Digital Design-Build: Academic Practice as a Model for Industry Transformation

ROBERT CORSER
University of Kansas

Introduction

Advanced digital design tools linked to mainly the most sculpturally ambitious and high budget projects that take advantage of this approach to design and construction. Even as the technology becomes more affordable, its adoption by the building industry remains slow and rarified. A notable exception to this trend is in academia where almost every design school has invested in CNC fabrication capabilities. Yet even here much of the work focuses on speculative projects that rarely transcend their obsession with non-rectilinear form. A few schools however, are testing the impact of these new technologies in more real-world scenarios. One example is the digital design and construction of a shade pavilion system for deployment in public spaces in New Orleans. This paper is a case study illustrating the potential for new technologies to transform design practice as evidenced in the shade pavilion project.

Although the cost of new digital technologies is dropping, they still represent a considerable outlay of capital, and for the technology to flourish, the benefits offered need to transcend new formal or sculptural possibilities. Other potential advantages include: a more streamlined design process with the opportunity for more testing and refinement cycles; the 'front-loading' of material and fabrication issues during the earliest design phases; faster and more accurate construction; more efficient use of materials and limited construction budgets; and high levels of dimensional precision necessary for complex pre-fabricated systems. numerically controlled fabrication began entering building design and construction in the early 1990's. Still today, it is These advantages contribute not only to successful construction outcomes, but crucially in academia, they add significant value to the educational experience.

The shade pavilion project grew out of the desire by students and faculty to respond to Katrina's devastation of New Orleans. This coincided with the faculty members' interest in testing new digital technologies and pre-fabrication strategies in a design and construction process that separated the clients and the designer-fabricators by over 1000 miles. The location of the project was New Orleans' historic but economically troubled 7th Ward. Inland from the French Quarter and adjacent to the devastated 9th, the 7th Ward was built largely by the city's renowned 'Creole Craftsmen' who worked collectively to build their own modest homes with similar architectural richness as the larger houses they were hired to construct elsewhere in the city. The project's client was a newly forming neighborhood group called *The Porch Cultural Center.*

The design-build team consisted of two studios taught separately, but focusing together on a project for *The Porch*. Early discussions generated a proposal to construct a neighborhood resource center consisting of a tool lending library and an adjacent shade pavilion for outdoor work and meetings. The clients also expressed the desire for numerous smaller interventions throughout the 7th ward. Because *The Porch* could not secure a permanent site quickly, it was decided to pursue a more modest intervention to rehabilitate a dis-used community garden site. The finished product would consist of a tool shed, product of the 4th year studio, and the shade-pavilion by the 3rd year students.

The tool shed was built of welded steel frames with plywood infill panels, and employed traditional hand fabrication for all elements except for the decorative patterns cut digitally into the faces of the panels. The shade pavilion was designed as a framing system capable of being easily enlarged or adapted to other sites. It was prototyped digitally and constructed as a framework of interlocking CNC cut laminated plywood members. Steel for the pavilion's base plates along with its custom acrylic roof shingles were also cut directly from digital files. Although the tool shed provided useful points of comparison between digital and manual modes of design and fabrication, this paper will focus primarily on the shade pavilion because of its intensive use of digital technologies.

Design and Prototyping

Design of the shade pavilion began with studies of vernacular Afro-Caribbean structures and joinery. Particular attention was paid to the complex bracing of roof trusses in 18th and 19th century Louisiana houses like the Bywater Mansion. Students were also asked to research reciprocal, self-supporting geometries called “nexorades” as an abstract, and more contemporary foil to the historic precedent. The requirement was to develop a system of relatively simple members that could be fabricated out of typical flat sheet materials, transported in stacked panels, and erected using only hand labor and simple tools. As a further challenge, their design was to be capable of being easily extended: the “seed” of an expandable entity.

