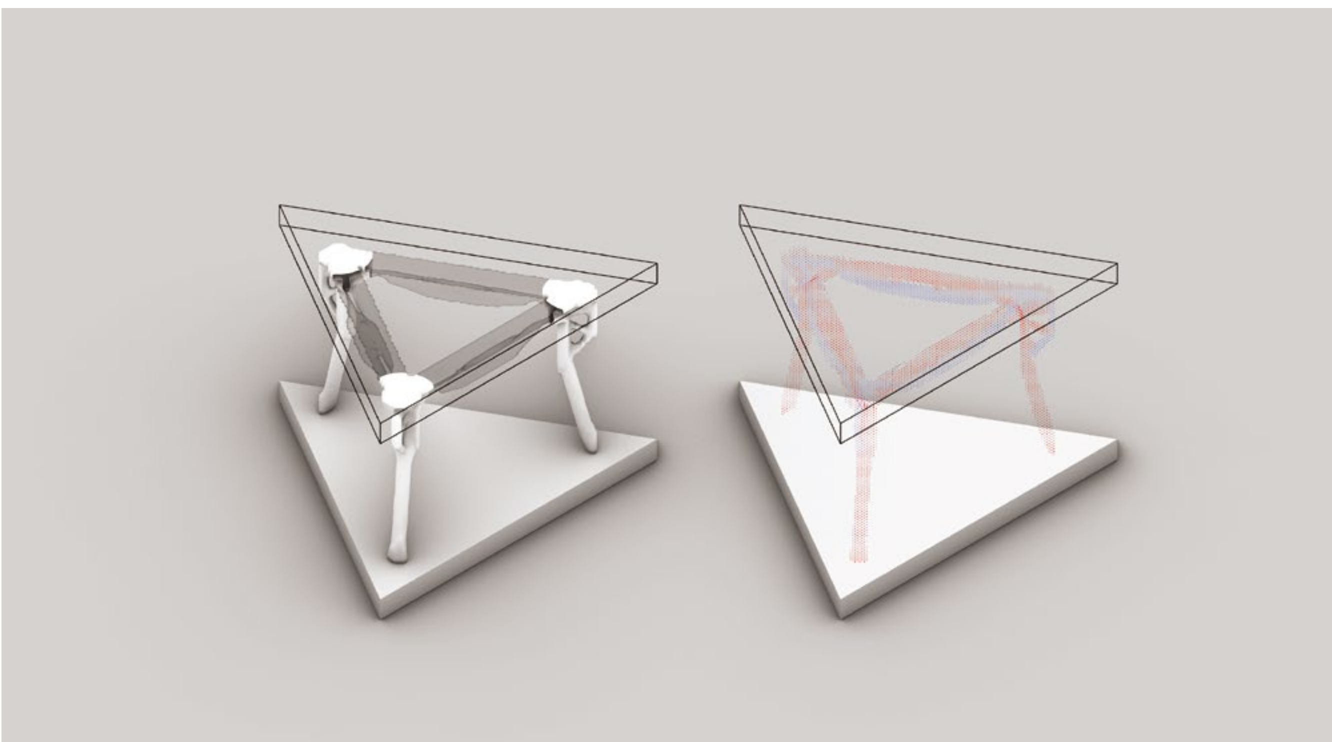

Figure 2: Topologic optimizations carried out during research.

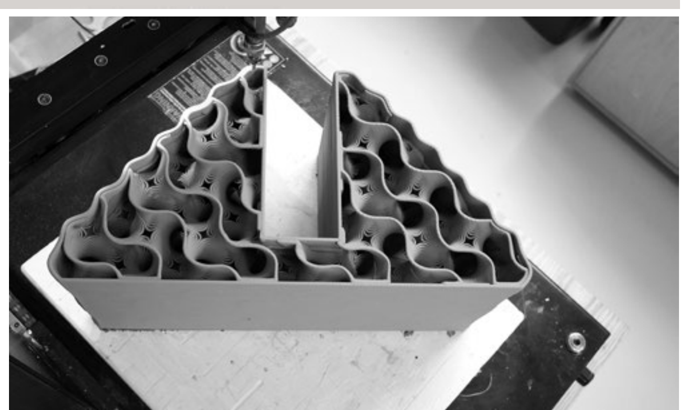

Figure 3: Printing process - Lutum 4.0 XL.

