Design-Build for Discovery: Applied Research on the Construction Site

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Abstract

The University of Arizona's architectural education program utilizes the dual learning vehicles of design-build pedagogy and affordable housing projects to investigate the cost effectiveness of regional vernacular construction methods paired with contemporary energy and water conservation strategies to control initial construction costs and long-term operational costs of single-family dwellings.

Earth, clay and stone, indigenous building materials with long histories in the arid deserts of the southwestern U.S., have diminished in use as labor prices have risen in the construction industry. Over the course of six design-build projects, Building Technology faculty and students experimented with and improved wall forming systems for rammed earth and pumice-crete, in order to reduce labor costs and bring these vernacular materials into use for affordable housing. The focus of the applied field research was the design of the wall forms and the sequence of building multiple walls with bond beams. Students built full scale wall mock-ups, created budget and energy models, tackled critical path construction scheduling, and interacted with subcontractors, inspectors, and building permit officials during design and construction of the housing units.

Our methods of earthen wall construction were refined over three main iterations and six projects, resulting in streamlined procedures, reduced construction time, and costs that were much lower than similar commercially built systems. The value of the design-build and research processes for students goes beyond exposure to the entire spectrum of housing design; the iterative investigations of wall forming systems across multiple projects teaches the value of Building Technology research and discovery through architectural practice.

Keywords: Design/Build, Pedagogy, Materials + Construction Techniques

Pedagogy

Twin goals of providing affordable housing with low long-term energy and maintenance costs to the low-income population in Arizona, and offering hands-on design-build learning experiences for architecture students at the University of Arizona led to a series of prototypical dwellings designed and constructed by faculty and students between 2000 and 2017.

Design objectives included the identification of low-cost building assemblies for maintaining thermal comfort in hot-arid climates. In order to build with locally available (earthen) materials, some experimentation with construction methods was necessary in order to contain costs.

Pedagogical objectives included involving students in all aspects of architectural practice; from site analysis, site selection and procurement, through schematic design, design development, and construction documents to the creation of budget and energy models, critical path construction scheduling, and interaction with subcontractors, inspectors, and building permit officials during design and construction in order to support their integration of the many aspects of the undergraduate architectural curriculum.

Figure 1. Projects 1-6; from left to right, Rincon Vista Classroom Facility, Gila River Reservation Residence, Tucson Rammed Earth Residences, and Scoria Residence.

Research: Methods of Affordable Earthen Wall Construction

Vernacular building materials and methods of construction were once the only choices for building dwellings in the arid southwestern region of the United States. Before the advent of the railroads in Arizona in the late 1800's, most homes were built of earthen materials and the limited small timbers available. Some indigenous peoples in the Sonoran Desert excavated "pit houses" that were roofed with small branches and trunks of mesquite trees and cactus ribs, then daubed with clay-rich soil. Because the living space was recessed 3 or 4 feet into the earth, the interior temperatures gained some stability from the earth itself.[1] Other indigenous peoples built of rammed earth and adobe bricks, constructing thick walls that served as thermal masses to regulate interior temperatures. Once the railroads began to deliver other types of building materials, the palette for residential construction gradually became homogenous with that for the rest of the nation. In the contemporary U.S. building economy, the use of earthen wall materials has been priced out of the mass production housing market due to the high amount of labor involved. Adobe blocks are still made mostly by hand, and the unit costs reflect that fact. Rammed earth contractors use heavy machinery to move wall forms and compact the earth within the forms in order to save on labor, still driving the prices skyward.

While using earthen materials to build thermal mass walls may still make sense today for environmental reasons, do-it-yourself labor is about the only way to bring costs down. Faculty and students at the University of Arizona began to experiment with lightweight, movable forms as a cost-saving measure, with the goal of building affordable housing that would also be energy-conserving due to the thermal mass of the wall assemblies. A series of full-scale built works allowed for experimentation with wall forming systems and gradual refinement of the methods that proved manageable by small groups of people without heavy equipment. Beginning with the leads in David Easton's book, "The Rammed Earth House"[2], faculty and students worked through three general iterations of form methods in six design-build studio projects.