Working in groups of four, the students developed and tested multiple approaches using computer modeling and laser-cut scaled models. Among the design directions to emerge from this study was an intriguing slot-and–tab structural cladding arrangement of interlocking plywood sheets. By offsetting the plan alignment of slots and tabs, and stressing the panels with thru-bolts, the resulting plywood surface achieved a structurally stable double curvature. Although this system created a compelling surface form, the students could not develop a convincing structural framework or deployment strategy, and the idea remains a compelling study in woven form-making. (Figure 1, top)

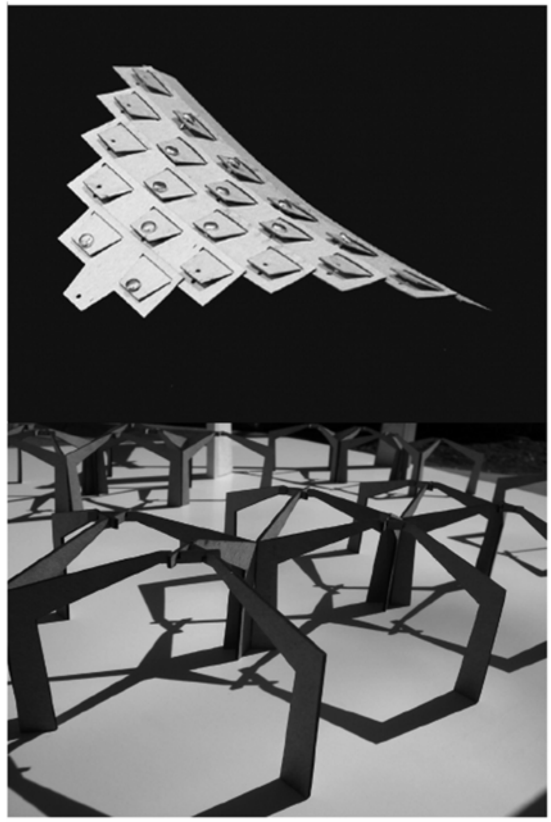

Fig. 1. Digital prototypes for cladding and framing systems.

Another group developed a framework composed of an asymmetrical three-pin arch made self-supporting by doubling one of the members to form a tripod. Through simple combinations of two basic module sizes, this system could sponsor numerous and interesting variations. The cladding approach researched by this team focused on acrylic panels and their design eventually incorporated a mortise-and–tenon system of purlins to accommodate different panel sizes and multiple angles between roof surfaces.
The major drawback of this system was the complexity of the “pin” blocks necessary to connect the laminated plywood arch frames at consistent angles. A third group took a similar approach, but their layouts were more geometrically regular. This system featured identical frame elements that were fully slotted to interlock in radial arrays. (Figure 1,

bottom) Difficulties arose surrounding the necessity of angling the slots in plan, and in the difficulty of assembling larger organizations around multiple vertical legs.
The fourth group developed a system of interweaving, L-shaped spanning frames, supported asymmetrically along one side by 'V' shaped columns. This framing system was simple to construct out of very few discreet elements and proved to be extremely stable structurally. The cladding scheme explored by this team was a complex triangulated arrangement of sprung plywood shells held in place by slots and tabs. Although formally compelling, this cladding approach created problems with creep in the stressed tabs and the need to weatherproof both the slots and the seams between shells. A further limitation of the framing scheme was that it could only reasonably be extended in a linear fashion. Still, the simplicity of the framing members and connections, combined with ease of erection and the framework's overall stability made it the chosen starting point for further development by the entire studio group. (Figure 2)

Design Development

Refinement discussions focused on several areas: the overall dimensions and modularity of the design, the structural capacity of notched or mortised main structural elements, and the cladding strategy. By assuming relatively flexible connections for the cladding system, damage from potential bending deflection would be minimal, and the framework was analyzed for shear stresses only. Structural loads were calculated using hurricane wind speeds, and members were sized using a maximum shear stress capacity for plywood of 110 psi. Because the total shear capacity of a member is a function of its cross-sectional area, all members were sized according to their smallest points, i.e. at notches and mortises. As loads were transferred from the cladding to the main framing members, it became clear that interlocking these with full notches would double the total required cross sectional area. Preliminary calculations indicated that unacceptably bulky members would result, and the first major design modification was made replacing the interlocked crossing frames, with a series of parallel, L-shaped frames on six foot centers, connected by rafters and bracing elements.

