VERSIONING:
Design and Fabrication of a Flat Pack Emergency Shelter

ROBERT M. ARENS
Cal Poly San Luis Obispo

EDMOND SALIKLIS
Cal Poly San Luis Obispo

ABSTRACT

This paper discusses the development of a rapidly deployed emergency shelter by an interdisciplinary team of faculty and students from the Department of Architecture and the Department of Architectural Engineering at Cal Poly San Luis Obispo. The authors saw this project with its equal emphasis on design, assembly and production as the perfect opportunity to apply the concept of versioning, a strategy that borrows heavily from the disciplines of industrial and packaging design. Versioning utilizes digital tools to combine form finding, the assemblage of materials and the means of fabrication in a single feedback loop that informs multiple iterations. Similar to rapid prototyping, versioning moves the design process towards a system of vertical integration whereby the designers drive how space is both conceived and constructed. This paper discusses the methodology of versioning and positions it within the larger concept of design intelligence. It then looks at it's application to the design and fabrication of four generations of prototypes used to develop a flat pack emergency shelter. Finally, the authors speculate as to whether this methodology could be expanded into a pedagogical model for interdisciplinary design studios for architects and engineers focused on small, community-based, design-build projects.

KEYWORDS

collaboration, construction, design, design-build, fabrication, pedagogy, public engagement

Figure 1: Erection sequence of the flat pack emergency shelter (version 3).

INTRODUCTION

In 2009 the authors of this paper, an architect and a structural engineer, were presented with a grant-supported project to develop the prototype for an emergency shelter that could be mass-produced inexpensively and rapidly deployed to disaster relief sites. A seeming simple project wrapped in multiple shrouds of complexity, the project demanded that we not only design an object, but also devise the process for its production, determine how it would be constructed and sourced, identify the most efficient assembly sequence, and outline a strategy for the shelters' distribution. We quickly realized that this unique project: 1) Is of a scale closer to product design than architectural design thus requiring a different way of thinking than the traditional design and delivery method; 2) Had an equal emphasis on design and execution and was the perfect opportunity to work across disciplines and leverage technology to prototype our ideas at full scale; 3) Was an opportunity to apply technology so as to promote technique rather than image thus de-emphasizing architecture as a stylistically driven product; and 4) Could involve a small group of students and become a scalable pilot study for a potential studio pedagogy.

The authors saw in this unique project the opportunity to employ the strategy of versioning, a tactic that relies more on prototyping than representation. Through the use of technology, the team would attempt to both expand the possibilities of design and create a true integration of the process of construction.

THE CONTEXT OF VERSIONING

Design Intelligence

In the early 2000s discussions surrounding architecture began to subtly shift from what was being designed by 20th century vanguard architects towards how 21st century post-vanguard practices implemented their projects. Observing the shift at the time, Michael Speaks wrote, "If philosophy was the intellectual dominant of early 20th century vanguards and theory the intellectual dominant of the late 20th century vanguards, then intelligence has become the intellectual dominant of 21st century post-vanguards. While vanguard practices are reliant on ideas, theories and concepts given in advance, post-vanguard practices are more entrepreneurial in seeking opportunities for innovation that cannot be predicted by any idea, theory or concept."[1]

The intelligence and innovation that differentiated the post-vanguards from the vanguards were not in the traditional realms of theory or concepts, but in the realm of materials and construction, realms that had been ceded by architects to specialists in separate fields. The depth of the problem was noted by Kieran and Timberlake who write, "The single most devastating consequence of modernism has been the embrace of a process that segregates designers from makers: the architect has been separated from the contractor, and the materials scientist has been isolated from the product engineer."[2] The post-vanguard practices had engaged technology, specifically parametric modeling and digital fabrication, and used it to integrate design with construction, thus becoming active collaborators in the entire process of architectural realization.

The term that Speaks coined to characterize the operative attitude of this new crop of architects was design intelligence. Speaks writes, "Design practices with high design intelligence quotients are able to manipulate the problem given to search for opportunities that can be exploited, thus allowing for a greater degree of innovation. Such practices also view design as dynamic and non-linear, and not as a process with a beginning, middle and end. Accordingly, the relationship between thinking and doing becomes more and more blurred so that thinking becomes doing and doing becomes thinking, engendering highly collaborative, interactive forms of practice that are already changing the face of architecture."[3]

