Builder's Paper / Paper Builders: Crafting Cellulose Construction Systems in Circular Economies

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Keywords: paper, circular economy, thin-shell dome, lamination, deposited

Architectural design research on local materials and vernacular building is increasingly moving toward an integrated model of design-build optimizing processes of digital modeling and fabrication. Conversely, this paper details a low-tech—though high-performance—alternative: exploring the construction of architectural structures using mass-produced, recycled paper products to offer a promising avenue toward grassroots sustainability as it intersects with circular economy and sustainable craft. Informed by architectural histories of environmentalism, the paper presents design research, architectural applications, and construction logistics in the form of documentation and discussion of two recently fabricated domestic prototypes and one speculative housing proposal, all tested at sites in the extreme climate of the American Southwest.

The first prototype documented investigates the application of paper strips soaked in non-toxic adhesive as casting material for convexo-concave thin-shell structures—showcasing the use of paper as a primary construction material using an inventive process that reduces material waste by half and limits the need for industrial equipment. The second prototype examines the usefulness of paper pulp as a facade solution applied similarly to stucco or plaster—yet offering a more renewable alternative. Lastly, the paper imagines speculative futures in which these technologies can become implemented at large scales to create resilient, Zero-Carbon Communities as safer and healthier alternatives for the environment and users.

CRITERIA

Given its experimental nature, the procedures for testing material performance are not well-established for bio-sourced paper construction and production systems. However, investigating parallel conditions in the field of earthen construction reveals a body of professional research outlining criteria for consideration. For instance, the Earthen Architecture Initiative at the Getty Conservation Institute proposes, among a variety of attributes, the following as significant factors: plasticity, permeability, compressive strength, shear strength, and expansion and contraction.[1] These categories may be of comparable value in relation to paper construction laminated in situ, and as such, have been synthesized in our research to refer to a given system's "stability."

Furthermore, as described by Anna Heringer in her 2019 book *Upscaling Earth: Materials, Process, Catalyst,* one of the most significant advantages of building with earth (and subsequently building with other organic materials) lies in its lifecycle.[2] When constructed without any chemical additives, these types of structures are fully recyclable and/or compostable—a phenomenon we will henceforth refer to as a material system's "circularity." Lastly, one of the biggest hurdles in harnessing the full potential of these advantages is the criteria Herringer describes in reference to stabilization, and which we will refer to as "durability"—or the ability of the given material to resist erosion and structural failure over time.[3] The following three prototypes outlined in this paper should thus be understood primarily as process-driven, experimental material systems analyzed and researched through one-to-one prototyping and on-site observations gauging the system's stability (its observed stiffness, strength, and initial ability to resist gravitational loads), durability (the ability to withstand environmental forces over time), and circularity (how much of the original material composition is recycled as well the materials subsequent ability to be recycled or composted after demolition).

It should be noted, the paper's goal is not to present a permanent and replicable technology but rather to initiate a cross-disciplinary conversation via a process of "thinking as doing."[4] In this vein, the prototypes and procedures documented here should not be seen as controlled experiments testing a manufacturable product, but rather as three informative anecdotes meant to share our experience and inspire others to continue experimenting with novel material applications.

PROTOTYPE 1: AGG HAB

The first prototype documented was fabricated in 2020 as part of a residency at Oakes Creek Ranch. Titled Agg Hab, or Aggregate Habitat, the structure stood as a temporary habitable prototype built to test the stability and durability of glue-laminated paper as

Figure 1. Interior view of Agg Hab prototype. Neal Lucas Hitch.

a viable material option for casting thin-shell domes. The design and construction were directed by a two-fold, process-driven strategy: simultaneously reducing waste during construction via an innovative process that utilizes designed symmetries within excavated formworks to cast their own mirrored roofs, while also introducing a new application for a widely-available and highly sustainable paper product.