Iteration One: Project 1

Project 1 was a classroom building for the University of Arizona's Department of Athletics and Recreation, sited in a large practice field and park near the main campus. The Rincon Vista Classroom Facility was meant to be energy-efficient, low-maintenance, and able to maintain indoor comfort even when the HVAC system was not in use. Rammed earth was selected by the design-build students and faculty members for the wall construction due to its ability to stabilize interior temperatures via thermal mass. The first iteration employed moveable, reusable plywood forms clamped to "volume displacement boxes" (VDBs) built of plywood and anchored to the foundation in order to create the rammed earth walls. After the walls were constructed in increments with the reusable forms, one-use forms that encircled all of the earthen walls simultaneously were constructed to pour a continuous concrete bond beam at the top of the walls. After completion of the earthen walls and bond beam, the VDBs were removed and the voids were filled in with windows and doors. This method depended upon having lots of regularly spaced window openings – a practice that worked well for a classroom building with one central space and many apertures. Using the VDBs to establish the heights for form boards and as attachment points for other materials allowed careful calibration of the lines left on the surface of the walls by the form boards, as well as the ability to line up the dirt lifts and the resulting "cold joint" lines between the lifts.

Figure 2: First rammed earth project in construction, showing VDBs and movable forms.

Figure 3: Second rammed earth project in construction, showing end boards and movable forms.

Iteration Two: Projects 2 & 3

The use of many regularly spaced and same-sized openings doesn't fit a residential design as well as an institutional building, due to the various uses of different rooms and therefore varying window and door openings. The second iteration of formwork, therefore, dispensed with the VDBs, and supported movable forms on concrete stem walls and temporary end supports anchored or braced to the floor slab. The second project, a dwelling for a Native American family on the Gila River Reservation, still employed the construction of separate, continuous forms around the tops of the completed earthen walls in order to pour a continuous concrete bond beam. This last step was difficult to support and level, and took three or four weeks of studio time to complete, which created a serious bottleneck in the construction schedule. With the end boards removed, there was no structure for attaching the forms except for the pressure of clamps. As the forms were leveled and clamped, they often slipped separated, and finalizing their alignment was a long process. Roof framing and interior partition wall framing had to be delayed until the entire bond beam was in place, as it served as the main lateral bracing for the structure.

One tangential innovation was made during the Gila River project construction. The homeowners, currently living in a traditional wattle and daub dwelling on the same parcel of land, requested the embedment of cactus ribs near the surface of the rammed earth walls, in order to achieve as aesthetic similar to their original dwelling (which was actually supported by the cactus rib framing). Students built full scale mock-ups of several possible ways to embed materials in rammed earth, until they found a way to anchor cactus ribs against the forms during high pressure tamping while allowing the surface dirt to fall away with gentle scouring once the wall forms were removed. They struggled with the notion of embedding what would essentially be a decorative material in a structural wall of a different type, but found a way to accomplish this while making it clear that the cactus ribs had no structural role in the rammed earth walls (by not bringing the saguaro ribs near the edges or corners of the wall panels).

Figure 4: Gila River dwelling with saguaro ribs embedded in entry wall.

An improvement was made in the process during the construction of the third project, a dwelling for a low-income family in Tucson, AZ. Since the holes left in the rammed earth walls by the removal of pipe clamps (that were later filled with earth) were always at the same heights all the way around the walls, the pipe clamps could be reinserted into the holes at the same height all the way around the structure and used as a scaffold for setting up and leveling the continuous bond beam forms. This minor adjustment shaved considerable time off of the construction period for the bond beam, but all other phases of the construction were still dependent on completion of the bond beam pour.

Figure 5: Third rammed earth project in construction; with pipe clamps supporting the continuous formwork for a bond beam.

Iteration Three: Projects 4, 5 & 6

The third iteration challenged the notion of pouring a continuous bond beam, and experimented with incremental bond beam pours in the tops of the forms already set up for the earthen walls – with continuous reinforcing steel that created the lateral stability and tensile strength of the bond beam. Full scale mock-ups were built to test the difficulty of extending the reinforcing steel through the end boards to create the required overlaps and negotiating corners with rebar bends. Faculty and students met with local building officials to confirm that the method would be approved by inspectors in the field.

