A Phylogeny of Formwork: Trans-Cultural Research in the Sonoran Desert

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Finding a relationship between the necessarily narrow and often arcane topics that are the focus of faculty research efforts, and the more general format of problems given to their design studios can be a challenge for teachers at any level in an architectural program. To then reframe the research for exploration in the community beyond the relatively indulgent setting of the university proves especially difficult. This case study illustrates a particularly fortuitous series of collaborations leading from a research idea to full-scale improvisation in a design/build studio and then to a significant application in an impoverished Native American community.

In hindsight it is clear that a full-scale laboratory is critical to the maturation of an embryonic research idea. The early idea remains speculation without the resources and opportunity to test and refine. But the phylogeny of an idea has no significance unless that evolution leads to more than just a perfect experiment. To have meaning, the results must extend beyond the context of the laboratory. Many design/build studio projects are ends in themselves; to have built is better than not to have built. Bringing an architectural idea through the entire cycle from paper to laboratory to community finally allows civic engagement.

TRACING A RESEARCH IDEA

The Design/Build faculty and staff and the College of Architecture were interested in learning the parameters, limits, and potentials of building with rammed earth, a construction method very recently adopted into the municipal building code. As is common with building codes, the text devoted to rammed earth defines performance criteria but provides no recipes. Without a body of knowledge to turn to for instruction, or experienced local tradesmen to apprentice with, novices are left with the need for full-scale experimentation. Questions about soil composition, forming methods, strength and plastic tolerance began to shape a research agenda. To blossom into an applied research project, however, the interest had to be cultivated within an opportunity to actually build.

A SERIES OF COLLABORATIONS

The initial collaboration developed when the University's Athletics and Recreation Department contacted the College of Architecture in 1996 with a request for assistance with the design of a new classroom facility. One professor in the College countered with an offer of a design/build project, and a partnership of two years duration was formed. A 4th year design studio took up the challenge to design an environmentally conscious, low cost classroom facility that could be built by novices in the construction trades. A second semester of design development and construction documents readied the project for ground breaking.

At this point in 1997, the professors destined to lead students through the construction of the chosen scheme (a structure of rammed earth and insulated concrete block) began to face the realities of functioning as building contractors with very little budget for equipment and overhead. An obstacle looming very large in the path of the classroom facility (the need to accomplish rammed earth work without investing in the expensive commercial formwork used in contemporary projects) led to a research goal that would eventually affect the community beyond the campus itself.

As the professors and the shop master in the College of Architecture worked to develop a forming system that would allow their students to accomplish the classroom building, the universality of the need became apparent. Rammed earth construction is currently a fairly expensive choice for wall systems, as the necessary formwork constitutes a major investment and the labor is specialized. Contractors who focus on rammed earth construction form the entire building at once with the steel reinforced forms typically used for poured-in-place concrete, and tamp the earth/cement mixture in a brief, intensive period. An alternative method of forming walls incrementally, with formwork that could be managed by two or three people and then reused, was necessary for low cost efforts. The efficiency of the large scale forming could be traded for the manageable system, if labor was plentiful and cheap. The problem of developing a low cost forming system for the Design/Build studio was the same as the challenge of bringing rammed earth into the affordable housing arena.

Rammed earth construction, a historical building method in the southwestern United States (as well as in Central and South America and elsewhere) with positive thermal, environmental, and aesthetic attributes, faded from use in the U.S. for hundreds of years and is recently being revived as a construction alternative for custom homes and other elite projects. The loadbearing system requires wall thicknesses of 12 to 24 inches which may taper in section from base to top. Having almost no insulation value, rammed earth walls serve instead as thermal mass, which slows down the transfer of heat from exterior to interior spaces during the day (and performs the opposite function at night). The rate of heat transfer through a rammed earth wall is about one inch per hour. In the desert climate, this means that the sun's heat works its way towards the interior spaces, but due to the wall thickness, does not complete the transfer before nightfall. The substantial drop in air temperature at night causes the walls to cool off again before sunrise. The possibility of gleaning most of the construction material from the site also makes rammed earth an economical and environmentally conscious choice of building construction. However, the high overhead cost of forms and scaffolding as well as the high labor investment take it out of the realm of affordability for most people. Research into ancient forming methods, soil composition, and wall dimensions led to speculation about a contemporary construction system that could once again be employed in the vernacular architecture of the region. The specific challenge of designing formwork for the University classroom facility had implications for further, and ultimately more significant research. Several rounds of formwork design and test walls prefaced the Design/Build Studio.

