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Testing, Modeling and Constructing Wood-Plastic Composite Catalan Vaults

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Abstract

This presentation will describe the application of new materials to a traditional building method. An overall goal of our current research is to invigorate the tradition of thin shelled roofs, by reinventing the Catalan laminated vaulting technique using new, ecologically-friendly building materials. In order to encourage architects and structural engineers to design such structures, proof-of-concept studies such as this one must be conducted and published.

1. Introduction: The Composite Material

The material we are using is generally classified as a wood thermoplastic composite and more specifically as wood-plastic composites (WPC). The wood used in WPCs is often a particulate, such as wood flour, but it can also be a mixture of short and/or bundled fibers. **[1]** Current commercial formulations of WPCs can have anywhere from 50% to 70% wood fiber reinforcement. The composite material we used in this study has a plastic matrix of high density polyethylene (HDPE) which can be obtained as virgin material or recycled from waste stream products such as milk jugs. This environmentally-friendly aspect of our material has generated enthusiasm for this project among students and granting agencies. Another interesting ecological aspect of this material is that the wood reinforcement can be harvested from invasive small diameter trees such as Salt Cedar. Or it can be made from sustainable high strength fibers such as kenaf or flax.

By far, the largest current market for WPCs is the outdoor deck market in North America. Consumers and contractors are attracted to its durability, lack of splintering, and low maintenance, and this has fueled a $3.2 billion market for this material. Yet the use of a WPC as a bending member, as one would use in outdoor decks, is not the most structurally efficient configuration. This is true because bending members such as deck boards must be fairly hefty to ensure adequate stiffness. A much more structurally efficient use of this material is to place it as a structural unit in a laminated vault. Such vaulting would not be used for decks, but rather, as a thin-shelled roof, as a stand-alone sunscreen, or as a load bearing component of a larger structure. It is this path that we have been researching in the Architectural Engineering Department at Cal Poly.

2. Catalan Vaulting

Traditional laminated vaults originated in the Catalan region of Spain, yet features of this vaulting technique have been found in other cultures. **[2]** The difference between Catalan vaulting and traditional masonry vaulting is that the tiles are laid flat, with a substantial mortar thickness between layers or courses (See Figure 1).

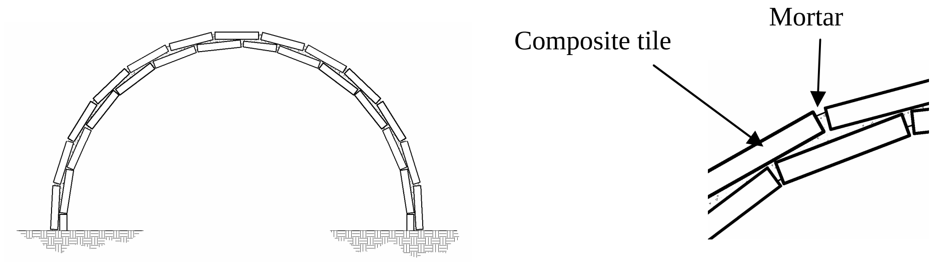

Figure 1: Elevation of Catalan Vaulting and Detail of Mortar and Composite Tile

The result is a thin shell that is essentially monolithic because of the tenacity of the mortar. This vaulting technique was made popular here in the US by the father and son team of Rafael Guastavino and Rafael Jr. Their firm, the Guastavino Company, was involved in over one thousand buildings, some of which are seminal in the history of neo-gothic and neo-classical architecture, such as St. John the Divine Cathedral and the Boston Public Library. A rule of thumb in all good thin shell design is the selection of the proper form. A properly designed thin shell structure will exhibit little or no bending and will carry loads primarily through compression.

3. Testing of the New Material

Unlike Guastavino’s Portland Cement mortar, we used a two component, acrylic based high strength adhesive such as Simpson AT. We also added a casting agent, which added some volume to the mortar, allowing us to create the curve shown in Figure 1. This mortar adhered best if the wood-plastic composite was first sanded with a very coarse grit paper.

We did several shear tests and a more extensive compression testing program. The average shear stress we obtained was 15.8 MPa (2300 psi) at failure. Since the laminated vaults will not experience substantial in-plane shear, this shear strength has been deemed adequate. Specimens of the wood-plastic material were tested in compression (See Figure 2). We found an average initial modulus of elasticity to be 2.96 GPa (430,000 psi).