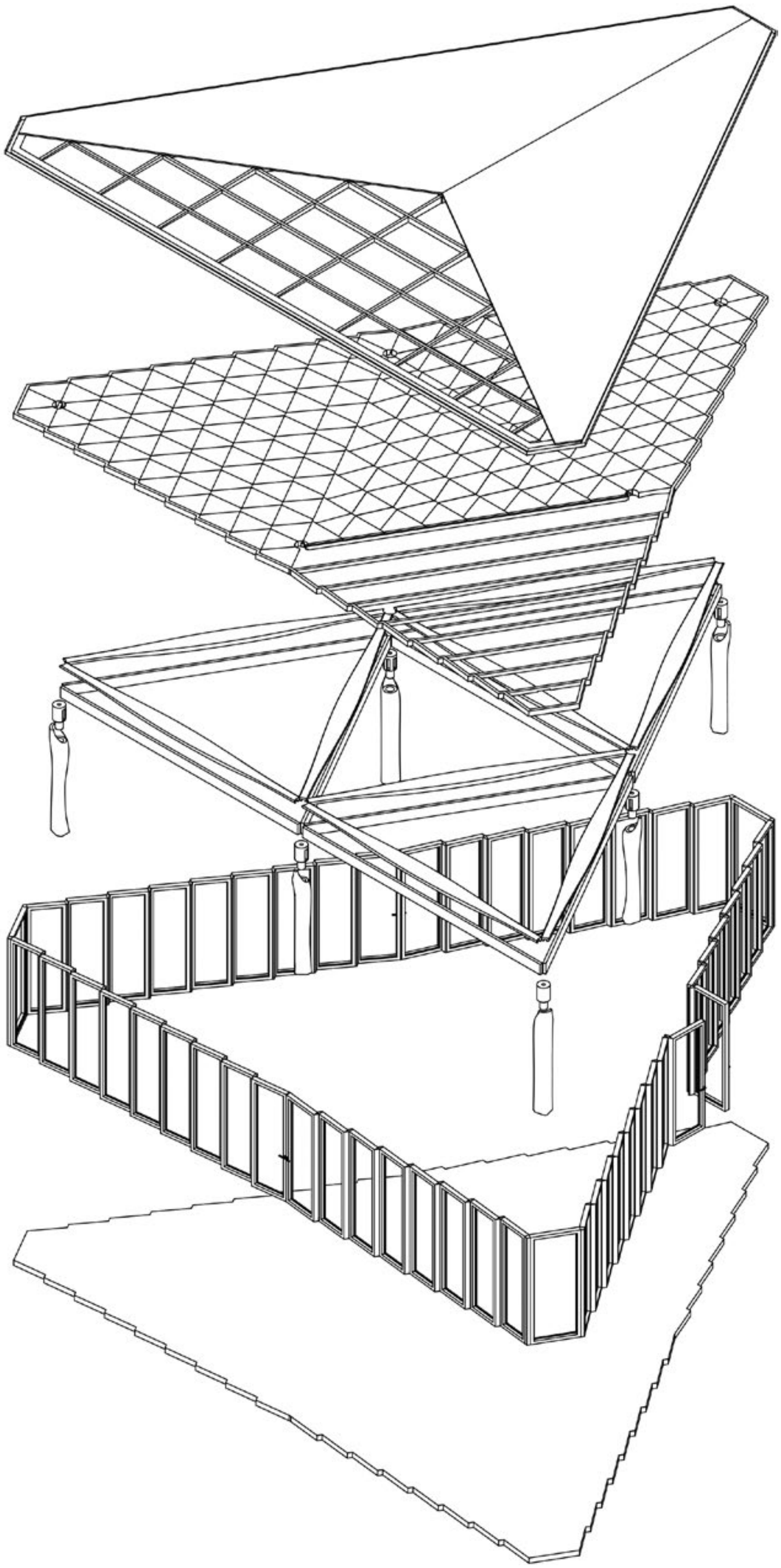

Figure 4: Exploded axonometric view of the hybrid architectural system.