THE FORMWORK RESEARCH

Before actual construction began on the classroom facility, formwork designs focused on the goals of mobility and reassembly. Early prototypes used plywood walls stiffened with steel sections, which were later replaced by aluminum in order to lighten the weight of the form. Aluminum angles allowed the plywood pieces to bolt together easily and doubled as handles for lifting and moving the forms. However, the pressure built up by the tamping made it very difficult to disassemble the forms, the sides bowed in spite of the stiffeners, the assembled forms were cumbersome to move around, and they could not be stacked one upon the other. This forced a working sequence of ramming walls in horizontal courses, which had the drawback of a small amount of horizontal form creep in the direction of the wall progress. Looking at precedent for ramming walls in vertical piers (ancient and contemporary Chinese, Moroccan, Australian, Californian1 methods), plywood walls, pipe clamps, and stiffening boards were used in a simpler configuration. After a few test runs with the revised formwork, fine tuning of pipe spacing and placement allowed the actual building construction to begin.

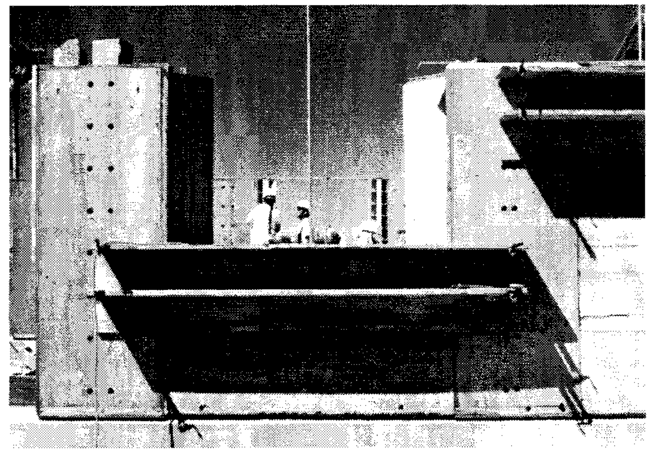

Fig.1 Incremental formwork for classroom facility

THE EARTHMIX RESEARCH

Composition of the earth mix was another variable in the design process that had to be tested and revised in several iterations. Generally, earth from the given site is tested by sieve and settlement to determine its composition in terms of particle sizes. Then, admixtures are designed to bring about the result of a well-graded mix. This mix is then combined with cement and water, and tamped into test cylinders for curing and compressive strength trials. The percentage of cement to total mix is the subject of much testing, and a number of versions must be tried to achieve the compressive strength required by building code. Color pigments are another variable that affect the final strength of the mix due to their fine particulate nature. In the case of the classroon building, scores of test cylinders were tamped and crushed before a reliable mix was discovered.

THE CLASSROOM BUILDING

For the architecture students, another type of learning took place once the construction phase began. Twenty-eight 5th year and graduate students registered for the 1997 Design/Build Studio that was to construct the classroom facility. Teams were formed to produce shop drawings for each wall and roof plane. Students organized and placed materials orders, met deliveries, and practiced skills such as welding, mixing mortar, and laying block. Carefully dimensioned sketches filled notebooks as students planned and prepared for each day's exertions. Tool belts lost their sheen, thumbs wore bandages, vocabularies grew. Faculty and students from the Recreation Department joined the effort, shoveling dirt and steering pneumatic tampers. The entire crew was energized by the participation of the clients. As the walls rose, the forming system was rethought, revised, and constantly improved until results became consistent.

