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Rapidly assembled emergency shelters made from "green" materials

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Abstract

This paper describes a research project conducted by the Department of Architectural Engineering, the Department of Architecture and the Department of Materials Engineering at California Polytechnic State University. We are developing a habitable temporary shelter that is durable, sustainable, economical, and rapidly assembled. A basic, repeatable module of the design is a hyperbolic paraboloid (hypar) panel, generated from extruded straight boards of high density polyethylene (HDPE) reinforced with waste-stream agricultural fibers. Our research has shown that the hypar is well suited for a rapidly assembled emergency shelter because it can be generated from straight line segments which can be trucked to the disaster site. Then, using our proposed assembly method, a large span thin shell structure can be rapidly constructed.

The paper will discuss the fabrication and the testing of the "green" composite material used for these shelters. This composite material itself was the starting point for a number of design ideas. The uniqueness of the material; its stiffness, strength, and ecologically friendly nature spurred us into thinking about how we could incorporate it into structures. Before designing with this material, we addressed some of its mechanics issues, namely how could we characterize this material under tensile loads and under bending loads. Also, we performed a detailed study of how the material reacted to intense ultraviolet light. Having addressed the mechanics, we began the task of designing a structure with this material. We chose an emergency shelter as our design goal because we decided that an emergency shelter composed of hypar modules could be constructed from straight-line segments of this unique, extruded material.

Keywords: thermoplastics, constitutive models, composites, hyperbolic paraboloid, emergency shelter, design pedagogy

1. Introduction

In this paper we describe innovative research in the fabrication, modeling and structural use of thermoplastics reinforced with agricultural fibers. These organic fibers provide outstanding strength and stiffness to boards fabricated from this eco-friendly composite. We describe our initial research in the following areas:

- Industrial-scale fabrication of thermoplastics reinforced with agricultural fibers. We utilized materials engineering concepts beyond the bench-top scale to research the effects of short fibers and long fibers in the durability, strength and stiffness of manufactured boards.
- Experimental and computer modeling of extruded plastic/ag. fiber board performance. We used nonlinear constitutive models coupled with finite element techniques to accurately predict the response of this material to short term loads.
- Architectural and structural engineering design and analysis of habitable structures made from these extruded boards. Our prototype structure is an emergency shelter. Such a shelter will be durable, sustainable, economical, aesthetically pleasing and rapidly assembled. We also will discuss pedagogical issues surrounding this design process.

There are three research goals described in this paper. A unique aspect of this research was its interdisciplinary nature; we had a diverse team of researchers working on a large project, and each branch of the research affected the other team members. The first research goal was an investigation into industrial scale fabrication of a material made of a readily available plastic matrix, reinforced with renewable agricultural fibers. We were fortunate to work with commercial partners who were responsive to our needs and provided much technical expertise. The second research goal involved a team of researchers who studied the mechanics and the material properties of this material. Tension tests, bending tests and accelerated aging via ultraviolet light were conducted on this material. The third aspect of this research used architects and structural engineers who studied possible forms and details of an emergency shelter made from this material.

2. Three research goals

2.1 Industrial Scale Material Fabrication

One reason that natural-fiber thermoplastic composites are not typically used in conventional structural applications is because of uncertainties in some of their design values.

Figure 1. Extrusion process

Architects, when evaluating the suitability of various materials, typically refer to design strength and stiffness values as aids in their preliminary sizing of structural systems. And today, many such composites, (known generally as wood-plastic composites, or WPCs) do not have the strength and stiffness of structural timber. Yet environmental stewardship requires designers to consider sustainability in all their decisions. A design philosophy that holds sustainability paramount, coupled with the fact that high-quality wood members are becoming more and more scarce and costly, make alternative building materials an appealing and competitive choice for structural engineers and architects. WPCs can be extruded (Figure 1) and as manufacturing research progresses through its link to materials engineering, it is becoming possible to create an alternative building materials like our natural fiber/ thermoplastic composite that is:

- more consistent in properties than structural timber
- aesthetically appealing
- competitively priced
- environmentally responsible

Our preliminary research with natural fiber/ thermoplastic composites shows that we can obtain excellent structural properties, ones that are competitive with structural timber. Furthermore, the extremely low coefficient of variation of natural fiber/ thermoplastic composite boards gives the designer great confidence in the design values. It is interesting to see how a small coefficient of variation can radically affect the final statistically acceptable design values. Table 1 demonstrates this by illustrating the relationship between bending strength, variability in bending strength and the commonly used design strengths calculated for wood building materials. This design philosophy shows how a material with lower strength can compete due to its superior coefficient of variation (LRFD, [1]).