Grasshopper with the tOpos plugin, this process optimizes material distribution for maximum performance and minimal waste. When combined with AM, topological optimization ensures precise material placement, fostering sustainable practices by reducing waste and promoting structurally sound, high-performance components.

In this study, a comprehensive topological analysis was conducted on standard structural elements, such as columns, beams, and slabs, to establish a well-informed and consolidated design framework (Figure 2). Fixed dimensions for these elements were maintained across tests to ensure consistent data comparison. The optimization results highlighted areas for material retention and removal, as well as the structural forces acting on each component. Based on this analysis, a digital model was developed that respects the distribution of masses and loads within the system. Compression zones were primarily addressed using ceramic materials, while traction forces were efficiently managed with wood and steel, resulting in a system that optimally balances material use and mechanical performance.

PRODUCTION EQUIPMENT AND PROCESSES

The production of ceramic components begins with creating the clay body, followed by shaping, drying, firing, and post-processing. Traditional methods like extrusion, moulding, or manual shaping require producing multiple parts to offset costs, but additive manufacturing introduces opportunities for precise, custom-designed ceramic components. This method employs a cartesian three-axis printer with a motor-controlled rotating spindle and a compressed air system for controlled extrusion. The primary control mechanism is a G-Code that governs every aspect of the printing process, from material flow to movement speeds. To achieve customization beyond standard slicing software capabilities, a Grasshopper computational model was developed, enabling precise control over dimensions and printing parameters. The system, though ideal for small-scale production and prototyping, highlights the need for more robust equipment for industrial applictions.

Post-printing processes are crucial due to the thin walls and substantial shrinkage of the ceramic material. Components undergo gradual and uniform drying to prevent breakage or distortion. Any imperfections are corrected, and contact surfaces are refined before firing. Components are carefully arranged in the kiln to optimize energy efficiency and ensure uniform heating. The firing process, essential for achieving the desired properties, involves significant transformations, including quartz inversion at 573°C and vitrification phases between 850°C and 1260°C, which result in a shrinkage around 25%. Adjustments to the firing curve were necessary to accommodate the dimensions and volume of the components, ensuring structural and geometric integrity after firing.

Finally, after firing, components are inspected for quality before assembly. The kiln's digital system allows precise adjustments to the firing process, promoting efficient energy use and minimizing thermal stresses. By integrating additive manufacturing techniques, customized control systems, and optimized firing processes, this methodology demonstrates the potential for ceramic components to expand the possibilities of masonry construction, blending innovation with traditional materials.

PROTOTYPE OF A MODULAR AM HYBRID ARCHITECTURAL SYSTEM

A possible modular architectural system composed of 3D-printed ceramic components was developed, leveraging digital design tools, computational optimization, and hybrid material integration to enhance structural performance and functionality (Figure 4). The prototyping phase aimed to explore the feasibility of these components, assess their mechanical behaviour, and identify potential challenges related to fabrication, assembly, and structural efficiency. By systematically investigating different structural elements—including columns, beams, slab blocks and its connections —this study establishes a framework for integrating AM in modular construction. Each of these components was designed and tested to evaluate its performance, adaptability, and potential for application.

A detailed development and evaluation of these structural components is presented. The columns serve as load-bearing elements, integrating hybrid materials to improve mechanical resistance and adaptability. The beams explore strategies for optimizing horizontal load distribution through ceramic-reinforced hybrid systems. The connections between structural elements focus on assembly techniques that enhance stability while maintaining modular flexibility. Lastly, the slabs investigate ceramic-based solutions for spanning horizontal surfaces, balancing strength, material efficiency, and lightweight design.