Project 4 was built as a dwelling for another low-income family in Tucson. In this construction process, the tops of the wall forms were used as the bond beam formwork, too, with the rammed earth stopping at the level of 7’-4” and the bond beam steel and concrete occupying the top 8’ of the forms. The rebar was extended through ½” holes in the end boards in order to create splices for the next wall segment. Rather than having 20” of rebar sticking out into the air, impeding work in the next wall segment, small end boards were created 20” back from the end boards of each wall segment, and the subsequent concrete pour allowed the flow of concrete back into the top of the previous form segment. These small end boards took some tinkering, to ensure that they would not become trapped by the pressure of the poured concrete, etc., but saved a great deal of time overall because framing could begin in other areas of the dwelling (where bond beams had already been poured) while the rammed earth walls were still being constructed in other areas.

Figure 6: Incremental bond beam construction in Project 4.

Figure 7: Rammed earth wall of Project 5; this wall constructed with industrial forms.

Project 5, also a residence for a low-income family, was another version of this method of pouring within the wall forms – except the design broke the rammed earth walls up into several parallel walls instead of a continuous rectangle. The rammed earth work went relatively quickly because the design-build program owned enough formwork to form one long wall without having to move the forms around. In this instance, a set of industrial concrete forms was also loaned to the project by a rammed earth contractor, to allow students to compare the methods of building with standard forms and equipment. Because the industrial forms are much heavier, the struggle was in lifting them and leveling them without a fork lift (equipment our school does not own). But, the results of the varying wall surfaces due to the different form sizes and the use of snap ties versus pipe clamps, was interesting for students to see.

Project 6 is the most recent project, which investigated the process of forming raked walls of scoria with incremental forms and incremental bond beam pours. Scoria is the local name for pumice-crete, a mixture of crushed pumice stone from local quarries with cement and water. It is poured into forms in a damp state, but is not tamped or consolidated under pressure the way rammed earth is.

This project, a residence for a low-income Tucson family, was engineered as an earthen structure rather than low-strength concrete (which is another possibility because the cement content is higher than in rammed earth). Low strength concrete construction does not require a bond beam, but does requires cylinder compression tests, and the mock-ups and test cylinders done by students ahead of the actual construction achieved the required compressive strength for low-strength concrete only half of the time. All of the results were well over the compressive strength required for earthen walls, so in this first prototype, the faculty leader chose the conservative route of using a bond beam. Designing the process of pouring incremental bond beam segments with continuous reinforcing steel at an angle turned out to be very difficult and time consuming. The incremental bond beam method devised for rake walls in earlier projects proved difficult to control because the forms hide the earthen walls, and the string lines that mark wall heights and rake angles were constantly disrupted as forms were moved. Originally meant to be exposed to view, the bond beam was later covered with roof flashing and ceiling trim in order to disguise the lapses in alignment. This challenge is one that remains for future iterations of the construction methodology.

Figure 8: Scoria walls with incremental bond beam.

Students were indispensable to these many iterations and refinements, brainstorming about methods and building mock-ups to test ideas and convince code officials of the efficacy of new methods. Each iteration was accomplished by two to three different studio classes, and therefore the students and faculty had to learn from their predecessors and extend the body of knowledge with each new project. In this way, students were not only learning about known building methods, but also experiencing the challenges and satisfactions of original field research. Bringing students into the process of inquiry during a construction process makes them partners in discovery, and encourages creative thinking even during the most performance-critical stage of building delivery.