Table 1. Basic mechanical flexural strength (Modulus of Rupture)

Material	Modulus of Rupture (MOR)	MOR coeff of variation	MOR std. deviation	Design strength *
Loblolly Pine	88.2 MPa (12,800 psi)	25%	22.0 MPa (3,200 psi)	24.7 MPa (3589 psi)
ag. fiber/plastic composite	55.2 Mpa (8,000 psi)	4%	2.2 MPa (320 psi)	24.5 MPa (3559 psi)

* for wood design strength = (MOR – MOR Std. Dev.*1.645)/2.1

In traditional determination of design values for wood or other materials, stress-strain data are collected for both short-term loads and conditions (such as hurricanes, wind storms, snow loads, etc) and long term loading (self-weight, shingles on a roof over lifetime of the building, etc.). In modern composites fabrication we have the flexibility of designing a material for both long and short-term loads. For example, a composite material could be designed to handle short-term loads by incorporating short fibers in a matrix as well as to handle long-term loads by incorporating long-fibers in the matrix.

The extrusion process shown in Figure 1 results in uniform boards of any practical length desired. Boards up to 4.8 m (16 ft) lengths have been successfully fabricated. The ability to create boards of such lengths inspired us to design hypars generated from individual straight line segments. Yet the extrusion process naturally aligned the majority of reinforcing agricultural fibers along the axis of the board, resulting in an orthotropic material. Orthotropic because the perpendicular axis had somewhat less fibers in line.

2.2 Experimental Tests and Computer Modeling

Here we propose new advances in the modeling of the mechanical properties of this composite material. Such research is important if designers hope to incorporate non-traditional materials into structural roles. The modeling requires macroscopic studies of the alignment of the fibers in the plastic matrix. Modeling also requires experimental studies of the performance of the material when subjected to tension, compression, bending and to a lesser extent, shear. Our studies on this material show that it is nonlinear through its entire stress versus strain path. Advances made in nonlinear studies are significant because many composite materials are in fact nonlinear, i.e. doubling the load on a specimen causes more than a doubling of the deformation. We have used a bilinear approximation of this nonlinear behavior, which is extremely useful in finite element modeling of such material (Saliklis et al. [2]). Figure 2 shows such nonlinear stress vs. strain behavior and the bilinear approximate model for one formulation of our thermoplastic/ag. fiber composite material subjected to tension. Here, the initial Modulus of Elasticity (stiffness) from a tension test along the extruded board axis (x axis) is 4388 MPa (636,000 psi). Our research has mechanistically linked the response along the x axis (0˚ from extrusion axis) to the y axis (90˚ from extrusion axis). The primary advantage of this bilinear modeling is that we can readily incorporate it into finite element analysis programs. Such programs can accommodate highly nonlinear curves for isotropic materials (material properties identical in all directions), yet they must use a bilinear fit for orthotropic materials (three principal directions).

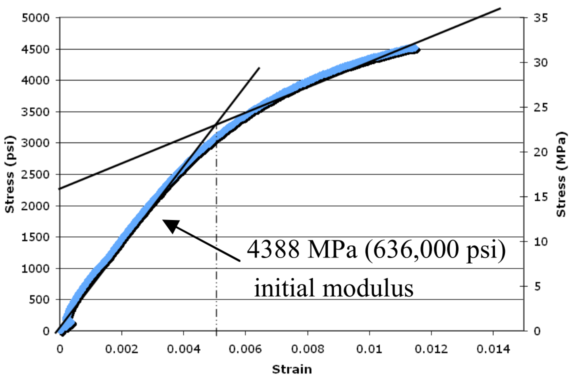


Figure 2. Nonlinear response, tension x axis

We have also conducted experiments studying how ultraviolet (UV) light affects the bending stiffness of this composite material. The purpose of these tests was to quantify the loss of strength that might occur if we used this material for a roof structure, a situation which clearly subjects the material to intense UV rays. We assaulted specimens with UV light for up to 2000 hours and then calculated the flexural modulus (modulus of elasticity in bending) using ASTM D790 (ASTM [3]) as shown in Figure 3.