Figure 2: Compression Testing

The stress vs. strain curve is nonlinear as other studies have found. [**3**] A bilinear curve can be used if the material is to be modeled as orthotropic. A multi-linear elastic model can be used in a finite element model if the material is assumed to be isotropic as was done in the present study. Figure 3 shows the multi-linear elastic constitutive model used in the finite element program which was arrived at through testing.

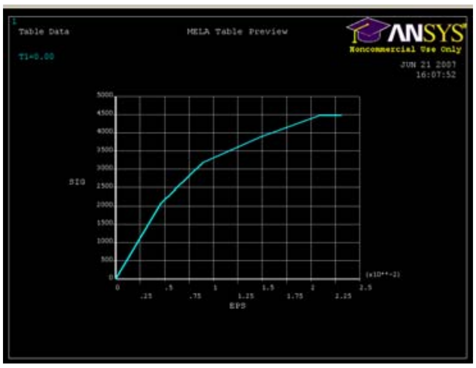

Figure 3: Experimental Compression Data

We used the commercially available finite element software ANSYS to capture the nonlinear material properties as well as the thin shell behavior of the structural units. While such finite element programs are robust, it is often quite tedious to input all of the geometrical properties. To increase the efficiency of the input process and to reduce the errors of manually drawing or entering the geometric data, we devised a means of using the program MATLAB to create the necessary input data which can then be pulled into ANSYS. To test the viability of this method, we focused our attention on spiral staircases. We created a MATLAB program that can automatically generate a staircase of any user-defined inner radius, outer radius, and pitch of the spiral. Such MATLAB generated output is shown in Figure 4. Having the MATLAB generated data file greatly increased our efficiency in exploring a variety of spiral staircase geometries and to do so in an error-free manner.

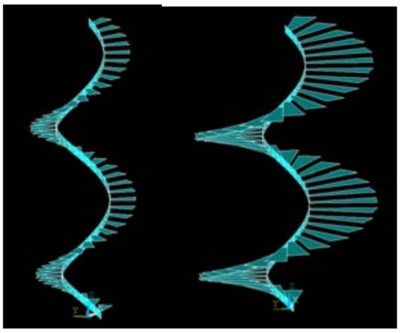

Figure 4: MATLAB Generated Geometry

We chose the spiral staircase as a prototype test case because of its dramatic geometry. It also provides interesting and challenging constructability issues; issues that must be solved at the bench top scale before attempting larger scale Catalan structures. Typical results that can be obtained from such finite element analyses are principal stress data and vertical displacement data. Other information such as collapse mechanisms can also be found. Figure 5 shows such a collapse study.

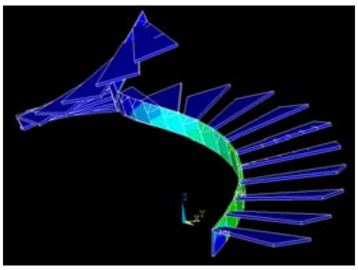

Figure 5: Finite Element Collapse Study

5. Preliminary Model Making

We have constructed several table-top size Catalan vaults made from the composite materials. Figure 6 shows a one meter tall spiral staircase. Other models took advantage of straight line generators to create barrel vaults or hyperbolic paraboloids (Figure 7).

Figure 6: Preliminary One Meter Tall Spiral Staircase

Figure 7: Straight Line Generated Forms

6. Future Work

This research will continue to explore larger physical models. We hope to solve constructability issues that will arise as well build on a larger scale. Ultimately, we will load test these larger structures and compare the finite element response to the physical experiments.

References

[1] Handbook of wood chemistry and wood composites; R. Rowell ed. CRC Press, 2005; p. 367.

[2] Collins, G. “The Transfer of Thin Masonry Vaulting from Spain to America”, Journal of the Society of Architectural Historians, Ocotober, 1968; p. 177.

[3] Saliklis, E. Urbanik, T. and Tokyay, B. “Method for Modeling Cellulosic Othotropic Nonlinear Materials”, Journal of Pulp and Paper Science vol. 29, no.12, 2003; pp.407-411.