Developing a working method with the rammed earth forms and earth mixing equipment required moving through a steep learning curve. Initial setting of forms and squaring, plumbing, and clamping was tedious until a logical sequence became obvious. Incorporation of small chamfer strips to create reveals between the rammed earth and concrete was very time consuming and caused logistics problems. The earth mixing had to be done by hand, as no earth moving equipment was available, and this slowed down the tamping progress and caused some wall sections to be over-tamped. But, as the construction proceeded, the students developed a rhythm for the work and synchronized the mixing of earth batches, the moving of scaffolding and forms, and the tamping. Eventually, they were able to understand the process and make suggestions for revised formwork, details, and earth mixing techniques. The two-person system of incremental forming became a reliable system with an investment of about $300 in plywood. As the students honed their expertise with this system, they also became more confident with solving construction problems in the field, trying innovative solutions, imagining how materials assemblies came together, drawing their ideas in their sketchbooks, and relying upon their intuition about physical problems. The impact on their design thinking was immediate and tangible.

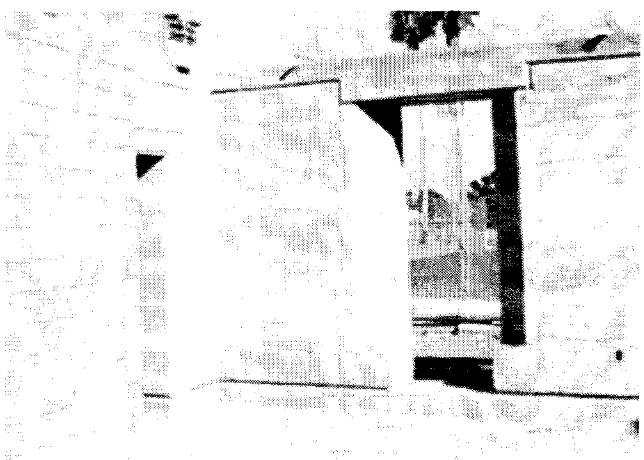

Fig. 2 Wall opening and bond beam of classroom facility

THE NEW CHALLENGE

Even as students shaped the classroom facility, the faculty began to realize the implications of the new forming system in the impoverished communities of the region. One of the Design/Build professors wrote a grant proposal for an educational partnership between the College of Architecture and a Native American community that was in dire need of additional housing. The Gila/Pima community had rejected government built housing that bore no affinity for their traditional building methods, and much HUD housing had been abandoned or vandalized. Desperate for ideas, representatives of the tribal Housing Committee had attended student presentations of environmentally sensitive housing proposals, and had already requested assistance from the College of Architecture. The tribal Housing Committee was enthused about the notion of a partnership that would train members of the community to build rammed earth houses for themselves with a low cost system of formwork and indigenous building materials. When the Kellogg Foundation funded the grant in 1998, a new collaboration was formed.

TRADITIONAL GILA DWELLINGS

Rammed earth was originally a building technique of Native Americans of this region, as was wattle and daub. Both have been replaced in this century by a composite wall system of wood and packed mud. Houses built with this system on the Gila/Pima reservation are referred to in English as "sandwich" houses. Most residents of the reservation live in a sandwich house, or grew up in one. While these houses require constant patching and replacement of the mud, they are valued by tenants for their maintenance of a fairly stable interior temperature in spite of the wide diurnal temperature swings of the Sonoran desert. They also hold considerable cultural value because they are a local tradition and are built by their tenants with found materials from the landscape (cactus ribs, plant stalks, earth) that remain part of the landscape when the houses deteriorate.