From Horizontal to Vertical Integration

The methodology that Speaks refers to, i.e. a non-linear process that incorporates testing to create a feedback loop, has long been the cornerstone of many design disciplines, particularly those that develop prototypes prior to high-yield production. More recently, a shift by architects to a similar methodology has begun to drive innovation and, in turn, design intelligence. This methodology, called versioning by some, is enabled by the adoption of new technologies that are moving the discipline from pixel-based representation to vector-based prototypes. Coren Sharples of SHoP Architects writes, "Versioning can be seen as an attitude rather than an ideology. It allows architects to think or practice across multiple disciplines, freely borrowing tactics from film, food, finance, fashion, economics and politics for use in design, or reversing the model and using architectural theory to participate in other problem-solving fields." She continues, "Versioning implies the shifting of design away from a system of horizontal integration (designers as simply the generators of representational form) towards a system of vertical integration (designers driving how space is conceived and constructed and what its effects are culturally)."[4]

The authors saw the emergency shelter project as the perfect opportunity to test the concept of versioning as a design/fabrication methodology. If successful, the forces that shape the shelter, the assemblage of materials, and the means of fabrication would be joined in a single feedback loop that would inform multiple iterations. Our hope was that the design intelligence gained from our form of versioning would propel the project into unforeseen directions.

THE CONTEXT OF THE PROJECT

Sheltering With An Extended Purpose

National and international headlines regularly point to the alarming frequency of natural disasters. Even a cursory glance at statistics compiled by international agencies reveals the extreme costs in human life and the enormous social and economic toll of these disasters. Recent data indicate that of the 245 disasters reported in 2009, 224 were weather related accounting for 55 million people affected, 7000 killed, and US$15 billion in economic damages. Worse yet, the frequency of natural disasters spiked dramatically in the 20th century, a trend that is likely to continue. [5]

The team chose to respond to the need for post-disaster relief due to the increased frequency and severity of natural disasters. Although there are many areas for consideration (medical attention, food and water supply, infrastructure, etc.) the combined expertise on our team led us to focus our effort on what is commonly referred to as sheltering, that is providing basic shelter for persons displaced due to the loss of their permanent housing.

As context, disaster officials, such as the Federal Emergency Management Agency in the United States (FEMA), view post-disaster housing in three ways: sheltering, interim housing and permanent housing. Sheltering refers to basic protection employed for short periods of time until the disaster subsides and the displaced population can return to their permanent dwellings. Interim housing refers to situations where permanent dwellings have been destroyed or rendered uninhabitable by serious disasters thereby necessitating temporary structures for displaced populations to occupy for extended periods (generally up to 18 months). Permanent housing refers to long-term structures used as permanent residences following natural disasters; these may be habitable or repairable existing structures that displaced populations return to, or may be replacement housing intended to take the place of structures rendered permanently uninhabitable.[6]

Due to complex and overlapping factors, the line between these three types of housing is often indistinct. Major factors such as the severity of many disasters and the shortage of resources (funding, labor, materials, etc.) contribute to secondary factors such as extended clean-up periods and the inability to repair or replace existing housing stock. Consequently, sheltering constructed of temporary materials is soon pressed into service as interim housing inhabited for years not months, a period well beyond the length of its intended life. Worse yet, most sheltering, if forced to function as interim housing, reaches the end of its useful life before permanent housing can be provided. Although ti would present a great challenge, we felt it was absolutely necessary to design a shelter that would address rather than ignore this troubling reality.

The Project Goals

Given the harsh reality of sheltering, namely that it is often used for interim housing in settings where the resources to replace it with permanent housing are limited, the team crafted the following set of goals for the shelter design. The goals address both short-term considerations of producing and providing a viable shelter, as well as longer-term considerations of the shelter's re-use in other locations or re-purposing in terms of permanent housing:

Efficiency: The design should employ materials that conserve natural resources and reduce waste. Additionally, the design should minimize labor during both the creation and erection phases of the shelter.

Lightness: The design should avoid excessive weight that would waste fuel during the shipping phase or human labor during the erection phase of the shelter.

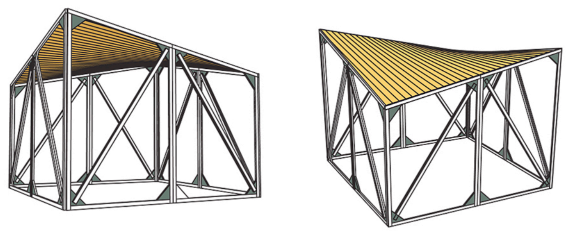

Figure 2: Digital model of a hypar-inspired approach to version 1.

Figure 3: Test samples of composite material subject to ultraviolet exposure.

Packability: The design should avoid redundant parts, and the shipping crate should have a compact footprint to facilitate shipping.