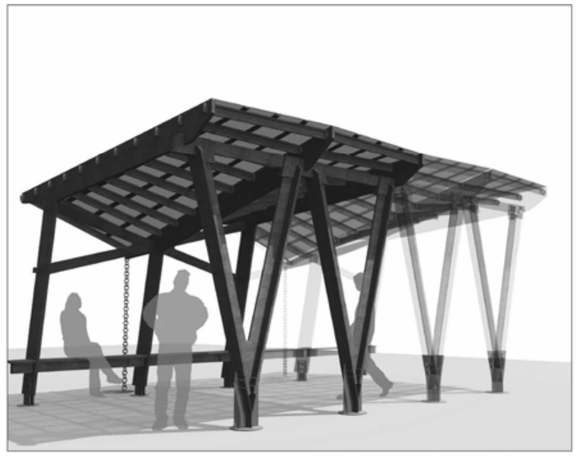

Fig. 2. Digital rendering of chosen scheme, showing potential for additional bays to extend the module

Another area of re-design was the overall shape and slope of the roof. Alternatives to the original mono-pitch design were explored and a system of alternating flat and angled main framing members was tested. This system allows the roof to transform from horizontal ridges on three sides to a rhythm of peaks and valleys along the fourth. Connecting these alternating main framing members with straight sub-framing rafters results in a subtly curving hyperbolic paraboloid surface form. (visible most clearly in Figure 3, top)

Cladding this surface requires sheets of material that can be slightly twisted from corner to corner. The smaller these 'shingles' could be, the less severe this twisting would be on each piece. A large number of 10 inch square aluminum panels were donated by an aircraft company, and tests confirmed that they could easily accept the twist. A cladding layout was established with fasteners set on 9 inch centers, allowing shingles to overlap by ½" on all sides. This generated a layout of delicate purlin strips at 9" on center supported by slender rafters spaced every 18 inches spanning between the main frames. Materials tested for the remaining cladding included un-painted aluminum and acrylic. The final cladding design combines both painted and clear-sealed aluminum panels and white translucent acrylic panels. Another important benefit of the small size of the shingles was that all of the acrylic panels could be precisely cut, including holes for mounting, using the computer driven laser cutter.

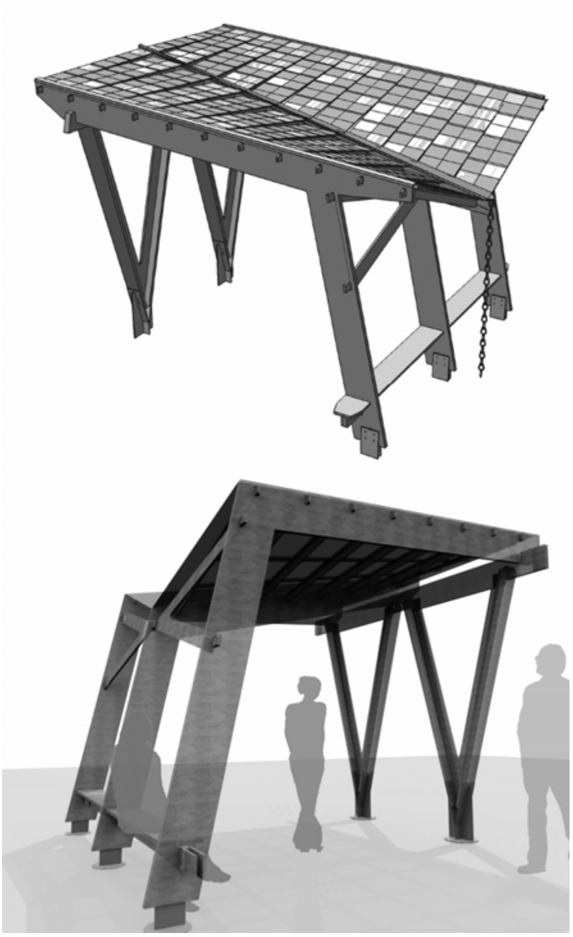

Fig. 3. First proposal (below) refined to add roof overhang and rain-chain (above).