COLUMN

Following tests identifying wood as the most suitable material to complement ceramics, the focus shifted to designing structural elements for the main system, starting with columns. These columns were conceived not only for their structural role but also to provide thermal insulation, ventilation, infrastructure pathways, cladding, and enhanced

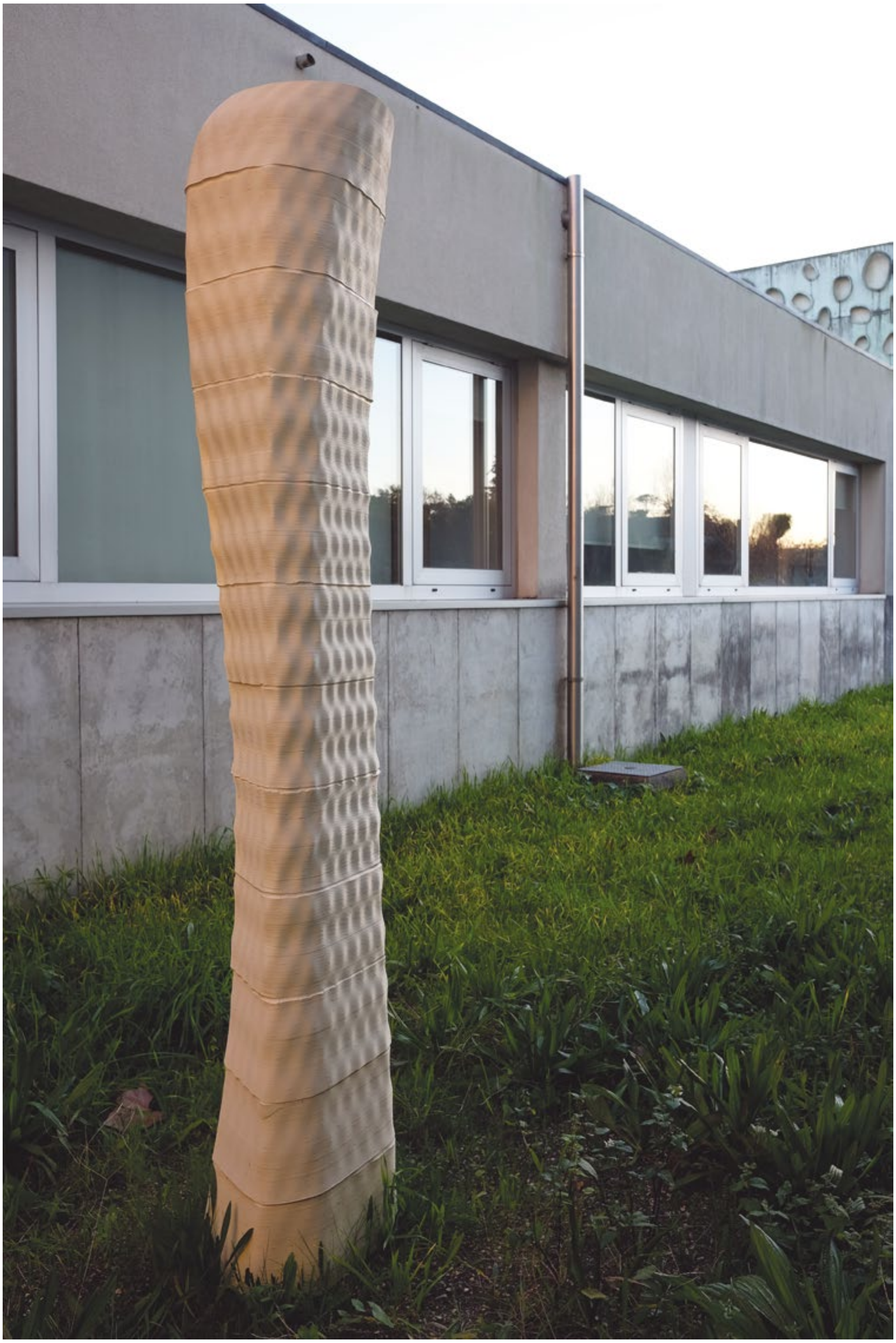

Figure 5: Hybrid column.