Pima communities have been located along the Gila and Salt Rivers for as far back as their history goes. The Pimas (also known as A Kimel O'otam, which means River People) were dependent upon the rivers for irrigation of their fields as well as for the materials to build dwellings and granaries. Pimas believe themselves to be descended from the Hohokam (a Pima word meaning "those who are gone")[2], who were renowned for their canal systems and earth buildings. The Hohokam migrated from Mexico into southern Arizona in around 300 BC and joined archaic people who already moved about the area hunting and gathering in small bands. They brought with them new lifeways that introduced farming and irrigation knowledge as well as permanent community locations and longer lasting dwellings woven of slender branches and plastered with mud. Around 1250 AD, the Hohokam began to build adobe walled houses that evolved into large, three or four story apartment buildings.

One major cultural icon for Native Americans in the region is the ruin of an ancient structure called "Casa Grande" today. It was a four-story watchtower or observatory built by the Hohokam tribe in the mid-1300s and became the first archeological preserve in the United States. Constructed of layers of caliche mud, the walls are 4 1/2 feet thick at the base and endure because of their mass and compaction. In 1350 AD, the Hohokam population began to decline for unknown reasons (presumably drought) and scattered into groupings of small houses once again. These communities became the Papago and Pima tribes, who lived this way until encountered by the Spanish in the 1600s.[3]

The Pimas built of arrowweed, willow and cottonwood, which required moderate rainfall. Until the 19th century, the two most common building types were the ki and the vato. The ki was a slightly excavated, brush and mud covered structure with a domed adobeplastered roof. This was used for shelter in cool weather. The vato was a four posted arbor covered with cactus ribs and arrowweed. This was where families cooked, ate and slept during the warmer times of the year.[4]

> " A vato or shade was usually just a few yards from this cooking place. This shelter of a type still used by the Pimas was made with four or six upright forked posts that held cross-poles on which arrow weeds were placed to make the shade. This shelter was open on all sides and used in the summer time when the sun shines hot.
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> Beyond the vato was the olas-ki, or round-house, made of mesquite posts, and arrowweeds. This type of house is no longer used. It was enclosed all around, with a little dirt and straw on top to keep the rain out. The only opening was a small hole about two feet wide and four feet high which was used as a door." - George Webb, *A Pima Remembers*

The later-period Pima and Papago houses were rectangular, flat-roofed structures with a post and beam frame covered with arrowweed and mud. Changes in housing practices since the 1880s have largely resulted from constant pressure by church and government groups; but the sandwich houses are not part of any government sponsored development plan and retain Pima characteristics.[5] They include locally available materials and employ locally known techniques while evolving to reflect the arrival of milled lumber. The walls are built of mud and straw which is packed into a frame of heavy vertical posts and lighter horizontal cross pieces that are spaced a few inches apart or staggered. The mud fills the frame cavity and gsqueezes out between the cross pieces, forming a composite wall. Most sandwich houses are plastered inside and out with a coat of mud, which must be repaired frequently. The packed mud must also be repacked frequently, especially after monsoon rains wash out areas of the walls. The roofs are framed with mesquite posts, crosshatched with saguaro ribs, and thatched with arrowweed and mud. Sandwich houses are still the most common dwelling type found on the Gila River reservation and new ones are still constructed as a matter of preference and also economy. Contemporary rammed earth techniques differ due to available technology and requirements of building codes, but the genealogy remains obvious. The reliance on the earth from the site, the intensity of the labor required, and the uncomplicated techniques involved make it an easy fit in the situation of the Gila/Pimas with their high unemployment and their housing shortage.

REVISIONS

As one faculty member and the next generation of students began to work in 1998 on the design of a dwelling for a Gila family, new considerations arose. The soil mixture had to be designed in order to make best use of the soil found on the site, and the family had preferences for integrating other traditional materials, such as cactus ribs and arrowweed thatch, into the house. Also, the faculty member wanted to revise the formwork to make fewer breakdown and set-up periods necessary, as those took more time and labor than the tamping. A period of design and testing followed, until the 1999 Design/Build Studio felt prepared to begin new construction.