Client Feedback

Preliminary digital models were used both to render images of the design and to construct scaled plywood prototypes employing the laser cutter for speed and accuracy. Rendered images were useful for both the design team to better understand the project, and for the client to evaluate the design and offer critical feedback. Their initial responses were quite positive but they expressed concern about the lack of a roof overhang at the rear edge over the built-in bench. (Figure 3, bottom)

Adjusting the design to include a rear overhang resulted in an overall covered area for a single bay of the system (consisting of 3 frames) of 12 feet wide by about 16 feet in depth. The scaled prototyping using the laser cutter not only revealed issues of assembly, but also the complexity of laying out and nesting together multiple parts so that they could most efficiently be cut out of rectangular sheets of raw material. The addition of the rear overhangs greatly complicated the layout of the sheets. Through multiple iterations, a new layout was devised that minimized waste in the cutting of the plywood. The final design was again prototyped in a physical model at a scale of one and a half inches to the foot, and renderings were generated for client approval. (Figure 3, top)

Fabrication

The design and prototyping process required 6 weeks of work, with the majority of time being spent on the initial generation of ideas. Once the overall direction was decided upon and detailed development began, the final design was fixed within 2 weeks, including one week dedicated to client feedback. Because students were working with accurate digital prototypes, issues like assembly, material thicknesses and fabrication strategies emerged early in the design development phase, and the transition from design to fabrication was both smoother and faster than with traditional approaches. Still, there remained a number of crucial issues to resolve including lamination strategies, finishes and dimensional tolerances.

Material research and testing led to the selection of exterior grade A/C Super-Ply from Roseburg Forest Products for the visible outer faces of all laminated members. This material features a high quality hardwood veneer on one face and is made with durable exterior glue. For economy, standard BB exterior grade plywood was selected for use on internal lamination layers that would not have a visible face. Layout of the CNC cutting patterns for the final fabrication was derived directly from the layouts used to make the laser-cut prototype models. The patterns however needed to be adjusted for two important factors: the distinction between inner and outer (veneer) faces of the plywood, and the necessary tolerances of slots and mortises. Careful attention was paid to the mirroring of pieces so that they would be cut with the veneer layer on opposite sides of the final laminated members. Once the parts were mirrored, new sheet layouts were developed to insure that the parts nested together efficiently on the 4 by 8 foot plywood sheets.

Once the final materials were selected and test assemblies made, exact as opposed to nominal dimensions could be used to refine the widths of slots and mortises. For example, the nominal 3/4" super-ply was measured to be actually 19/32" thick. Although this might seem like a negligible amount, when members are made up of as many as 6-layers of plywood, the actual thicknesses quickly become quite important. (Figure 4) Further, allowances for glue between layers, and the thickness of the two-coat weatherproofing finish needed to be taken into account to arrive at joints that would be snug, but workable. Full-scale mock-ups, especially of the thickest members, resulted in dimensions that could confidently be used for slots and mortises, with additional tolerances added for workability. This precision and the elimination of guesswork or generalized estimation is a hallmark of digital fabrication that makes it more akin to industrial manufacturing than traditional on-site construction.

