# Bridging Technology and Sustainability: 3D-Printed Clay Formwork in Architectural Pedagogy

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**Abstract**

This paper examines an undergraduate Bachelor of Science in Architecture seminar focused on designing and fabricating reusable, zero-waste concrete formwork using a 3D-printed mixture of clay and paper composite known as paper clay. The course integrated digital design tools, robotic fabrication, and traditional hand-building techniques to explore limiting waste in the creation of complex concrete structures that would present significant challenges for standard formwork methods. Driven by the need to reduce the environmental impact of concrete construction, the seminar investigated the potential of 3D-printed paper clay as an alternative to traditional formwork materials. The seminar's pedagogical approach, grounded in experiential learning theory, emphasized hands-on prototyping, concrete casting, and mold design. Key outcomes of the final projects demonstrated novel applications of paper clay for the creation of complex geometries with openings, alongside explorations of smoother surface finishes and robotic carving of clay formwork as an alternative to 3D-printing. These findings highlight promising new fabrication methods for creating custom, recyclable concrete formwork suitable for intricate designs, further underscoring the pedagogical value of experiential learning in cultivating a deeper understanding of material properties and design implications for sustainable architecture. This research suggests a method for reducing the environmental impact of concrete construction through reusable, recyclable formwork and emphasizes the importance of integrating new methods of fabrication into architectural education.

**Introduction**

Concrete is ubiquitous in the construction industry[1], yet its production significantly contributes to global carbon emissions, accounting for up to 7% of total emissions[2], and generates substantial solid waste[3]. Formwork, essential for casting concrete, represents 35 to 50 percent of construction costs[4] and often leads to considerable waste. Formwork can play a significant role in concrete's carbon footprint, making its limitation crucial. This paper explores an undergraduate seminar that investigates sustainable methods for creating concrete structures through the use of 3D-printed, zero-waste, reusable formwork made of a wet clay and paper composite mixture called paper clay. This paper presents a study on integrating digital design and fabrication technologies with traditional ceramic methods, offering students a hands-on approach to sustainable architectural design. It also delves into the history and current research of clay 3D printing in architecture, equipping students with the skills necessary to produce complex formwork iterations while addressing the inefficiencies associated with conventional formwork systems. By integrating digital design and fabrication technologies with traditional ceramic methods, the seminar offers students a hands-on approach to sustainable architectural design. Furthermore, the course delves into the history and current research of clay 3D printing in architecture, equipping students with the skills necessary to produce complex formwork iterations while addressing the inefficiencies associated with conventional formwork systems.[5,6]

This research is driven by the need to reduce the environmental impact of concrete construction by exploring the potential of paper clay as an alternative to traditional formwork materials. By combining 3D printing with hand-building techniques, the seminar seeks to develop a method for creating complex geometries while minimizing waste.

The seminar's primary objectives are to:

- Investigate the use of 3D-printed paper clay to create reusable, zero-waste formwork for concrete casting.
- Provide students with hands-on experience in small-scale prototyping, concrete casting, and mold design.
- Equip students with skills in digital design, toolpath generation, and material techniques related to sustainable architectural design.
- Foster a deeper understanding of material properties and design implications, particularly in computational design and digital fabrication methods.

The seminar's pedagogical approach is grounded in experimental learning theory, emphasizing hands-on experience and reflection, which is critical for understanding sustainable design practices. Experiential learning and constructivism play crucial roles in architectural education, as they encourage students to engage with real-world challenges and actively construct their understanding through hands-on experiences. This seminar's approach to sustainable formwork embodies these educational theories, allowing participants to integrate digital design, robotic fabrication, and traditional ceramic techniques in a meaningful context.

**Literature Review**

The construction sector generates approximately 35% of the global solid waste each year.[3] Buildings and construction are responsible for 36% of global energy-related $CO_2$ emissions, with 11% stemming from the manufacturing of building materials and products.[7] Notably, cement production alone accounts for up to 7% of global emissions.[2] The production of concrete structures exacerbates this issue, as single-use formworks are often required for casting concrete. Formwork can represent 35 to 50 percent of a project's overall cost.[4] The number of concrete construction projects worldwide continues to rise.[5] By reducing the use of concrete and eliminating formwork waste, it is possible to significantly decrease waste when casting concrete structures.

