Jessica Mandrick
E90 Project Proposal
Swarthmore College
Department of Engineering

Thin Shell Concrete Structure Design and Construction

1 Introduction

The ACI code defines a thin shell as a: "*Three-dimensional spatial structure made up of one or more curved slabs or folded plates whose thicknesses are small compared to their other dimensions. Thin shells are characterized by their three-dimensional load-carrying behavior, which is determined by the geometry of their forms, by the manner in which they are supported, and by the nature of the applied load.*" Concrete shell structures are able to span large distances with a minimal amount of material. An arch, spanning tens of feet, can be mere inches thick. In maintaining this economy of material, these forms have a light, aesthetic, sculptural appeal. I am planning on designing and constructing a thin shell concrete structure for my senior design project. The structure constructed would be at a maximum size, ten feet by ten feet, which may be scaled down if necessary during the design phase. I will be working on this project with Rebecca Burrow who is assisting as part of a directed reading arranged through Professor Siddiqui. Rebecca is currently abroad.

Thin shell concrete structures are pure compression structures formed from inverse catenary shapes. Catenary shapes are those taken by string or fabric when allowed to hang freely under their own weight. As string can bear no compression, the free hanging form is in pure tension. The inverse of this form is a pure compression structure. Pure compression is ideal for concrete as concrete has high compressive strength and very low tensile strength. These shapes maximize the effectiveness of concrete, allowing it to form thin light spans.

2 Project Plan

2.1 Structural Design and Analysis of Thin Shell Structures

A structural design of the thin-shelled concrete structure will be computed using catenary and geometrical shape equations. The design will be anticlastic meaning that its main curvatures run in opposite directions, like the hyperbolic saddle. It may be formed out of a combination of two intersecting hyperbolic paraboloids, forming a hyperbolic groined vault (**Figure 1**) or a similar complex shape. The hyperbolic paraboloid (**Figure**

2) could be formed as a curved surface or from straight boards, and is the only warped surface whose stresses can be calculated using elementary mathematics (Faber 1963). The analysis becomes more complicated when multiple shapes are combined and the resulting equations will need to be derived or computed via numerical analysis. The resulting shape will be modeled by ANSYS software. A variety of forms and dimensions will be modeled until both aesthetics and strength of shape are maximized. AutoCAD software will be used to produce engineering drawings of the final design.

Figure 1: La Concha Motel Lobby Las Vegas (Save La Concha)

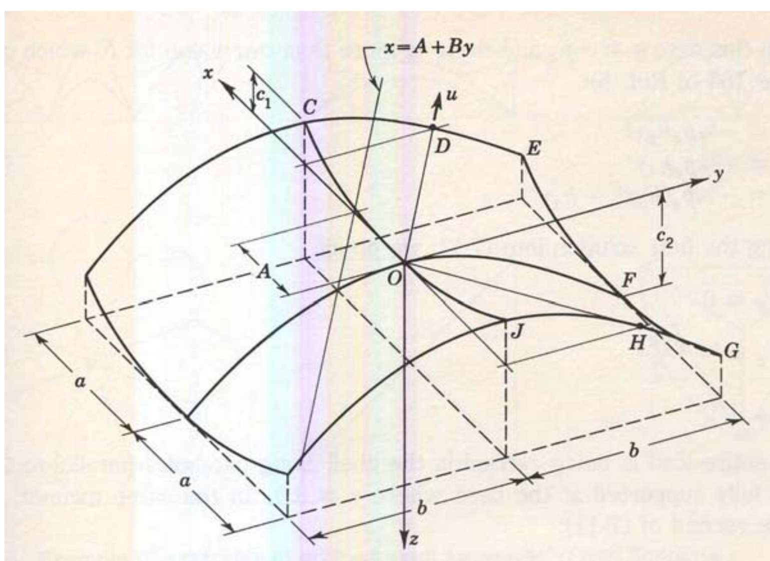


Figure 2: Diagram of a Hyperbolic Paraboloid (Billington 1982)

$$z = \frac{y^2}{h_2} - \frac{x^2}{h_1}$$ *where* $$h_1 = \frac{a^2}{c_1}$$ $$h_2 = \frac{b^2}{c_2}$$	**Equation One** **Surface of a Hyperbolic Paraboloid**