Another aspect of the lamination process revealed by the full scale tests was the need for guide holes to be cut in the corners of all pieces, allowing for the insertion of a wood dowel to insure accurate alignment of all laminated layers during the gluing and clamping process. Without these guides, it proved quite easy for pieces to become mis-aligned and require either re-working to clean up edges, or worse, re-sawing to open up the required clear space in slots and mortises. Before fabrication could begin the CNC sheet layouts were adjusted one final time to allow for enough clear space between parts so that the router bit could pass through cleanly. A decision to use faster moving 1/2" diameter bits for all outside cuts resulted in a minimum spacing of 1-1/2" between parts and a minimum distance of 1" from the edge of parts to the edge of the plywood sheet. Smaller 1/4" bits were used for all inside cuts: slots, mortises etc, in order to leave the smallest possible leftover radius in the corners.

It is important to note at this juncture that a traditional set of working drawings was not produced for this fabrication process. Instead, the digital model itself was refined and its profiles adjusted for export in a format suitable for digital fabrication. What was necessary graphically was a schematic

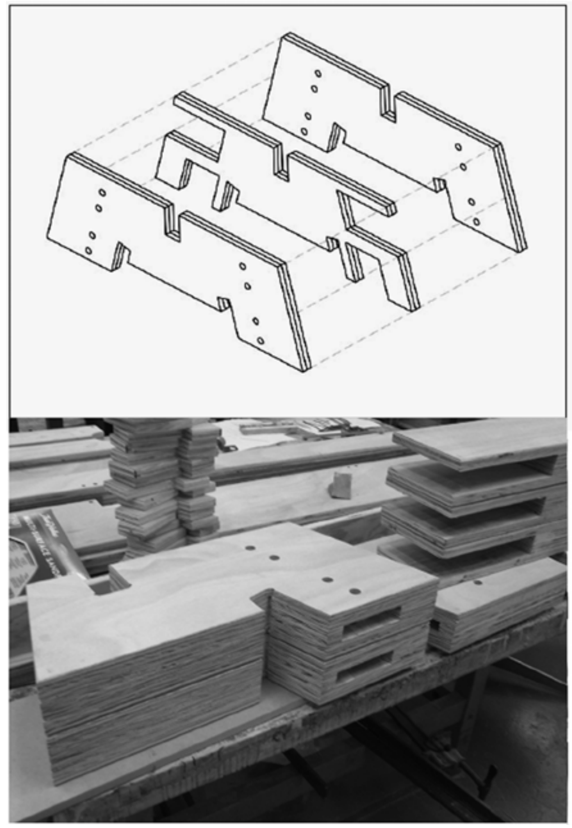

Fig. 4. Complex laminated plywood blocks.

illustration of the layering of pieces, especially given that some individual members of the pavilion's frame were laminated out of as many as six or eight layers. (Figure 4)

It was also crucial to name and number all parts in a coherent manner so that someone working on the gluing-up of a member could know exactly what piece to put where. Additional diagrams and views of sub assemblies and the final assembly process were also produced. These proved quite helpful in the fabrication of the steel base plates, especially the complex "V" shaped assemblies for the front columns. Lacking CNC steel cutting facilities, the students turned to a professional fabrication shop that donated both materials and time on their CNC plasma cutter. Again, diagrams were produced for information and to elicit feedback from the steel fabricators, but the actual exchange of dimensioned information for fabrication was directly from the digital model to the digital tool.

By far the most time consuming aspect of the pavilion's fabrication process was the gluing, sanding and finishing of the individual parts. Still, given the fact that the students participating in the project had almost no prior carpentry or construction experience, this process proceeded smoothly and with few errors, due in large part to the fact that the exact layering process had been prototyped at various scales and documented in clear assembly diagrams. Simultaneously, more than 100 acrylic roof shingles were cut, complete with screw holes, using the laser cutter, a device usually used only for scaled modeling and prototyping. Once all pieces were cut, laminated and finished, a complete test assembly was performed behind the school of architecture building. Although several tenons had to be shaved down for easier insertion in the mortises and a few bolt holes needed re-drilling, no other dimensional discrepancies were encountered.