Recent studies have focused on clay as a viable material for 3D-printed formwork. The project "Cocoon"[8] explored the use of clay formwork for concrete elements, specifically columns, emphasizing the potential for complex geometries and minimal waste. Other notable works, such as "Elemental | Ornamental"[9] and "Endless Columns"[10], examined variable 3D-printed clay molds for metal casting with sand and wood bounding boxes. Additionally, "Hexcrete"[11] combined 3D-printed clay units with traditional hand-joining methods to create larger, more complex formwork. This research also investigated the use of paper clay—a mixture of clay and shredded paper—to enhance the strength of clay and reduce its weight, a common practice in ceramics for creating large, lightweight sculptures (Figure 1).

The course draws from projects such as "Cocoon,"[8] "Elemental | Ornamental,"[9] and "Endless Columns,"[10] as well as "Hexcrete,"[11] to introduce students to this emerging fabrication process (Figure 1) and to explore reusable, zero-waste formwork techniques in a pedagogical setting. This seminar addresses this gap by offering a hands-on approach that combines these

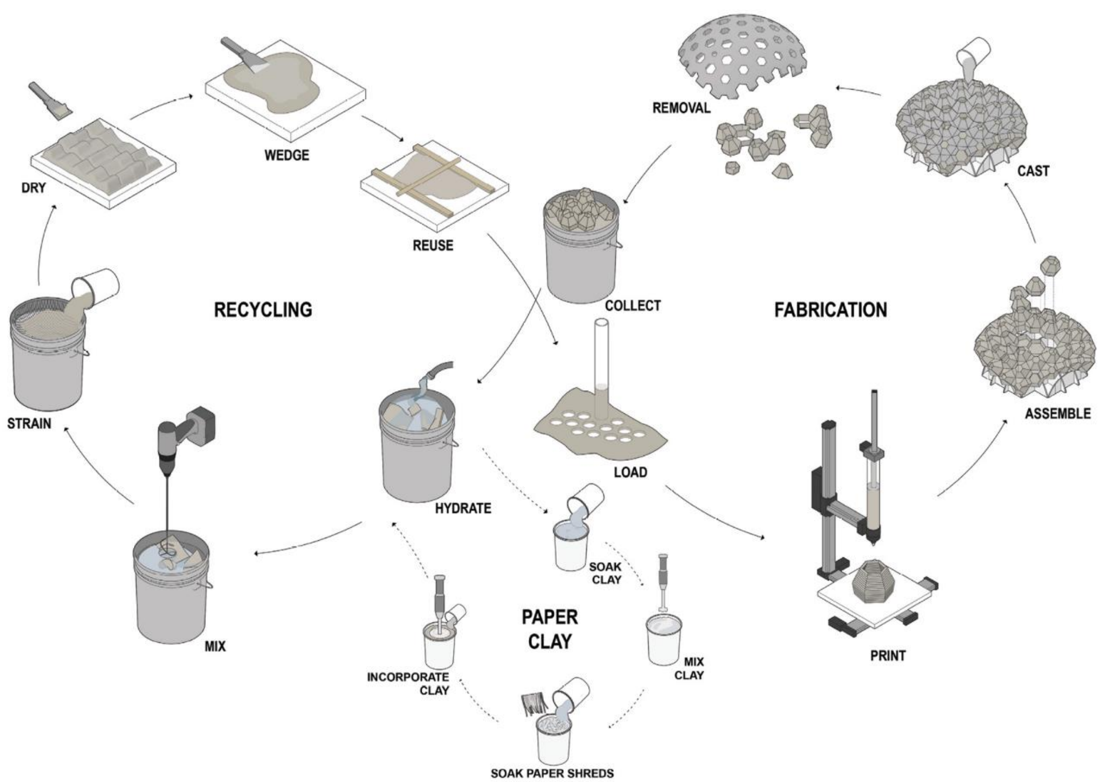


*Fig. 1. This diagram illustrates the paper clay workflow, including clay recycling processes and the fabrication and casting workflow.*

elements and emphasizes the complete fabrication process, from digital design to material testing and casting.

**Methodology**

The seminar employed a hands-on, project-based approach to explore the potential of 3D-printed paper clay formwork, integrating digital design and fabrication techniques through a series of assignments designed to progressively build student skills and understanding. The course structure included four collaborative 2-week assignments, culminating in a 7-week final project that allowed students to conduct novel research investigations.