Figure 6: Hybrid beam.

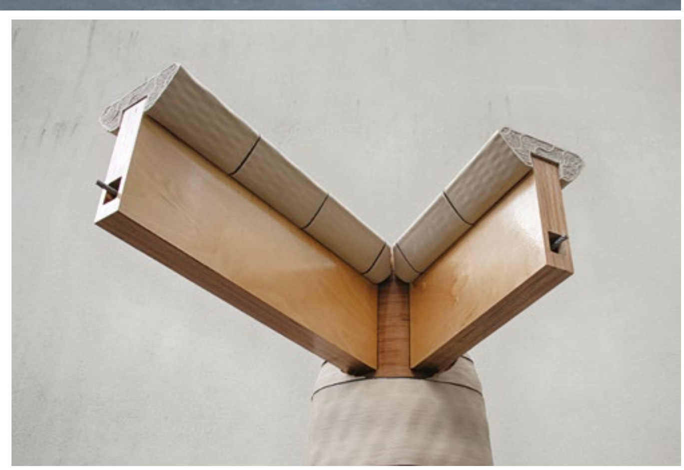

Figure 7: Connection between beams and columns.

fire resistance, emphasizing their potential to augment existing systems rather than replace them entirely. Initially designed as lost formwork for reinforced concrete, the columns evolved into an alternative system featuring ceramic staves with internal honeycomb structures, separated by MDF spacers to avoid contact. Topological optimization informed the column's shape and mass distribution, while a steel tensioning element was incorporated to compress the assembly into a monolithic unit and accommodate dynamic structural loads, ensuring strength and integration with other system components.

BEAM

Building upon the principles established with the column prototypes, the research transitioned to the development of beams as the next structural element. Unlike vertical elements, horizontal beams face distinct force distributions, with compression and tension acting in different areas, necessitating a hybrid approach. Ceramic components handle compression, steel resists tensile forces, and MDF boards facilitate load transfer and alignment. A 2,7-meter beam prototype constructed using hollow bricks, MDF, and galvanized steel rods, demonstrated excellent performance, withstanding significant loads without deformation.

To enhance the initial design, a novel model was developed using a wooden "core" to connect 30 ceramic pieces, reinforced with concrete to improve compressive strength and cohesion. This version optimized assembly and reduced the beam's weight by over 50% compared to reinforced concrete beams.

CONNECTIONS BETWEEN COLUMNS AND BEAMS

The connections between vertical and horizontal elements are crucial for the stability and load transfer in framed structures. In the developed constructive system, which uses discretized ceramic components and complementary materials, these connections are vital for solidifying the entire assembly, especially considering the system's non-monolithic nature and the potential for disassembly. Various connection concepts were developed, inspired by traditional construction methods, and categorized into four structural schemes with different blocking types. Ultimately, a functional connection was prototyped using wooden components for flexibility and ductility. These components, consisting of overlapping cylinders with specific cavities and a central hole for steel cables, connect columns and beams, reinforcing structural integrity and counteracting lateral movements. The steel cables passing through the components enhance the stability of both the beams and columns, effectively unifying them into a single structural unit.

SLABS

Slabs, as horizontal, planar elements that make up the floors and roofs of buildings, are essential components of a typical building system. In conventional construction methods, ceramic materials are often incorporated—either entirely or partially—into the creation of these fundamental structural elements. Prior to finalizing a system for the construction of slabs, a series of component geometries and operational approaches was considered for preliminary analysis. This process follows the same methodology used for the earlier architectural elements, with the aim of evaluating the potential of each typology to determine the best possible approach for the final system's design phase. The objective was to identify the most effective solution and any challenges that might arise during the implementation, laying the foundation for further refinement.