The shell will be subject to analysis of stress and deflection using ANSYS finite element software. This software will reveal critical areas and may lead to modifications in the design if the strength of the concrete shell is surpassed at any point. The structure will most likely be modeled using plates. A sufficient number of plates will be chosen such that the curvature of the shell is approximated. In "An Introduction to Shell Structures", Michele Melaragno presents a chapter on computer analysis of shells and domes. For a 360 degree circular domes structure she breaks the shell into 36 radial lines each with 11 circumferential divisions. These divisions may be used to approximate the number of plates needed to model the hyperbolic paraboloid. Melaragno also suggests that thin shell structures could be modeled using tension and compression members in a space frame which approximates the shape of the shell. When this space frame is analyzed for stresses and deflections, the axial stresses indicated tension and compression, and the stresses in diagonal members represent the shears within the thickness of the shell. **Figure 3** is a diagram indicating the application of this method to a hyperbolic paraboloid.

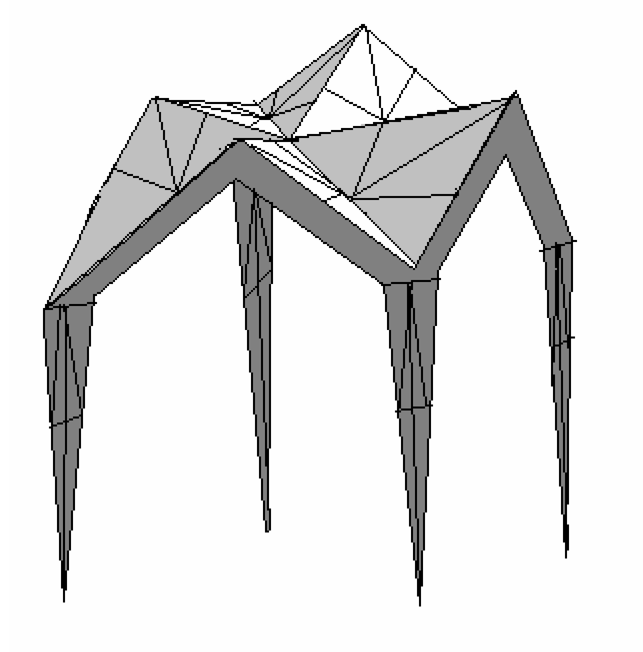


Figure 3: Hyperbolic Paraboloid modeled as a space frame.

2.2 Materials Testing and Selection

There are two directions in which the materials for this project could be chosen. The first direction derives from the fact that these structures use very little material. They are therefore well suited for third world countries where resources are limited but manual labor is abundant. The formwork used for these structures is often reusable and could be used to make several structures of the same form. In the case that this technology was developed for third world locations, low technology materials would be used. This would include utilizing cheaply obtained steel reinforcement and a standard cement mortar mix without additives.

The second direction for materials selection would be to explore new technology products. This would include the use of additives in the concrete to increase its strength and therefore reduce its thickness and stresses. Lightweight concrete may also be used reducing the weight of the structure. Swarthmore alumnus John Roberts, class of 1939, owns Solite Corporation which specializes in lightweight concrete expanded shale aggregate. He may be consulted for information regarding the use of this material and possibly for a donation of supplies. This material is a coarse aggregate and so could only be utilized if the material is available in particle diameters small enough to fit within the thickness and reinforcement of the shell. Solite expanded shale material was donated for use on the green roof of Swarthmore College's Alice Paul dormitory, so a small sample may be obtained from this location for testing. I will also contact Swarthmore College Facilities to see if there is any additional material remaining from this project.

Carbon fiber reinforcement products could be used instead of traditional steel reinforcement. These materials are much lighter in weight that steel but are capable of withstanding the tensile stresses in concrete. They are also corrosion resistant, another improvement over steel reinforcement. These products are still relatively new within the engineering field and have not gained widespread acceptance. Research would have to be conducted on the performance of these materials before their usage in the structure. This research would include tension testing and bonding strength with concrete. Tension testing would utilize the green machine to stretch the carbon fiber until significant yielding or failure occurred. Tensile tests would also be used to measure tensile strength in Fiber Reinforced Polymer (FRP) bars if appropriate literature or factory values cannot be obtained. I have not yet determined an appropriate test to measure bond strength for carbon fabric. Cost and availability of these materials will also be taken into account when deciding if their use is feasible.