Constructability: The design should employ a limited number of components with simple connections that can be constructed with basic tools and little labor. No ladders or scaffolding should be necessary during the erection phase.

Adaptability: Since disasters can occur anywhere and everywhere, the design should be adaptable to a wide range of climates. Therefore, the design should employ a combination of both universal components and climate-specific components.

Reusability: The design should promote either the re-use of the shelter at other disaster sites, or the re-purposing of the shelter's components and/or materials in rebuilding efforts of permanent housing.

VERSIONS OF THE SHELTER

Version 1: Exploring Materials and Methods

Our initial version of the shelter was a testing ground for its size and proportion, as well as the use of modularity and a composite material that had captured our imaginations. Sketches and a digital model were used to guide the construction

Figure 4: Version 1 built at half-scale using composite materials and plastic sheeting.

of a quick and crude half-scale prototype (see fig. 4) that explored the use of standardized composite elements configured into eight simple diagonally-braced frame modules and joined together to at their edges to establish the body of the shelter. The frame, once established, could be clad with a variety of materials with our initial test exploring the general the use of inexpensive plastic sheeting.

The composite material (which has not been extensively tested or used commercially) was selected for its potential as a strong and sustainable material with the promise of wide architectural application. Its matrix is comprised of polypropylene reclaimed from obsolete irrigation tubing used in agriculture and destined for the landfill. The fibers that lend the material its tensile strength are harvested from kenaf, an inexpensive and fast growing plant from the hemp family. Materials Engineering students conducted tests on the composite using an accelerated aging chamber to assault the composite material with UV light in order to assess the bending stiffness of the material as a function of UV degradation. Architectural Engineering students performed dozens of axial load tests and shear load tests to gather a body of data that was developed into a model that can accurately predict the strain of this material given a state of stress. Ultimately this material was determined to be too dense and heavy to meet our objectives of lightness and packability, but our testing added to the body of knowledge (design intelligence) on this interesting material

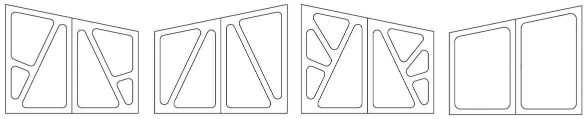

Figure 5: Wall panel configurations A-D (l to r) tested in version 2.

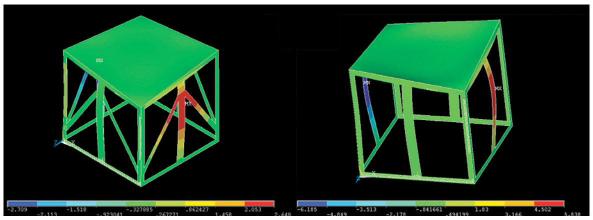

Figure 6: FEM analyses of B-type panels (l) and D-type panels (r).

that may eventually find its way into the architectural lexicon.

In addition to our realization regarding the composite material's excessive weight, version 1 clarified several key factors of the design which would influence version 2. First, given the complexity of the mechanical connections we'd have to consider one-piece panels rather than built-up frames as wall structure. Second, the floor element, initially thought to be the shelter's simplest component, held the potential to serve an important dual purpose as a shipping crate. Version 1 ultimately became a valuable tool for assessing appropriate materials and construction methods to support our project goals.

Version 2: Expanding Our Options

We began version 2 with two major decisions informed by version 1: we would test our ideas at full scale and consider alternate materials. Working at full scale would be the best way to gather valuable feedback regarding space, structure, materials, assembly, packability and production. Shifting our material choice away from the PP/kenaf composite to the use of plywood would allow us to work with a readily available material which had a similar strength profile but lighter weight.

Since efficiency and constructability were two key project goals, the dimensional module of plywood in the US (48" x 96" x 0.625") became a key formal and proportional determinant. Thus the shelter was designed as a 96" x 96" spatial module, with the floor consisting of two 48" x 96"

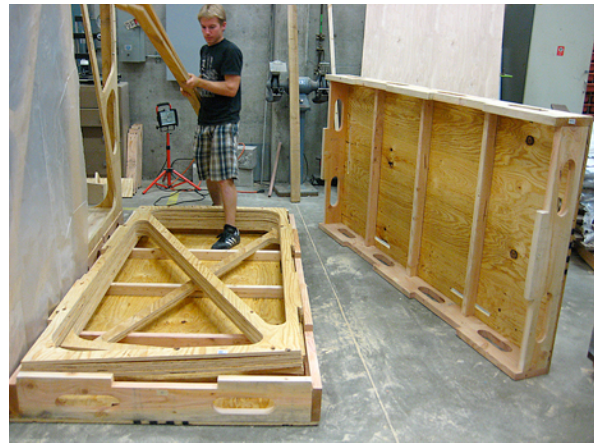

Figure 7: Floor panels are designed to serves as the shelter's shipping crate.