To proceed with the exploration of potential solutions, four distinct component types were conceived, each varying in mass distribution and structural schemes. These designs were influenced by traditional ceramic vaults and their operational principles, necessitating lateral beam supports for reinforcement and stability. The support elements designed for these components, used to assess the maximum capacity of each geometry, were made entirely of wood, closely following the section design of traditional prestressed beams. Each type of component included two lateral supports: one at the top and one at the bottom. The mechanical tests conducted on these components revealed significant differences in their capacity to withstand stress. Types A and B demonstrated positive results, with type A achieving an average capacity of 10 kN and type B reaching 7 kN, despite having thin 1.5 mm thick walls. However, the performance of types C and D was far beyond initial expectations, with their mechanical resistance proving much higher than the previous types. Even when subjected to the maximum allowable capacity of 45 kN, it was not possible to push these components to their breaking point in the initial phase of testing. All specimens of types C and D were subjected to tests with a wooden base and applied force up to the 45 kN.

Given that the ultimate goal of these tests was to determine how each component responds to compressive forces, the investigation proceeded by pushing the specimens to failure, subjecting them to additional tests under more challenging conditions. For this second round of tests, the wooden elements, which had previously been used to simulate beam supports and absorb surface tensions, were replaced with steel components to create more unfavourable conditions for the ceramic material, thereby reducing its mechanical strength. The results of these tests confirmed that type D exhibited the highest stability and resistance among all the components analysed, establishing it as the most reliable option.

After the testing phase was completed, the next step was to produce a section of the slab, which would eventually be assembled with the other prototypes. The design of this slab adheres to the same principles of mass distribution as the topological optimization models used for other components of the constructive system. However, there is still room for further rationalization and simplification of the geometries to ensure better compatibility with the production equipment available. The slab system is based on the same concept applied to beams, using longitudinal wooden elements that rest directly on the main beams. These wooden elements serve as the foundation for placing the ceramic vaults, replicating the operational structure of conventional lightweight slabs. To enhance the mechanical capacity of the system, post-tensioning elements may be incorporated into the wooden beams without significantly increasing the dimensions of the slab components. Once the joists and vaults are assembled, a cork plate, approximately 5 mm thick, is placed over the vaults to further consolidate the structure. Wooden boards are then attached to the beams using screws, and the final flooring is installed on top of these wooden boards, completing the assembly of the slab. This design allows for both the structural integrity and flexibility needed for the final system, demonstrating a promising integration of traditional materials and modern construction techniques.

RESULTS AND DISCUSSION

The system developed in this research, along with the principles guiding its design and the practical results achieved during the prototyping of various models, reinforces the belief in the viability of manufacturing medium-sized ceramic architectural components using PEM. These components can be effectively integrated into real-world contexts, transforming the built environment into a more cohesive and environmentally conscious space. The proposed system represents a major step forward in sustainable construction methodologies, offering the flexibility to customize each element for specific performance, form, or function while ensuring seamless integration within a unified framework.

By strategically allocating materials based on a structural arrangement derived from topological optimization, the system ensures optimal material performance under various forces. Additionally, design principles for assembly and disassembly allow for the creation of a fully reversible system that can be easily repaired or modified—damaged components can be replaced without significant limitations. This approach optimizes material usage throughout the entire process, from design to production, contributing to the development of a more sustainable built environment. The compression tests conducted validate the material's considerable potential for use in load-bearing structures, demonstrating that ceramics offer substantial advantages over traditional concrete, which is commonly used for such applications.

While the findings are promising, it is essential to recognize the challenges inherent in this production process, especially regarding the material properties and their varying responses at different stages of production. The system presented was initially developed within a controlled laboratory and experimental context, and transitioning to practical construction applications would require necessary adjustments. The production equipment used is designed for small to medium-scale components and limited production volumes. Furthermore, controlling the different phases of ceramic material, particularly during drying and firing, presents challenges. To improve the system's scalability, consideration should be given to materials with lower shrinkage and reduced deformation during these phases, ensuring the structural integrity of larger components while facilitating their practical application. For this investigation, fine stoneware without chamotte was selected for its adaptability to the extrusion system, but for larger-scale components, a different material might be more appropriate to avoid potential issues during production.

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Figure 8: Types of slabs components.

Figure 9: Hybrid slab.

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