Fig. 3 Traditional Gila/Pima sandwich house

FORMWORK REVISITED AND EARTHMIX REDESIGNED

The experiences of the classroom facility construction led to changes in the forming system that included doubling the height of the forms, reducing the number of pipe clamps and walers, using the PVC sleeves left within the walls as conduits for the bond beam formwork. The refinements and innovations that occurred throughout this process of research, design and construction could only have happened in this iterative cycle of inventing and testing. The different soil found on the Gila site also caused redesign. The earth from the Gila family's site was high in silt and clay due to their location in the flood plain between the mostly dry Santa Cruz and Gila Rivers. A sand and gravel company on the reservation had the necessary admixtures - natural clean sand material mined from the riverbeds and small pieces of granite leftover from a crushing operation (known as crusher fines). Together with the sand and silt, a suitable mixture was found.

THE RAMMED EARTH GILA DWELLING

The configuration of the dwelling was a simple rectangular plan (similar to the typical sandwich house) on an eight-foot module to correspond with the form dimensions; adapted to the family's preferences for orientation, view, and outdoor living practices. This process of configuration, which was informed by many discussions of space usage, indoor vs. outdoor plumbing, indoor and/or outdoor cooking, cooling and heating systems, the use of electricity and the re-use of household water, will not be outlined here as it is a study in itself, of a different sort. The considerations that directly

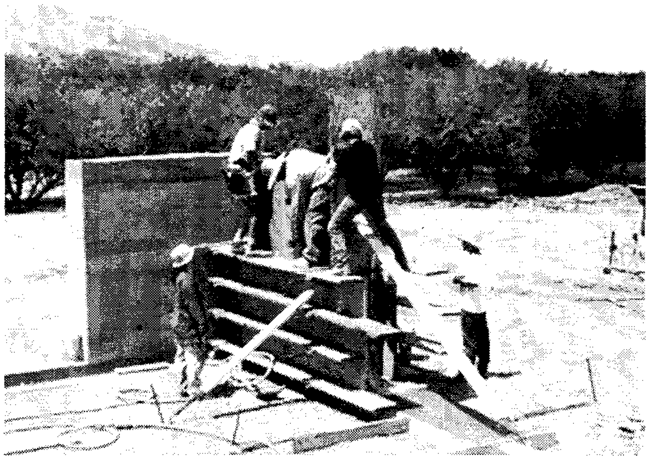

Fig. 4 Formwork revisions on Gila residence

Fig. 5 Wall with embedded cactus ribs on Gila residence

affected the construction practices, however, have a place in this text.

The Gila family has a strong affection for their present home, although it is very small and in poor repair. They do not wish to see it razed by the tribal Housing Authority when their new home is complete, and hope to keep it on as a storage building or guest quarters. It is over 70 years old and was built by the late grandfather of the family. The appearance of the mud and saguaro rib walls is a desirable attribute for this family, who asked for a similar appearance in some location of their new home. The challenge to incorporate saguaro ribs into the formwork and earth tamping system of rammed earth led to several experiments with strips of milled lumber and cactus ribs and different methods of embedding them into the earth or attaching them to the formwork. The goal was to leave one face of the cactus ribs revealed once the forms were removed. Initial attempts to tie strips and ribs into forms using hemp or wire failed, as did efforts to create a reveal in the surface of the rammed earth with ribs exposed behind it. The desired end result was finally accomplished by laying the ribs against the formwork one by one as the tamping progressed, anchoring them into the rammed earth with 3-inch drywall screws, and brushing them with a wire brush to subtract the covering surface once the forms were removed. The sagauro ribs could not extend the full length of the forms because the ends would then be exposed and eventually pull free from the wall mass. The decision was made to set the ribs in 12 inches from the end of the form, which also allowed the visual understanding that they served an ornamental rather than structural purpose.

Another challenge was to bring the familiar materials of the vato into the roof of the deep porch, which would serve as outdoor living room. Reservation building officials had already outlawed the use of the traditional thatch materials inside the house due to concerns about flammability. The porch rafters were a framework for accepting the traditional layers of cactus rib and arrowweed that was acceptable to the building inspectors. Students mocked up several alternative versions of how the materials might be assembled. The final detail requires lighter rafters at a closer interval at the entry section of the porch, in order to accept several inches of split saguaro ribs and arrowweed but still end up at the same level as the rest of the porch for sheathing.