We analyzed two formulation of thermoplastics, one was a homopolymer, the other a copolymer matrix. Figures 4 and 5 summarize our findings. Figure 4 shows an initial flexural modulus of 3737 MPa (542 ksi) with very little change over the course of 2000 hours of UV exposure.

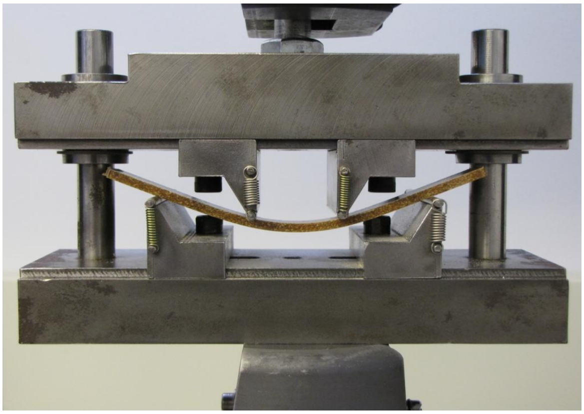
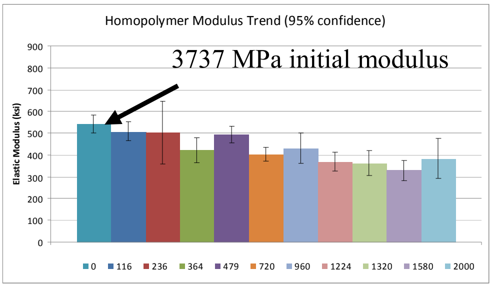


Figure 3. Bending test

For the copolymer, the initial (0 hours of UV) flexural modulus was 5277 MPa (765 ksi). Then there was a marked decrease in flexural modulus during the first 400 hours of UV assault, but after that, the effect leveled off. This is shown in Figure 5.



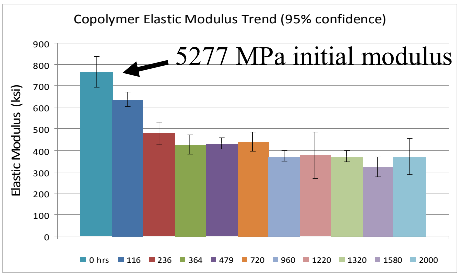


Figure 4. Homopolymer bending modulus **Figure 5. Copolymer bending modulus**

The bending modulus data is corroborated by results from other researchers (Lundin et al., [4]) Our conclusion was to safely assume the bending modulus of elasticity to be 400,000 psi (400 ksi or 2758 MPa) for design work. We still are in the process of exploring shear response and finalizing our bilinear approximations of this material.

2.3 Emergency Shelter Design Ideas:

The third overall goal of this project to design a prototype rapidly assembled shelter which can temporarily house people in response to a disaster. Our design uses the undulating hyperbolic paraboloid as a basic structural unit, and we used green materials to construct the shelter. We have used 3D modeling tools such as Rhino and the finite element program ANSYS (Fig 6) to experiment with form-finding. We also encouraged sketching and small wooden model making as a means of generating design ideas. Our design work is still preliminary, yet the ideas we have uncovered have arrived by linking the chain of:

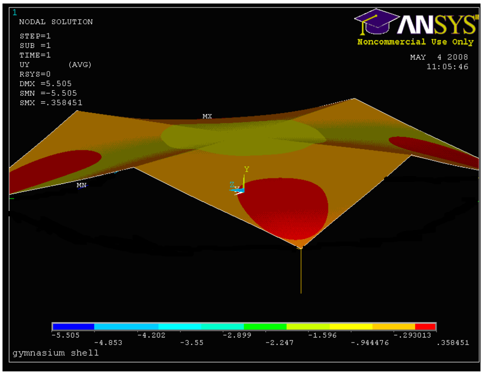


Figure 6. Finite element model

- industrial scale manufacturing
- material modeling and characterization
- 3D form finding

Our initial design idea explored the idea of a hypar roof generated from straight line extruded boards. The hypar roof would be supported by a very light, airy wall structure as hown in Figure 7.