Construction started with the digging of two mirrored, convexo-concave holes, each four-and-a-half feet deep. These holes were then cast with multiple layers of an organic compound, consisting of large paper strips laminated together into a quarter-inch sheet using non-toxic adhesive, not dissimilar to the process used when making children's papier-mâché. Next, the casts were removed from their respective molds and flipped over to form duplicate, bulbous, paper shells, each mirroring the footprint of the others excavated formwork and spanning over twenty feet. Finally, the shells were each installed on top of the adjacent molds, which were repurposed to become the semi-subterranean foundations of the structures—reducing waste by eliminating the need for demolition and/or removal of formwork post-build. This way, when matched with its mirrored shell, a four-and-a-half-foot excavated hole will create a nine-foot interior space, simultaneously keeping construction at a manageable scale, cutting material use in half and minimizing the need for skilled labor typically associated with larger architectural productions; no industrial equipment was needed to flip the domes, and all maneuvering of the paper shells post-lamination was done by hand with a team of three.

Process

Each of the domes was cast using an experimental process that involved the utilization of conventional papier-mâché techniques—commonly used in children's crafts—implemented at the scale of habitable architectural construction. The mixture consisted exclusively of recycled paper products impregnated with ordinary, non-toxic wheat paste, made by boiling water and flour on a stovetop. The two specific paper products used in the

Agg Hab prototype were Ram Board and Builder's Paper, each consisting of 100% recycled material and, in the case of Ram Board, at least 90% post-consumer waste.[5] The wheat paste was "cooked" pre-construction and transported in 5-gallon jugs to the site. The paper was then soaked in tubs of paste on-site and applied in layers to the excavated holes. Next, the laminated casts were left to dry for 24 hours, removed from their molds, and installed on top of the corresponding holes.

Observations

The two domes built to form the Agg Hab prototype proved to be adequately self-stable, effectively resisting gravitational loads and heavy winds over the course of a few days. Furthermore, 100% of the paper structure was made from recycled materials, and no chemical adhesives were used, making the project fully circular in the sense that it existed as, at least, the second usage of the product, and, after being recycled or composted, could be reused in other projects. However, when exposed to moisture, the project's stability was significantly decreased, affecting the system's overall durability. Light resistance to rain and dew were demonstrated, but over time the structure succumbed to failure when exposed to long-term rain, intense winds, and sun.

PROTOTYPE 2: SHORT STORY

The second prototype tested, dubbed Short Story, was built as an accessory building/addition to an existing house in Spring Valley, Nevada, investigating the application of composite paper-pulp as a material alternative to stucco or plaster. Constructed using a typical stick framing system but clad with an experimental, organic building envelope, the project provisions for a diversity of spaces and flexible uses while offering a more sustainable exterior cladding solution made entirely from recycled and waste products.

The process of construction started with the erection of a 64 square foot wooden structure built using conventional wood-frame techniques that was then retrofitted with plywood sheathing and polycarbonate inlays. Next, dirt extracted from the site was mixed with pulped paper products and applied to the building exterior in successive coats. Finally, the mixture dried in place, generating a polychromatic aesthetic condition on the facade that developed from a pale, sandstone tone and pulpy texture near the base to an earthy, oxidized hue and thick, fleecy texture at the top.

Process

The exterior surface of Short Story is materialized as a continuous vertical gradient of color and texture made from applied paper pulp wrapping around a field of shifted and scaled apertures. In contrast to the typical stick-framed insulated wall—conceived additively through the lamination of sheets, stacks, and layers of rigid industrial materials—the project instead constructs an argument for the depositional construction of a wall section.

The cosmetic cladding was realized through the continuous transition between two "raw" materials, paper and adobe, articulated in a loose aesthetic resolution. Applied as both insulation and render for the walls, the material is made through an onsite manufacturing process that blends Builder's Paper—a widely available paper product made from 100% recycled material—with collected post-consumer waste and varying amounts of clay-rich dirt excavated from the site.[6] Then, the material is sprayed on in multiple coats with a pure paper-pulp mixture at the top slowly dissolving into a compound mostly consisting of mud at the base, magnifying and dramatizing its texture