modules and each side panel (8 total) being a maximum size of 48" x 96". To take advantage of digital design and fabrication capabilities, all plywood panels were modeled using Rhinoceros software and cut using a computer numerically controlled (CNC) router with Rhinocam as the interface. The introduction of digital fabrication at this stage not only allowed our work to be more precise, it also allowed us to study possible high production methods that could be used to fabricate the shelter components in bulk.

Also tested in this prototype were floor designs that could also function as packing crates (see fig. 5), friction joints requiring little or no hardware, and plastic or tyvek sheeting used as cladding materials. Four variations of wall panel configurations, all designed with weight reduction and stiffness in mind, were tested in the prototype (see figs. 5). The variations were extrapolated into four distinct finite element models and analyzed using ANSYS software. The deformation shapes were quadratic in both in-plane directions. Loads on the shelter were estimated since we had yet to determine the design wind load: we used a lateral wind load of 958 Pa distributed to one wall, and a load of 479 Pa uniformly distributed downward on the roof.

The FEM analysis was critical to our decision-making. Since panel D (see fig. 5, far right) exhibited significant deformation while panels A, B and C showed little, it allowed the team to choose the lightest and simplest design, panel B (see fig. 6, second from left), on which to base

Figure 8: The exterior of version 3.

Figure 9: The interior of version 3.

the next prototype. Stresses were low in all four configurations, thus they were of little concern.

Version 3: Synthesizing Our Outcomes

Our objectives for version 3 (see figs. 1, 8-9) were to optimize the structural frame, explore cladding options, and refine the design's details, especially those pertaining to the interlocking joints and the floor/crate clamshell.

On the surface, the shelter's floor was the simplest component of the structure, but its dual role as floor and shipping crate made it a challenging design/fabrication problem (see fig. 7). As a floor, it was required to meet live and dead load requirements. As a crate, it was required to accommodate stacking and lifting while also being able to resist torsion. Finally, it would need to meet these requirements while being light and efficient. Drawing from versions 1 and 2, our design response for the floor of version 3 was to add a substructure for stability and strength, cut serrated edges using the CNC router to accommodate interlocking between top and bottom halves of the crate, and add holes to facilitate lifting, reduce weight and provide ventilation below the floor during use.

Physical prototyping and CNC technology allowed the team to refine the simplicity and effectiveness of the interlocking connections used for all aspects of the shelter. Relying on the precision afforded by digital fabrication, connections are mainly friction-fit allowing simple construction with few or no tools. This approach also reduced reliance on hardware, thus lowering the overall cost and weight of the shelter.

Having clad previous versions with plastic or tyvek sheeting led to concerns about its durability and its contribution as bracing to the frame. On version 3 we explored thin sheets of recycled corrugated polypropylene, a material that is light, strong, inexpensive and available in a range of translucencies. In addition to these favorable qualities its dimensions (48" x 96" x various thicknesses) corresponded to the plywood module used for the floor, roof and wall panels.

Figure 10: Honeycomb panels ready for testing in version 4.

Through prototyping we found that clear 4mm thick panels with scored openings for doors and windows worked well as wall cladding, while thicker panels of 6mm gray PP effectively braced the roof and reduced solar gain (see figs. 8-9).

NEXT STEPS

Version 4: Optimizing the Superstructure

The team believes the knowledge gained from the first three versions of the shelter have led to sound approaches for several but not all aspects of design/fabrication. The modular plywood base performs well as a crate during shipping, as a floor during use, and as generic construction materials for use in future rebuilding efforts. The friction-fit connections, enabled by precise CNC fabrication, reduce reliance on hardware and tools, and simplify field erection. The recycled corrugated polypropylene functions well as cladding since it is light, weather-resistant, inexpensive, durable and re-usable. The plywood superstructure used in versions 2 and 3, however, was strong and durable to a fault. Since their specialized shape would most likely preclude their use in future rebuilding efforts, we determined that the wall frames could be built of lighter, less durable materials. Even though the team had been influenced by packaging design in our approach to the floor/shipping crate, we looked even more closely at the packaging industry for insight into mass produced, yet stable structures with limited lifespans. This borrowing of tactics from other fields is embedded in the spirit of versioning which encourages working across multiple disciplines.