*Course Structure*

Instruction was combined with lectures, workshops, fabrication, and desk critiques. Each 3-hour class session began with a faculty presentation, followed by hands-on activities and group work that fostered an interactive learning environment.

Workshops at the start of the semester introduced students to digital workflows, clay 3D printing, and casting techniques. Students used Rhinoceros 3D modeling software and its visual scripting language, Grasshopper, to design complex formwork systems. Grasshopper played a key role in generating the custom GCode for precise printer control.

Students created a paper-clay mixture by combining 25% shredded recycled paper and newspaper with 75% clay. This involved shredding, soaking, and emulsifying the paper to achieve a uniform consistency (Figure 1), enhancing the clay's strength while reducing its weight.

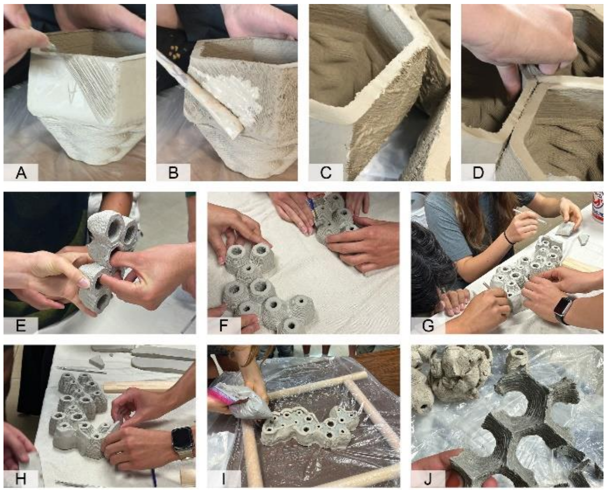


*Fig. 2. Unit joinery process: (A) scratching of the lower half, (B) applying the liquid clay to the surface, (C) aligning the correct sides, (D) applying pressure to weld units. (E-F) Students learning how to create and cast hand-built paper clay formwork in an in-class workshop with pre-printed units.*

The seminar utilized a Potterbot 10 Pro clay 3D printer to fabricate formwork units, with students learning the complete digital workflow, including clay preparation, printer setup, and print monitoring.

Assembling the 3D-printed units involved traditional ceramic methods, such as scoring and applying liquid clay (slip) as an adhesive. Flat slabs of clay were used to patch gaps and create bases for the formwork. The assembled formwork was then filled with Rockite® (expansion cement), chosen for its rapid curing time. After curing, the clay was removed either manually or allowed to dry, shrink, and fall off the cast. The clay removal processes allow for easy collection and recycling.

The collected paper clay was rehydrated into the slip and then passed through a fine mesh to remove any casting material, as it could clog the 3D printer's nozzle. The slip is then placed on plaster slabs to remove excess water, ensuring a workable texture for printing. The clay is kneaded or wedged to ensure uniform consistency. It is stored within sealed containers to prevent desiccation (Figure 1).

*Assignments*

All assignments were conducted in groups of four students, fostering collaboration and collective problem-solving. Each project required the design of a formwork system that fits within an 8 x 8 x 12-inch boundary. Students created portfolios to document their progress on each assignment. Presentations were structured to last approximately 10 minutes, allowing each group to effectively communicate their design concepts and findings while receiving constructive feedback from their peers, instructor, and graduate students.

The first assignment explored modular clay formwork systems, serving as an essential introduction to clay 3D printing, hand-building (Figure 2, Images A-D), casting, and digital fabrication workflows. While the historical context and contemporary projects related to clay 3D printing and formwork were introduced through lectures and reading the project paper, the hands-on assignment allowed students to engage directly with the material. Students created a system of modular 3D-printed clay units that, when aggregated, served as formwork for concrete architectural elements such as walls, tiles, or columns (Figure 3, Rows A and B). The project builds on prior research from a graduate student's studio project completed a year prior to the course, specifically the "Hexcrete"[11], published with a former student. An in-class workshop introduced this fabrication method, utilizing pre-printed modular units, which enabled the entire class to collaboratively create and cast hand-built formwork before commencing the assignment (Figure 2, Images E-J).