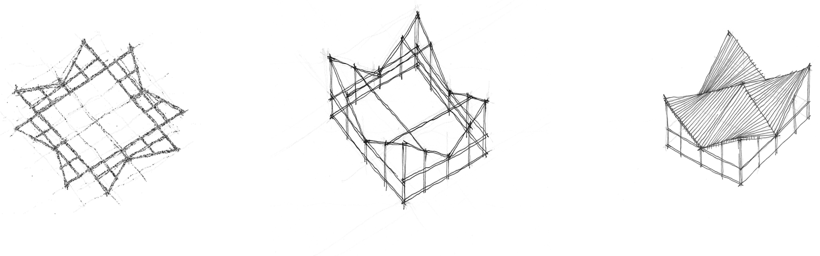
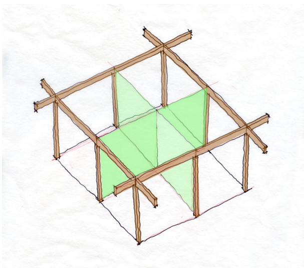
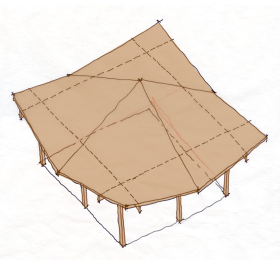
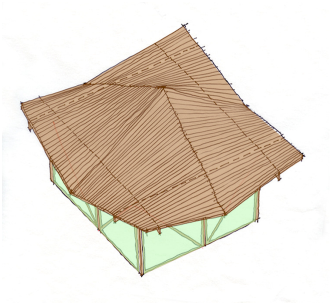


Figure 7. Preliminary shelter design







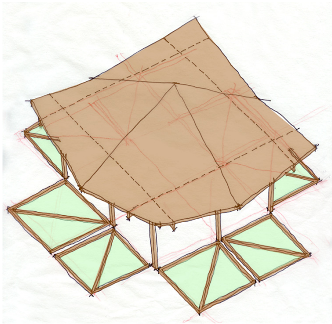


Figure 8. Second generation shelter design

We continued to explore the idea of supporting a hypar roof with thin segments, by adding additional thermal or weather envelopes on the walls, as shown in Figure 8.

Small scale model making exercises allowed us to explore the following scenarios. Either we prescribed the hypar with a straight "edge-beam" boundary as shown in Figures 6 7 and 8. Such a configuration would call for straight line thermoplastic/ag. fiber board segments of differing lengths.

Or alternatively, we could use uniform length thermoplastic board segments, and deal with a gap that is generated between hypar modules. These gaps provide interesting architectural possibilities for natural lighting, but of course, they pose new waterproofing challenges. Figure 9 shows four such modules made up of identical length thermoplastic/ag. fiber composite boards. One advantage of the hypar modules with the gap is that each module is constructed from identical straight line segments, providing some ease of construction. A dowel rod through the center of each modulelso aided rapid assembly. This dowel rod is seen in Figure 9.

Figure 9. Four hypars making up roof

Physical model-making coupled with virtual 3D models allowed us to progress towards a more refined roof design wherein we took advantage of the straight lines that run through the centerlines on the underside of each hypar module.

We called these “header beams” and they created ideal connection points for the interface to the wall system. Figure 10 shows a virtual model of the underside of a roof made of four modules. Each module has two orthogonal “header beams”.