Observations

While not structural in the sense that the paper is load-bearing, the Short Story prototype nonetheless showcases the usage of a fully recycled—and as such, circular—product's ability to be applied at a large scale in a residential setting. Additionally, the paper in this instance appears effectively water-resistant and is being watched over the course of the following months for signs of deformation and/or erosion. As described by author Charlotte Malterre-Barthes in her 2021 essay for *Non-Extractive Architecture: Designing Without Depletion,* one of the greatest responsibilities of contemporary architecture lies in acknowledging the association between architectural materials and their geological genesis.[7] The documented iteration of the technology thus identifies deposited paper-pulp as a stable, durable, sustainable, and locally-sourced exterior coating offering promise as a facade solution foreseeably implementable in a number of applications and diverse scenarios.

PROTOTYPE 3: DIG/DUG CITY

Finally, both of these prototypes were synthesized into a proposal submitted and shortlisted in 2021 for Land Arts Generator Initiative's Fly Ranch competition—an open call asking participants to propose grand visions for an "off-the-grid," regenerative metropolis to be located on property acquired by Burning Man Project in 2016.[8] Our Proposal, Dig/Dug City, outlined the masterplan for a vast eco-city consisting of numerous mirrored, earth cast shells each composed of laminated and/or deposited pulp paper material applications—combining the technologies previously outlined in the paper and accumulating them into a singular vision for a regenerative, zero-carbon community.

The city, proposed in the vein of new-age, self-reliant utopias including Arcosanti in Arizona and Black Rock City in Nevada, is conceived as a closed-loop—or circular—system maintained by the "self generation of inputs" in which all infrastructure is made from recycled materials, and all waste can be recycled or composted.[9] Phase one of development is planned to center around the construction of large, open-air community centers that will function as gathering spaces, lecture halls, and cafeterias. Smaller living units and roads will then form naturally around these hubs. The first community center is currently in development and is planned to be built in the next two years.

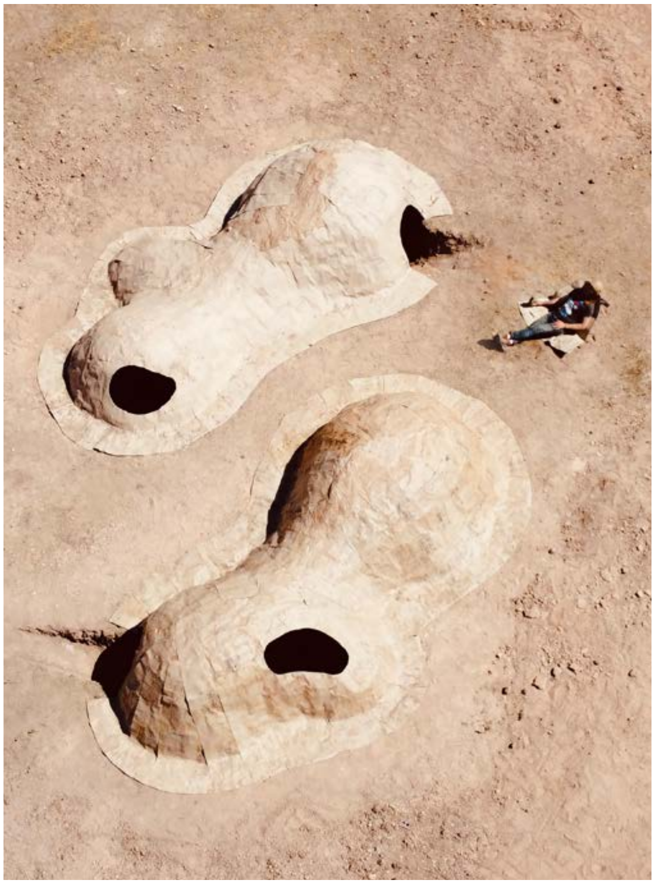

Figure 2. Aerial view of Agg Hab prototype. Neal Lucas Hitch.

Figure 3. Exterior view of Short Story prototype. Brendan Sullivan Shea.