The second assignment focused on column design, drawing from precedent research projects such as "Cocoon,"[8] "Elemental | Ornamental,"[9] and "Endless Column."[10] This task challenged students to push the


*Fig. 3. (A) and (B) Assignment 1 focused on exploring modular clay formwork systems, serving as an introduction to clay 3D printing, hand-building, casting, and digital fabrication workflows. Team (A) utilized various tessellating forms to create tiles, while Team (B) employed an hourglass prismatic figure for double-sided formwork. (C-F) Examples from Assignments 2-4 investigate columns with openings. (C) and (D) examined closed toolpaths to create voids and open toolpaths for the casting material for Assignment 2. (E) and (F) showcased more complex designs incorporating various prints and hand-building techniques, building on skills learned from Assignments 1 and 2.*

boundaries of traditional formwork by incorporating openings and utilizing Grasshopper to generate complex, parametric geometries. The design of the openings in the cast required precise formwork planning, allowing students to explore sophisticated toolpath logic and enhancing their understanding of material deposition (Figure 3, Images C and D).

The third and fourth assignments encouraged students to expand upon their previous projects by creating a new formwork system that leveraged the knowledge and skills acquired from the earlier assignments. Students were instructed to refine their earlier designs or develop entirely new concepts inspired by the course's established precedents. This assignment emphasized the importance of experimentation and risk-taking, inviting students to explore new possibilities in formwork design and to view casting failures as opportunities for growth rather than setbacks. It encouraged them to push beyond traditional boundaries, considering intricate openings and complex casting techniques. Student groups explored hybrid approaches creating columns out of modular or multiple components then using hand building techniques to join them into one formwork (Figure 3, Rows E and F) Together, these two projects set the stage for the final project.

The final project required students to develop a novel research inquiry through design and fabrication, culminating in a 600-word paper and a poster presentation. Novelty was a key directive, requiring students to build upon their accumulated knowledge and skills to conduct a self-directed investigation into an area not previously covered in the assigned academic papers. This project aimed to synthesize previous work, allowing students to explore specific research questions based on their earlier experiences with 3D-printed paper clay formwork. This comprehensive assignment enabled students to apply their insights and skills to a self-directed investigation, enhancing their understanding of 3D-printed paper clay formwork.

*Feedback Mechanisms*

Students receive regular feedback through desk critiques, peer evaluations, and graded rubrics throughout the course. The course structure promotes an iterative design process, allowing students to refine their designs based on the insights gained from these evaluations. Peer evaluations specifically assess individual contributions to the team and are shared solely with the faculty to maintain confidentiality.

Projects are evaluated on several criteria, including fabrication craft, conceptual experimentation, drawing and documentation, digital model craft, text and verbal presentation, and professionalism. The assessment criteria for the final project address components such as the research question and experiment, abstract, introduction, methodology, results, and conclusion sections of the final paper and poster presentation.

This framework integrates experiential learning and constructivism, encouraging students to actively construct their knowledge through the design and fabrication process as they receive and implement feedback at each stage.

*Theoretical Framework*

The seminar's pedagogical approach is grounded in experiential learning theory, emphasizing learning through hands-on experiences and reflection. By engaging in the complete fabrication process—from digital design to material testing and casting—students develop a deeper understanding of sustainable design practices. Additionally, the course incorporates elements of constructivism, encouraging students to actively construct their knowledge through collaboration and exploration.

This structured yet flexible approach facilitates skill development, fosters creative exploration, and deepens students' understanding of sustainable material practices