2.3 Development of Formwork

Formwork developed for this project needs to mimic the curved surface of the concrete shell in order to serve as the appropriate form for it. In construction practice, there are several materials used for formwork. Wood, one of the earlier materials used, can be bent into curved surface when in thin sheets. These thin sheets are attached to a stronger wood framework underneath constructed of a material such as 2x4's. Inflatable pneumatic formwork has been used for circular concrete shell structures. A concrete base is cast, and the pneumatic membrane is attached to the top. It is covered with concrete and a second membrane is placed on top. The bottom membrane is allowed to inflate with air sealing a thin shell of concrete between the two membranes. In the late 1960's the Dow company looking for a new market for their "Styrofoam" product developed a process known as spiral generation to create formwork from thin layers of foam, the formwork is adhered together by heat lamination and is layered inward to create a spherical dome (Melaragno 1991)

For my project, these methods will need to be modified from a spherical form to a more hyperbolic form with multidirectional curves. I plan to construct a wooden support structure out of 2x4's or Uni-Strut to hold a lightweight shapeable material. I have already consulted with machine shop technician Grant Smith on materials to use as this lightweight material. I proposed using a process similar to the Spiral Generation Method in which thin sheets of foam would be stacked and carved at the ends to produce the desired shape. This idea is generated in graphical form in **Figure 4**. Sample pieces of foam were cut to a curved shape in the machine shop to demonstrate the feasibility of this method.

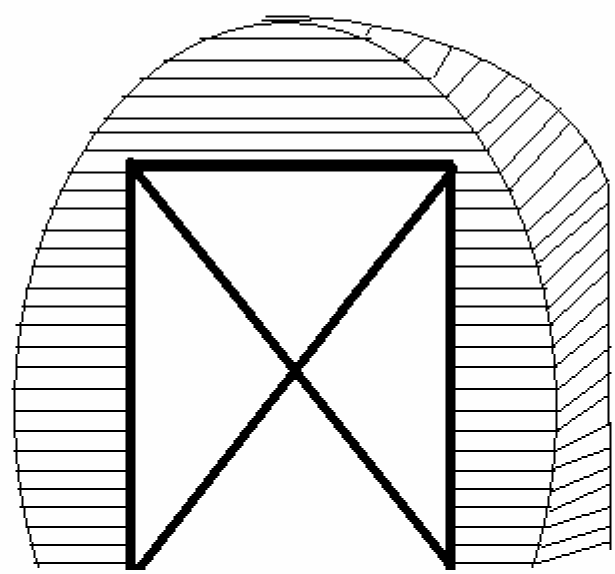


Figure 4: Foam Formwork for a Curved Section, This formwork would be used on ¼ of a hyberbolic paraboloid, and would then be removed and reused on the remaining portions. It is a foam curved shape supported with an inner brace of wooden 2x4's.

2.4 Construction

Construction of the thin shell concrete structure would occur upon the completed formwork. Reinforcement would first be prepared and spaced from the formwork so that it will be suspended in the center of the shell structure. Fabric reinforcement would be added for tensile strength and also as a medium for the concrete to adhere to upon the formwork, holding it in place until sufficiently dried. Many assistants will be needed to complete the task of construction. Up to 40 ft^3 of material will need to be poured and the capacity of our mixer is only 1 ft^3. Another mixer could be rented our borrowed which has a larger load capacity and can run simultaneously with the department mixer. A mixer source has not yet been identified.

3 Project Costs

As the shape of the structure has not yet been designed, its surface area will be approximated with that of a spherical half dome. The surface area for a dome has the formula S.A. = $4\pi r^2$, considering a half sphere with a 7 foot radius to achieve the desired height, the surface area would be 308 ft^2. For a structure one and a half inches thick, this leaves a maximum volume of 39 ft^3 of material. (Although shells in the past especially those designed by Felix Candela in Mexico have been less than one inch thick ACI requirements for covering reinforcement are stricter in the United States. It is assumed that the shell will need to be thicker than one inch, but this will not be known until the reinforcement is designed. The code states that the shells thickness but be sufficient to satisfy strength provisions in the code, and that the thickness of the shell is often dictated by the required reinforcement (ACI). Additional concrete material will be required for four bases under the legs (4 x 3”x2’x2’) = 4 ft^3 and for testing and experimentation. Overall it is estimated that 40 ft^3 of concrete could be used. It is assumed that no course aggregate will be used due to the thinness of structure, therefore only fine aggregate will be required. A low slump mix will be required so that the concrete will adhere to the formwork without sliding. An example of a low slump cement mix contains 0.6-0.75 lb concrete to 1.0 lb of sand (Penn State). It is estimated then that (0.75/1.75*40=17 ft^3 of cement needed) and (1/1.75*40=23 ft^3 of sand needed). One bag of cement weights 94 lbs and is 1 ft^3 in volume.