Process

Initial site visits for this construction project were undertaken in June of 2021, the time of which a site was chosen, tests measuring soil conditions were initiated, and a third, small-scale prototype was erected testing the permanent and weatherproof application of our paper-dome technology.

Built onsite at Fly Ranch in Nevada, this final prototype was made using the same process as Agg Hab but at a reduced scale and utilizing waterproof wood glues instead of wheat paste. Fabrication of the prototype was executed by a small crew of three and began by digging a hole with an eight-foot diameter and four-foot depth. Next, that hole was laminated using strips of Builder's Paper and Ram Board soaked in non-toxic waterproof wood-glue rated type 1 for resistance against water.[10] The cast was then monitored for two days while drying within its mold. Once fully hardened, it was removed, coated in three additional layers of waterproof glue, and flipped over the top of the initial hole to create a shallow habitable space, where it is currently being monitored to observe its durability and stability over the course of one year.

Observations

Initial observations indicate that the prototype built using this process exhibits significantly improved durability but ultimately displays decreased stability. The waterproof glue used during construction adds sufficient protection from the weather and maintains the circularity of the system but falls short in achieving the same rigidity as the wheat paste compounds, ultimately resulting in minor deformations that could lead to overall failure as time passes, hindering the durability of the system. Further observations and additional testing will guide the direction of future construction.

FINDINGS

The three aforementioned prototypes evidence the versatility of laminated and pulped paper as a self-stable, circular, and potentially durable building material capable of diverse applications as both a facade solution and primary building material. Agg Hab and Short Story demonstrate the stability of paper on a large scale, and initial testing for Dig/Dug City shows promising results for the long-term application of the technology. Furthermore, the utilization of recycled paper products such as Ram Board and Builder's Paper make the projects inventive examples of construction that can aid in developing a circular economy.