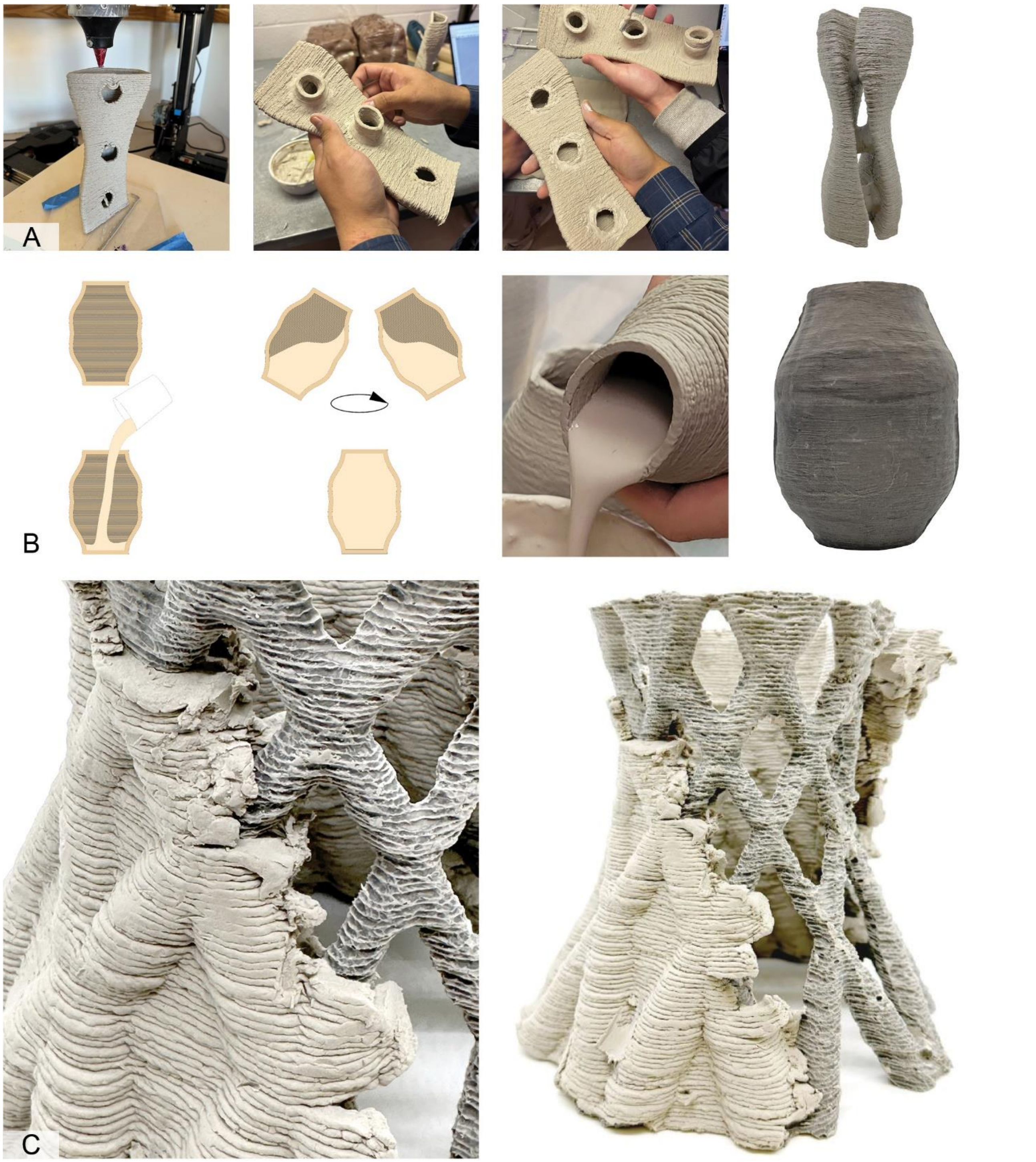


*Fig. 4. Final Project work: (A) Students hand-building five 3D printed pieces to create a novel column to create a complex form. (B) A student group 3D printing formwork; adding liquid clay (slip); rotating to coat the surface, removing layers marks, and pouring out surplus slip; casting into the coated clay for a smoother finish. (C) Fabrication of a complex diagrid column using toolpaths that are closed to create voids and open to space for the diagrid concrete cast.*