The walls of the Gila residence were built in nine days with the participation of members of the Gila River Community construction crew. Gila tribe members formed and poured the footings for the rammed earth walls. Four to six of the crew worked with the students each day and continued the work after the semester ended. During the first two days of wall building, the Gila crew mixed earth and cement, and observed the forming process. By the third day they were engaged in the forming and eventually adapted it for unique situations brought upon the project suddenly, such as the building inspector's request for a recess to contain the electrical panel box. The last two days of wall building were done entirely by the Gila crew, as the Design/Build studio turned to the challenge of forming for the concrete bond beam.

The rammed earth formwork proved to be manageable by two people, although a third person was useful in tightening

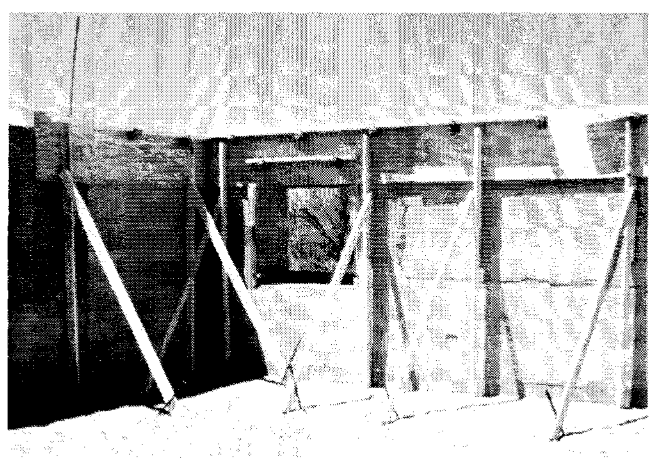

Fig. 6 Formation of bond beam on Gila residence

the clamps and checking for level and plumb. The cost of the earth materials imported to the site (sand and gravel admixture) was approximately $400, and the formwork cost $300 not including the pipe clamps which were already on hand. The formwork is re-usable, although it does suffer from contact with the tampers over time and the edges get rough. Some of the formwork was used in forming the bond beam; most was saved for the next house. As designed, the system works well for the single, low cost house. To build houses in greater quantities might involve staggering the phases of construction so that one component of the small Gila construction crew was always pouring footings while another followed and tamped walls, for example. The cost of plywood for new forms would have to be figured in for about every third house. The reaction of the Gila family, their neighbors and the construction crew has been strong and positive because of the resemblance to their traditional sandwich houses, in appearance, smell, and surface temperature. The second rammed earth house is already scheduled for construction by the trained crew, using the same soil mix and forms.

In summary, the cycle of research, building, research, and building has led from technical requirements to a powerful design and construction experience to an opportunity to use the results in service to the larger community. Research ideas, when pursued in the context of design/build opportunities, can escape from the paper upon which they are conceived. It is the research ideas that in the end make the design/build experience meaningful beyond the skills, design understandings, and human interactions that are the immediate benefit for students. The research contributions carry their impact past the design/build project that is isolated in time and space.

ENDNOTES

1 Easton, David. The Rammed Earth House. Chelsea Green Publishing Company, Vermont, 1996.
2 Webb, George Buzzing Feather. A Pima Remembers. University of Arizona Press, Tucson, 1959.
3 Gregonis, Linda M. and Karl j. Reinhard. Hohokam Indians of the Tucson Basin. University of Arizona Press, Tucson, 1979.
4 Easton, Robert and Peter Nabakov. Native American Architecture. Oxford University Press, 1989.
5 Van Willigen, John. Contemporary Pima House Construction Practices. The Kiva; Journal of the Arizona Archaeological and Historical Society, Inc. Vol. 36, Number 1, Fall 1970.

PHOTOGRAPHIC CREDITS

All photographs were taken by the instructor of the design/build courses and students involved in the design/build projects.