Formwork:

Foam or Wooden Slats – estimated up to $100 dollars

2x4 boards – used boards will be sufficient, obtained from shop

Adhesive - $20

Shell:

Cement – 17 ft^3 = 17 bags = $15*17 = $255

Fine Aggregate – 23 ft^3 * ($20/ yd^3) = $20

Carbon Fiber or Steel Wire Mesh, will need at least 300 ft^2 of material, price is highly dependent upon product chosen.

Other Costs:

Printing Plots: $50

Transportation: $20

Mixer Rental: ?

Total Cost: ≈$500

Suppliers will be contacted to try to arrange a donation of materials to alleviate the cost.

4 Realistic Design Constraints and Sustainability

This project involves the use of concrete as a construction material. Concrete is a material proven to be very hard, durable, and weather resistant. It will need little maintenance over the course of its life. This is great in terms of upkeep while the project is located on site. However, these properties remain once the material is disposed. The concrete is not recyclable and will end up in a landfill at the end of its useful life. This is an unfortunate side effect of such a trusty building material. Another disadvantage to concrete construction is the amount of energy required to produce concrete. Concrete is formed by burning rock in a rotating kiln at extreme temperatures. Fueling this kiln involves tremendous amounts of energy which has an effect on both the Earth's resources and pollution to the environment. Despite these negative side effects, concrete is used in large quantities in construction projects throughout the world. The abundance of the rock materials it is composed of make it relatively cheap and much construction is conducted without any reference to the impact the production of the concrete had on the environment. This project will show small contractors that it is possible to reduce concrete consumption by more appropriately designing structures where it is efficiently used. Our thin shell concrete structure will use a minimum of material for an extended span. If a college student can perform this operation, so can a contractor.

This project will also serve an aesthetic purpose in its chosen location. A proposal is being submitted to the Swarthmore College Arboretum in the hopes that the project can be located on the Swarthmore College Campus. It will be available for the public to see and appreciate. It may house a seasonally rotating sculptural object, a permanent sculpture, or a plant bed. Hopefully it will also increase interest in engineering, among those who see it.

5 Critical Path and Gantt Chart

ACTIVITY	ACTION
A	PROPOSAL DRAFT
B	PROPOSAL
C	LEARN ANSYS
D	LITERATURE REVIEW and ARBORETUM PROPOSAL
E	LEARN AUTOCAD
F	STRUCTURAL DESIGN AND ANALYSIS
G	CONCRETE MIX DESIGN
H	MATERIALS PURCHASE
I	TESTING OF MATERIAL PROPERTIES
J	AUTOCAD DRAWINGS
K	FORMWORK DESIGN
L	CONSTRUCTION OF FORMWORK
M	CONSTRUCTION OF REINFORCEMENT
N	CONSTRUCTION OF SHELL
O	CURING OF SHELL
P	INSPECTION AND ANALYSIS
Q	REPORT
R	PRESENTATION