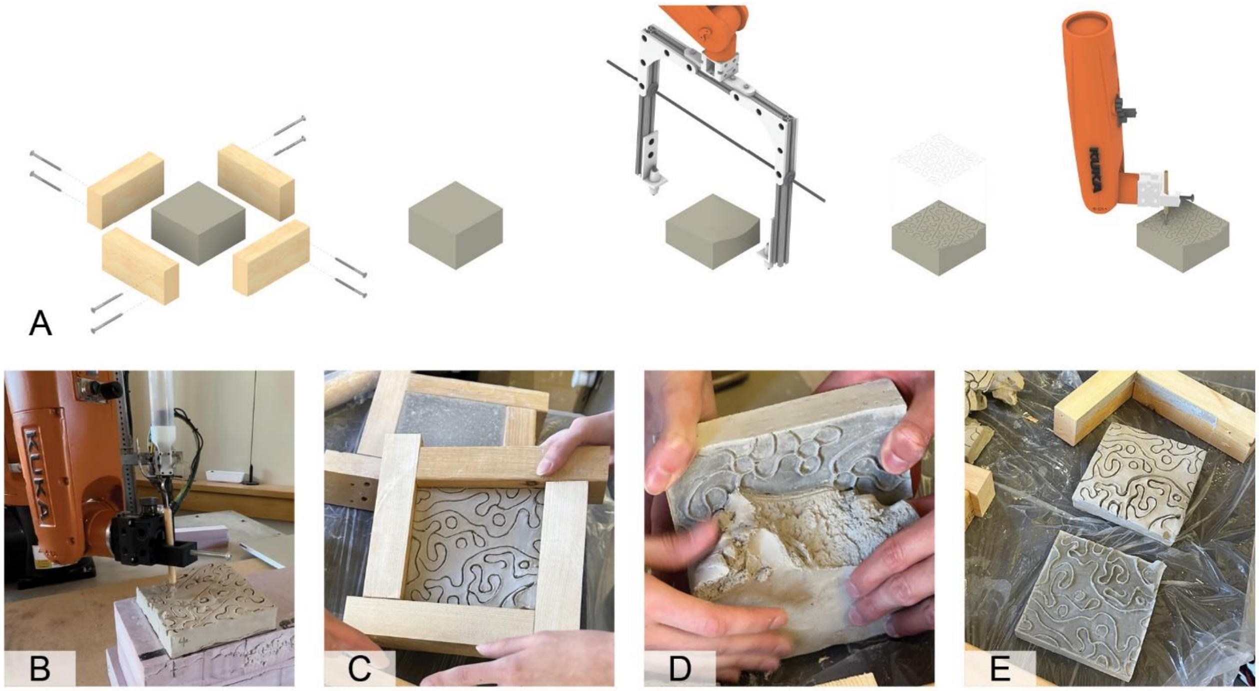


*Fig. 5. (A) Reusable wooden boundary box created with wood and screws, filled with clay; the wooden formwork is then removed, and the shape is carved and engraved robotically. (B) The robotic arm carving the clay. (C) The wooden boundary serving as formwork for concrete casting. (D) Removal of clay from the concrete cast. (E) Final concrete tile with the clay formwork separated from the wooden boundary.*

in architectural design. Through this framework, students not only gain technical skills but also enhance their ability to think critically and adaptively in real-world contexts.

**Results**

The seminar yielded several significant outcomes that highlight the potential and considerations of this innovative approach.

*Viability of Complex Geometries*

Student projects successfully demonstrated the ability to create intricate forms within concrete casts through various techniques. This included manipulating 3D printer toolpaths to generate closed paths for cast voids and open paths for the concrete (Figure 4, Row C). Furthermore, the integration of traditional hand-building methods allowed for the creation of complex column designs (Figure 4, Row A), showcasing a synergy between digital fabrication and manual craftsmanship.

*Surface Finish Refinement*

One research group explored methods to improve the surface quality of the concrete casts. While applying slip to the formwork interior presented challenges due to the dissolution of the clay, the successful application of a sponge to smooth the formwork before casting emerged as a promising technique for reducing the appearance of layer lines, suggesting a pathway for enhanced aesthetic outcomes (Figure 4, Row B).

*Robotic Carving for Customization*

The seminar also explored the potential of robotic carving on clay within reusable wooden boundary boxes. This method enabled the creation of custom shapes and textures, further expanding the possibilities for unique architectural expressions in concrete. The process involved filling a wooden formwork with clay, robotically carving the desired shape and texture, using the carved clay within the wooden boundary as formwork for concrete casting, and subsequently separating the clay from the hardened concrete (Figure 5).

**Conclusion**

This undergraduate architecture seminar successfully demonstrated the significant potential of integrating 3D-printed paper clay with digital design and traditional hand-building techniques to create reusable, zero-waste concrete formwork. The experiential learning approach proved invaluable in fostering a deep understanding of sustainable design practices and material properties among the students. Key outcomes highlighted the feasibility of using paper clay to fabricate complex geometries, including those with openings that challenge conventional formwork, and offered promising methods for refining the surface finish of concrete casts. The seminar also explored innovative alternative fabrication methods such as robotic carving of clay within reusable boundary boxes for concrete casting.