Our current focus is on kraft paper-faced honeycomb panels used as dunnage products by the packing and shipping industry to protect and secure merchandise. These panels have some of the characteristics that attracted us to plywood: they are panelized, modular, and are routable using CNC equipment. Their cross-sectional properties give the 48” x 96” panels (see fig. 10) a surprising strength-to-weight ratio, although panels will be nearly twice as thick (1”) as their plywood counterparts. This additional thickness will necessitate a slightly wider (and heavier) crate, but this additional weight will be offset by the lower weight of the paper panels themselves and a more efficient lifespan use of material. Cradle-to-cradle advantages should also occur: the paper cuts easily resulting in a shorter routing schedule at the front end, and even though they have a shorter lifespan the panels are easily recycled at the back end. A parallel design project is ongoing to find uses for the panel “voids” left over in the production process. Current investigations center on flat pack furniture to be supplied with each shelter or sold through retail outlets to fund relief efforts.

Open Source, Worldwide Distribution

Through the iterative process, the design team was able to distill the project down to three simple materials that are either left close to their original state (plywood floor panels and polypropylene wall cladding) or are shaped using digital fabrication (crate edges and superstructure panels). Our hope is that the narrow palette of inexpensive and simple materials facilitates their distribution and that digital fabrication facilitates their production and sets the stage for a number of potential production/distribution models.

An obvious approach would be to produce and distribute the shelters from a single location where materials and crated shelters could be warehoused until a disaster occurs and shipment is necessary. A more intriguing and cost beneficial model would be to stockpile a far fewer number of shelters and produce/distribute them on-demand from countless hubs located around the globe. In the case of the latter, partners with

CNC capabilities and suppliers of materials would be identified in strategic locations and engaged as part of a global network of shelter-providers ready and able to provide shelters from the closest point and hopefully quickest way possible.

CONCLUSION

"Can the forces that make the object, both in the generation of the broad strokes and specific resolutions, combine with an intelligence of fabrication to become a 'process product'?"[7]

On its most immediate level, this project provided an opportunity for our team of faculty and students from the disciplines of architecture, structural engineering, and materials engineering to work collaboratively to answer the "process product" question posed by Coren Sharples. Although our project is not complete, the authors believe that versioning, a methodology that uses digital tools to compress design, testing, assembly and production into a single process, has potential as a pedagogical approach with wider applications. Although full-scale prototyping and testing have limitations, the spirit of versioning—a collaborative, open model of problem solving with more emphasis on technique and less on representation—has its place in academia and could help to foster a climate of convergence between disciplines. Perhaps as reassurance, Sharples follows her question with "Here the form, the forces that shape it, and the assemblage of materials in which we execute the ideology are part of the same gesture. This is not a call to replace the human act of design with algorithms, but a critical search for a common language between design and execution."[8]

In the bigger picture, the design team saw this project as an opportunity to help distressed populations by applying our combined talents to the design of an efficient, economical, and environmentally responsible emergency shelter. Although the scale of global disaster relief is overwhelming (and trending alarmingly higher), the design of a short-term shelter that could be mass-produced was a challenge well suited to our combined disciplines of architecture and engineering. We recognize that emergency shelters have recently been the focus of many talented designers and that numerous innovative approaches have resulted from their efforts. In the spirit of design intelligence we see ourselves as part of this movement and hope to contribute to this expanding body of work.

ACKNOWLEDGEMENTS

The authors wish to thank the following students for their participation and valuable contributions: Kristin Akin-Zimmerman, Crystal Baez, Jorien Baza, Gustavo Bermudez, Christina Blattner, Ian Carney, Christine Carpenter, Katie Greenstein, Kathy Kao, Ben Hait-Campbell, Scott Leinweber, Tam Tran, Yang Wang and Ren Zhuong,

REFERENCES

[1] Speaks, M. 2002. "Design Intelligence: Or Thinking After the End of Metaphysics." *Architectural Design*. Vol. 72, No. 5.

[2] Kieran, S and Timberlake, J. 2004. *Refabricating Architecture*. New York: McGraw-Hill.

[3] Speaks, M.

[4] Sharples, C. 2002. *Architectural Design*. vol. 72, no. 5.

[5] See the United Nations International Strategy for Disaster Relief at www.unisdr.org.

[6] FEMA, 2008 Disaster Housing Plan.

[7] Sharples, p. 9.

[8] Sharples, p. 9.

Figure References

Figure 1-7, 10: Photo by author
Figures 8-9: Photos by Josef Kasperovich