Test Assembly

The test assembly also confirmed early expectations that assembly of the frames in a "kneeling" position would prove both feasible without temporary bracing and a convenient and safe situation for installing the cladding shingles without the need for scaffolding or extensive work on ladders. This is important given that the fully erected height of the pavilion ranges from 8 feet at the lowest point of the gutter up to almost 12 feet around the other three sides. Once the shingles were all installed, aluminum flashing and gutters were measured and fabricated for later installation in New Orleans. The final trial for the test assembly was the choreography required for the pavilion to be tilted up from its kneeling position and set on its front V-columns. Although we had calculated the weight of the pavilion and the force required to rotate it, everyone was surprised at how easy the tilt-up process proved in actual practice.

Another important benefit of the dimensional precision with which the pavilion was fabricated was the ease with which it was dis-assembled for shipment. If tenons had had to be hammered or forced into or out of place, this process would have been much more difficult and potentially damaging. Since the sheer number of shingles made their installation quite time-consuming, the team decided to leave them attached to the purlins and rafters, and to dis-assemble the roof in four large sections. The main frames were unbolted and their 3 layer scarf joints were slid apart for packing. Ultimately all of the parts for a single bay of the pavilion were able to be stacked flat and packed into the back of a standard sized cargo van.

Installation

Once on site in New Orleans, the scarf joints were re-assembled with glue between the layers, and bolts were installed to hold the layers together while the glue dried. Strings were set for alignment of the legs, and holes were dug for foundations. For simplicity, the base plates were not designed as adjustable two part systems, but rather as simple post bases set in place with temporary bracing while concrete was poured around them in formwork consisting of plastic buckets. Once the foundations were set and the main frames assembled, it took only a single day for the re-assembly and raising of the pavilion. Final foundation bolts were secured in pre-drilled holes and the project was capped off with the ceremonial installation of the rain chain at the end of the gutter.

Conclusion

The shade pavilion element of the Porch community garden was completed on May 6th 2006 after only two days of on-site installation. Total material expenditures were approximately $ 2500, and calculations of material usage indicate that less than 10% of plywood surface area was left over as waste.

Fig. 5. First complete shade pavilion installed in New Orleans community garden.

The entire project was a half-semester, or roughly eight week assignment. Studies of precedents and potential framing systems took about 4 weeks, and after little more than a week of refinement work, the final design was prototyped, fabricated and installed in approximately three weeks.

This compressed timeline was only possible because of the efficiencies of digital design and fabrication. More important than efficiency though, was the accuracy and repeatability of CNC fabrication that made it possible to produce complex framing elements made up of numerous laminated layers. Even with pattern blanks to follow, cutting these layers with hand controlled power tools would have been nearly impossible to accomplish with sufficient accuracy or speed. Certainly, the student's level of ambition in terms of the number and complexity of the slots, mortises and tenons used in the design would have been greatly limited by the prospect of laying out and cutting them by hand.

This project, designed and fabricated by third year architecture students, illustrates many potential benefits of digitally integrated design-build practice, including:

- More design and refinement cycles
- Front-loading of material and fabrication issues in the design process
- Ability to quickly respond to client feedback, even when well advanced in the design development process
- Greater ability to test and verify material and assembly conditions before fabrication
- More of a "manufacturing" approach featuring pre-fabrication and assembled systems
- Higher quality and faster production with less manual labor
- Greater material efficiency leading to less waste and lower costs

The shade pavilion differs significantly from many contemporary applications of digital technology that usually focus on *what* new physical forms are possible rather than on *how* new approaches to building can emerge. In the tradition of master-builders, issues of construction were brought into the design process from the very beginning: a benefit of digital design that is often suppressed in more formally speculative projects. By recuperating aspects of a traditional language of joinery, made possible through laminating complex CNC-cut layers of plywood, the New Orleans shade pavilion illustrates a more tectonically grounded example of the new forms of practice emerging from the convergence of digital design and CNC fabrication.