Significantly, the explorations and successes of this seminar served as a direct inspiration for subsequent research, now supported by a newly acquired grant, focused on developing thin shell structures using clay 3D printed formwork. The seminar's foundational work in sustainable 3D-printed clay formwork, its investigation into creating complex geometries, and its emphasis on reducing the environmental impact of concrete construction directly align with the objectives of the funded proposal. The proposal aims to scale these techniques for larger architectural applications, specifically the creation of a large-scale pavilion utilizing discretized unreinforced concrete elements cast in 3D-printed clay formwork. This progression from an undergraduate seminar to funded research underscores the critical role of experiential learning in identifying promising avenues for innovation in sustainable construction. Future research will undoubtedly build upon the insights gained in this seminar, further optimizing paper clay mixtures, refining fabrication techniques for larger scales, and exploring the structural performance of complex geometries achieved through these methods, contributing significantly to a more sustainable and resilient built environment. Ultimately, this work reinforces the importance of integrating sustainable material practices and cutting-edge fabrication technologies into architectural education to cultivate future designers equipped to address pressing environmental challenges.

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**Notes:**

1 UNEP (2016). Resource Efficiency and Resource Productivity: Assessment Report for the UNEP International Resource Panel. Available at: https://wedocs.unep.org/20.500.11822/2155

2 Anderson, J. and Moncaster, A. (2020). 'Embodied carbon of concrete in buildings, Part 1: analysis of published EP', Buildings and Cities, 1(1), pp. 198–217.

3 Llatas, C. (2011). 'A model for quantifying construction waste in projects according to the European waste list', Waste

Management, 31(6), 1261-1276. https://doi.org/10.1016/j.wasman.2011.01.023.

4 Peurifoy, R. and Oberlender, G. (2011). Formwork for Concrete Structures. 4th ed. McGraw-Hill.

5 Leder, S., Weber, R., Vasey, L., Yablonina, M., & Menges, A. (2020). 'Voxelcrete- Distributed voxelized adaptive formwork' in Werner, L. and Koering, D. (eds.) Architecture and Fabrication in the Cognitive Age: Proceedings of the 38th Education and research in Computer Aided Architectural Design in Europe Conference, Berlin, Germany, 16-18 September 2020, pp. 433-442, Available at: https://doi.org/10.52842/conf.ecaade.2020.2.433

6 Jipa, A. and Dillenburger, B. (2022). '3D Printed Formwork for Concrete: State-of-the-Art, Opportunities, Challenges, and Applications', 3D Printing and Additive Manufacturing, 9(2), pp. 84-107. https://doi.org/10.1089/3dp.2021.0024.

7 IEA (2019), Global Status Report for Buildings and Construction 2019, IEA, Par Paris https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019, License: CC BY 4.

8 Bruce, M. Clune, G. Xie, R. Mozaffari, S. and Arash A. (2021). 'Cocoon: 3D Printed Clay Formwork for Concrete Casting' in Bogosian, B. Dörfler, K. Farahi, B. Garcia del Castillo y López, J. Grant, J. Noel, V. Parascho, S. and Scott, J. (eds.) Realignments: Toward Critical Computation Proceedings of the 41st Annual Conference of the Association for Computer Aided Design in Architecture, 3-6 November 2021, Online, pp. 400-409. Available at: http://papers.cumincad.org/cgi-bin/works/Show?acadia21_400

9 McGee, W. and Peller, A. (2018). 'Elemental | Ornamental' in Anzalone, P. Del Signore, M. Witt, A.J. (eds.) On Imprecision and Infidelity: Proceedings of the 38th Annual Conference of the Association for Computer-Aided Design in Architecture, 18-20 October 2018, Mexico City, Mexico, pp. 198-203.

10 Sutherland, T.S. Marshall, W. and Lee, D. (2018). 'EndlessColumns' in Anzalone, P. Del Signore, M. Witt, A.J. (eds.) On Imprecision and Infidelity: Proceedings of the 38th Annual Conference of the Association for Computer-Aided Design in Architecture, 18-20 October 2018, Mexico City, Mexico, pp. 204-209.