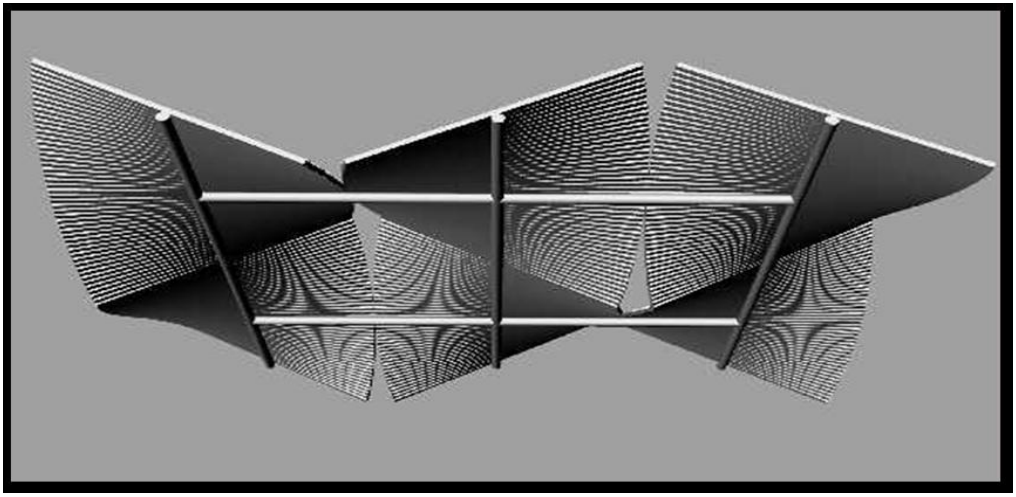


Figure 10. Virtual model of hypars resting on header beams

The possibilities of a gently pitched hypar wall module were also explored with virtual and with real models, shown in Figures 11 and 12. We are still researching the viability of such wall modules.

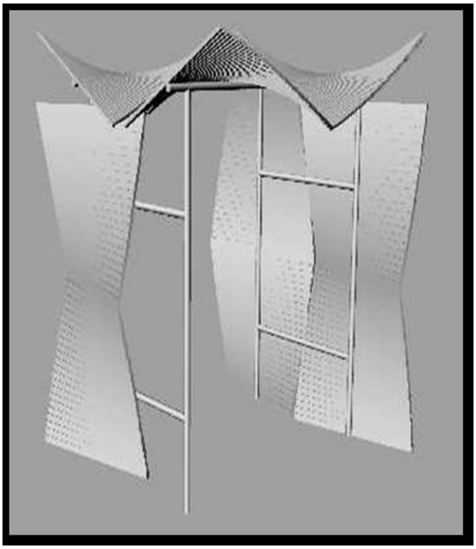


Figure 11. Virtual model with undulating walls

Figure 12. Physical model with undulating walls

Our current generation of models uses a unique property of the thermoplastic/ag. fiber extruded board. Because of its remarkable strength, as described in Section 2.2, we are able to produce thin, somewhat flexible sheets of the material. These thin sheets are currently 0.14 m (5.5 in.) wide but they can theoretically be up to several meters in length. Our current concept is to create a monolithic hypar shell from built-up layers of these thin strips. The thin strips would be laid onto a template (either permanent, made of thermoplastic boards, or temporary and re-useable). Overlapped sections would be glued using an epoxy based glue. We have experimented successfully with several types of epoxy adhesives. Sections could readily be thickened based on structural analysis (finite element) considerations.

Figure 13 shows the hypar with two overlapping strips of composite material. Figure 14 shows a new strip being overlaid onto the existing monolithic shell.