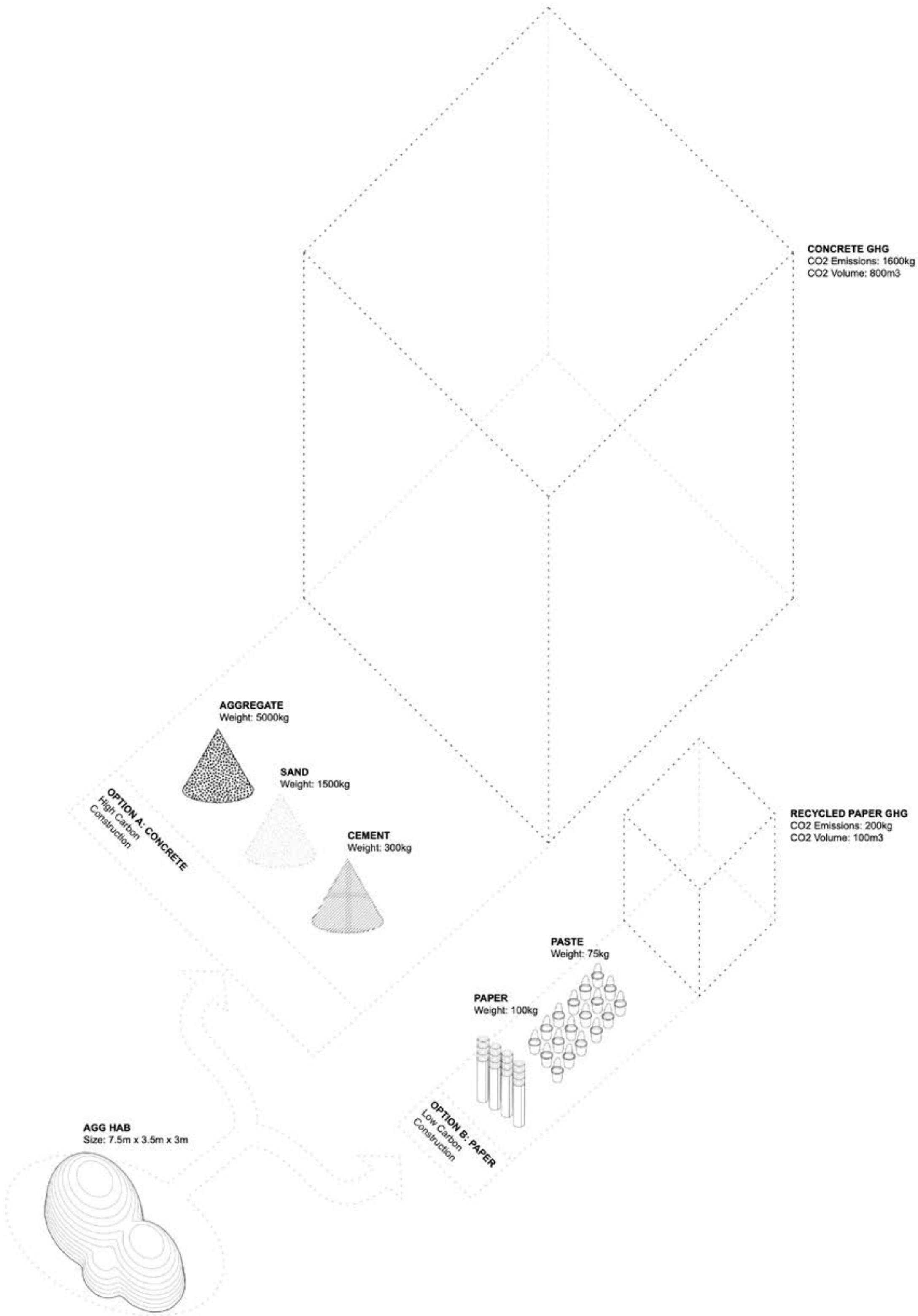

Figure 4. Comparing Material Flows of Concrete and Paper Construction Systems for Agg Hab.

Further inquiry

The biggest challenge for our team now lies in the weatherproofing of the domed structures at a larger scale as we make plans to expand the Dig/Dug City prototype. Lamination using waterproof glues improves the system's durability but eventually decreases the material's stability—making it more prone to deformation over time. As such, diverse solutions are currently being tested and considered to negate such outcomes.

One common but not ideal workaround used in many high-profile contemporary buildings made from organic materials is the addition of cement—a low-hanging solution that significantly increases durability and stability, but that nullifies one of the product's most desirable attributes; namely, its circularity (once cement is added, the project can no longer be composted or recycled).[11] As such, ongoing tests are geared toward creative solutions aimed at achieving relative weatherproofing using only passive techniques without the need for non-organic binders.

Figure 5. Aerial view of Dig/Dug City prototype. Neal Lucas Hitch.

Immediate interests include methods of waterproofing post-lamination through the application of tapes, waxes, and other sealers—an option that might maintain the stability achieved with wheat paste/paper compounds while also providing some protection against the elements. Other considerations involve the introduction of steel reinforcement between sheets of laminated paper and the addition of plastic to the outer layer of the structures. Modifications to the foundations of the domes, landscaping to better engineer water runoff, and the addition of other organic matter into the paper/glue mixture are also being explored.

Conclusion

Learning from those already working with paper, earthen, and other organic building materials, expanded testing procedures, collaborations, and the sharing of results will be important moving forward. The study of Shigeru Ban's permanent work using cardboard tubes and Anna Heringer's gospel of earth construction have been of particular help throughout the whole process.[12] As the techniques and procedures continue to develop, we hope the projects, plans, and prototypes presented here can inspire others interested in organic and circular building systems to pursue their unique interests, share their work, and ultimately help push the technology forward.

Paper parallels its rivals in many dimensions—it is strong in compression, tensile, and easy to work with—but it also exceeds them: both laminated and pulped paper are highly ductile, lightweight, cost-effective, and completely non-toxic. Most notably, paper is both recycled and recyclable—making its use in our research circular by providing a second use for the material while also maintaining its ability to be reused. As such, the potential for the product is virtually limitless, with the research presented here only scratching the surface of the technology's full range of possibilities as a promising material option that could eventually be used to offset the overuse of carbon-intense, non-renewable products like concrete and other cementitious materials.

ENDNOTES

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