Project Costs

At the time of the first design-build studio involving rammed earth wall construction in 1998, the cost per square foot of wall face charged by building contractors in Tucson, AZ was $24. (The cost of the materials per square foot of wall face was $4.80). Contractors cited the cost of labor and equipment as the reason for this high price, but it was also due to the fact that there were only two contractors who built with rammed earth and the demand was high once several projects by local architect Rick Joy received national design awards and were published widely. Using the movable forms and student labor calculated at minimum wage, the studio project was built for $10.80 per square foot of wall. The difference in costs between contractor-built and school- built earthen walls has grown wider over the years, as rammed earth construction becomes even more expensive ($75 a square foot of wall face in 2019) due to shortages of contractors working with the material and difficulty in finding skilled laborers. The cost of the most recent design-build dwelling built of rammed earth, in 2013, was $20.30 per square foot of wall face, including student labor hours valued at $10/hour. In today's dollars, that would be $22.15 per square foot of wall face.[3] These comparisons illustrate the cost saving that can be had with movable forms and without the necessity of heavy equipment, suggesting that a DIY construction may be the most affordable option for homebuilders with a small group of laborers and rudimentary construction skills.

Pedagogical Results

Students participate in the design of these experiments and learn through the iterations of past trials and results. In this way, they are brought into the long-term research agenda of the faculty and are partners in discovery. Their involvement in a trajectory of research that spans decades may be as significant as their short-term learning about the materials and methods of construction, coordination with other trades, budget considerations, interactions with building officials and client groups, and the resolution of details with design intentions in the field - but the short-term experience is where they report the most satisfaction.

The following excerpts from testimonial letters, student course evaluations, or required field work journals are typical of the feedback we receive about their learning experiences:

"(The) design build studio which I was involved in over the course of two semesters in 2016 was without a doubt the most rewarding and greatest experience in my college education. As students, we were able to lead the entire process of designing and building a home for a low-income family in Tucson. (Our) professor guided us through every step of the way from finding and purchasing a suitable plot of land into conceptual design and design development through construction documents managing a real-world budget and through every phase of construction and ending the process with selling the home to a deserving family. This experience was formative in my evolution as a designer and as a human being. I know that the experience is something that every student who was lucky enough to be involved is proud of and will cherish for life."[4]

"From 2007-2008, I was part of Professor Hardin's and Folan's studios – designing and building a 3 bedroom - 2 bath house that we built for an out of pocket expense of just over $100,000[5], allowing it to be affordable to working class population in the barrio in which it was built. As a student in the Design Build studio, we were tasked with not only the labor to construct the house but to manage the construction process. Our class inherited the project as a foundation, rough framing, and an undeveloped set of Construction Documents. As a studio, we designed the details and were tasked with their execution. This process solidified an understanding of construction details, process, and the challenges design decisions can cause or solve. I was on the team in charge of overall budget management, which was critical for a home that was going to be sold to low-income families via a HUD-approved first-time homeownership program. We were also tasked with the coordination of materials and subcontractor labor. Learning the process and execution of construction in a hands-on environment lent itself to a deeper understanding of other elements of my education. Of course, this prepared me more thoroughly for the real world of construction. "[6]

Conclusions

While the design-build program at the University provides for hands-on educational opportunities and community outreach experiences for the students in the School of Architecture, it also serves as a field-testing vehicle for design hypotheses of many kinds. Some of the hypotheses involve explorations of methods of construction in relation to costs, and others investigate the efficacy of wall assemblies with regard to energy use. This kind of applied research differs from laboratory testing, where the small-scale wall panels are isolated from any other factors such as human use and flaws in workmanship. The conditions of construction and inhabitation of the design-build dwellings are similar to what happens all over the region in the production and inhabitation of standard housing stock and so allow for comparison to the most common circumstances.

Students who participate in the design-build research and building projects generally come away with a strong sense of purpose, a realization of the significance of their contributions to the community, better understanding of materials and methods of construction, and some knowledge of the long-term research trajectory particular to building technology in the arid southwest climate.

[1] Easton, Robert and Peter Nabakov. *Native American Architecture.* Oxford University Press, 1989.

[2] Easton, David. *The Rammed Earth House*. Chelsea Greene Publishing Company, White River Junction, Vermont, 2007.

[3] 2019 minimum wage in Arizona is $11.00, however, and the total is not adjusted for that.

[4] Andrew Marriott, UA SoA Class of 2017

[5] This included land and soft costs

[6] Maggie Kane, UA SoA Class of 2009