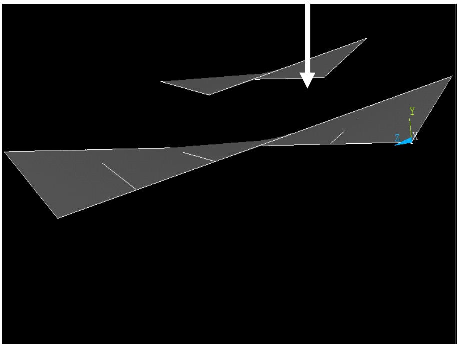


Figure 13. Overlapping thin strips

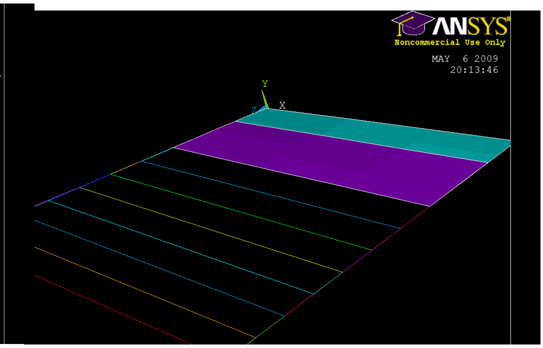


Figure 14. Additional strip added

Figure 15. Thin strip following hypar

Figure 16. Thin strips on hypar

We are currently exploring the use of thin strips overlaid onto a loosely woven hypar template. The overlapping, glued strips will form a monolithic thin shell. The design possibilities afforded by this new building technique are limitless. And they arose because of the interaction we have had with three different departments at our University (Materials Engineering, Architecture and Architectural Engineering) and because we have closely linked our design ideas to what can be manufactured at an industrial scale. Without the interaction between materials engineers, industrial manufacturers and architects and structural engineers, we would not have arrived at this design idea. Figures 15 and 16 show the concept.

3. Pedagogical Insights

The participants in this project saw it as an opportunity to build an integrated multidisciplinary team and create a rich learning experience for all involved. The team was lead by faculty members from the departments of Architecture and Architectural engineering and comprised of students from the departments of architecture, architectural engineering and materials engineering, as well as consultants from industry.

At the onset, efforts were made to ground the project with group discussions about the rich tradition of thin shell concrete design pioneered by visionaries such as Eduardo Torroja, Felix Candela, and Heinz Isler. The elegant structures of Torroja and Candela in particular, exhibit mathematical rigor yet aesthetic vitality that can only result from an intimate familiarity with the design, analysis and construction of thin shells. This design approach, described by Billington [7] as “function follows form”, resulted in structures in which the deformation of the shell (its mechanics) was dictated by the form. Following such approach, improper form with excessive bending, poor performance and high cost, could be avoided. The introduction of these luminaries to the group not only brought their work to the attention of students who were not familiar with it, but the efficient, economical and elegant designs by these individuals inspired the entire group to seek the same qualities in our own work.

Although project tasks were somewhat organized by discipline (material engineering students tested the physical properties of the composite material, architectural engineering students tested the mechanical properties of the boards, and architecture students conducted form and construction studies) the faculty leaders endeavored to integrate the various participants and expose students to each other’s work. One way this was done was to hold weekly meetings to discuss developments and findings within the group. Meeting locations were rotated between the various testing facilities and workshops to expose the entire group to the procedures being used by the different disciplines.

The team formed by architecture students and engineering students was supervised by faculty from both disciplines. This supervision allowed the faculty members to explore different pedagogies when interacting with the two student groups (Switzer [6], Dym [7]). We took the opportunity to show the students the rich tradition of thin shell concrete design pioneered by visionaries such as Eduardo Torroja, Felix Candela, and Heinz Isler. These designers were mathematically rigorous, economically scrupulous, yet aesthetically unbridled. They championed a path of design that searched for form in relation to the function, i.e. mechanics of the shell (Billington [8]). Improper form is to be avoided because such shells will bend, perform poorly and be exorbitantly expensive. We have constantly encouraged our students to seek forms that are rational and beautiful, forms that are economical and easy to build, using materials that are sustainable and elegant.

6. Conclusion

A path that links industrial-scale manufacturing to materials modeling to form finding has been fruitful in providing us with guidance in our research. We began with a unique material, a composite material made of a plastic matrix reinforced with agricultural fibers. Our relationship with the manufacturer of the material has allowed us to examine different cross sections of extruded boards, and most recently, thin sheets of extruded material. With this unique material, we set out to explore the design of a thin shell hypar roof, and we chose a rapidly assembled emergency shelter as our first project. We chose the hypar because it could be assembled from straight, extruded composite sticks. The research on form finding has used architecture students and faculty as well as structural engineering students and faculty. We also closely examined the material under ultraviolet light and we characterized its nonlinear behavior. It is the interdisciplinary nature of this project that allowed design ideas to progress freely and creatively.

Acknowledgement

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