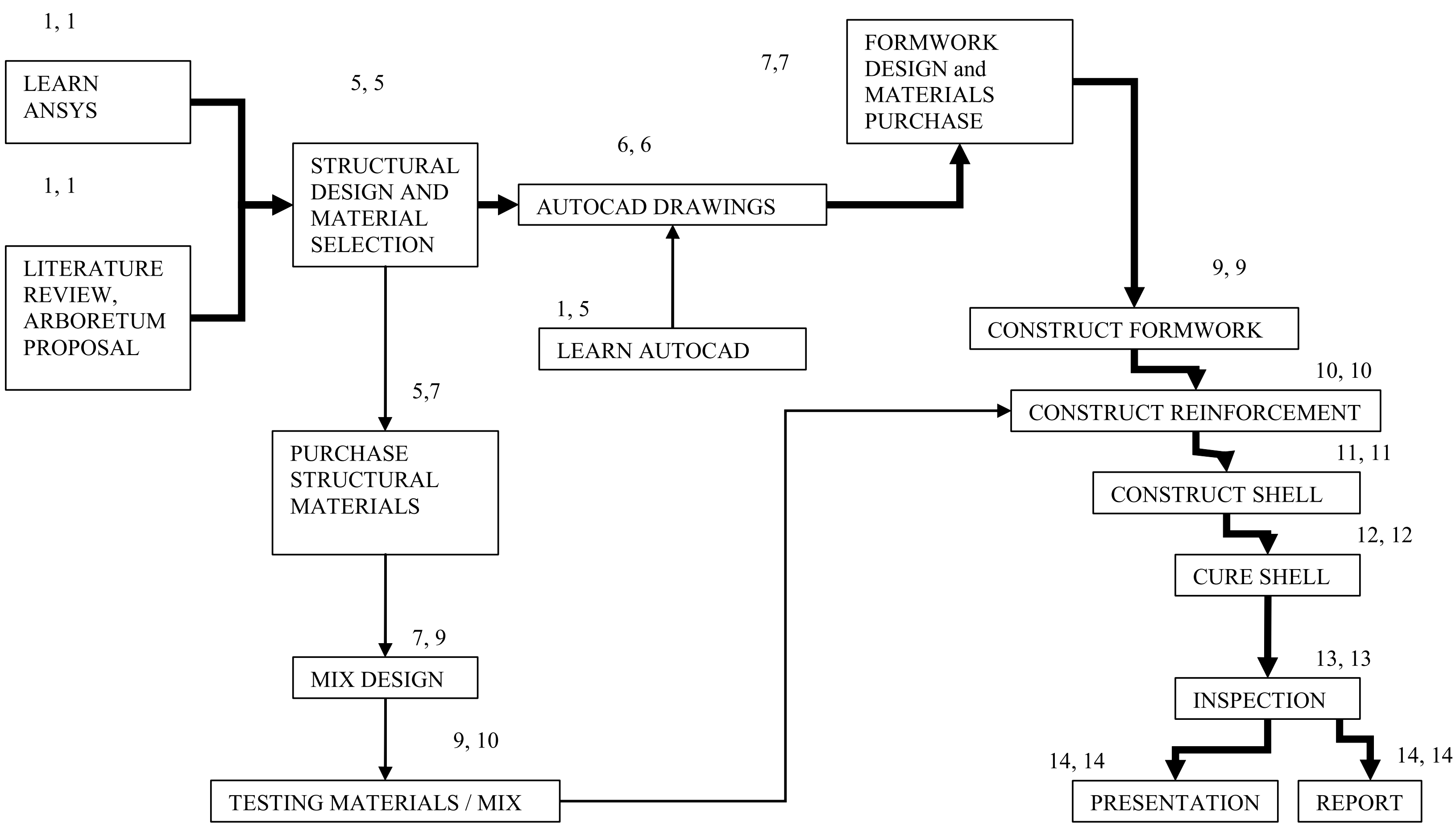
Figure 4: Activities Listing

ACTIVITY	NEEDS	FEEDS	DURATION (weeks)	EFFORT (hours)	ACTION
A	x	B	1	12	PROPOSAL DRAFT
B	A	x	1	12	PROPOSAL
C	x	F	3	20	LEARN ANSYS
D	x	F	3	20	LITERATURE REVIEW and ARB. Prop.
E	x	J	1	20	LEARN AUTOCAD
F	C, D	J, H	4	60	STRUCTURAL DESIGN AND ANALYSIS
G	H	I	2	30	CONCRETE MIX DESIGN
H	F	G	1	5	MATERIALS PURCHASE
I	G	M	1	15	TESTING OF MATERIAL PROPERTIES
J	E, F	K	3	40	AUTOCAD DRAWINGS
K	J	L	1	35	FORMWORK DESIGN and PURCHASE
L	K	M	2	25	CONSTRUCTION OF FORMWORK
M	L, I	N	1	15	CONSTRUCTION OF REINFORCEMENT
N	M	O	1	50	CONSTRUCTION OF SHELL
O	N	P	2	5	CURING OF SHELL
P	O	Q	1	10	INSPECTION AND ANALYSIS
Q	P	x	1	10	REPORT
R	P	x	1	10	PRESENTATION
			TOTAL	394	

Figure 5: Needs, Feeds, Duration and Effort

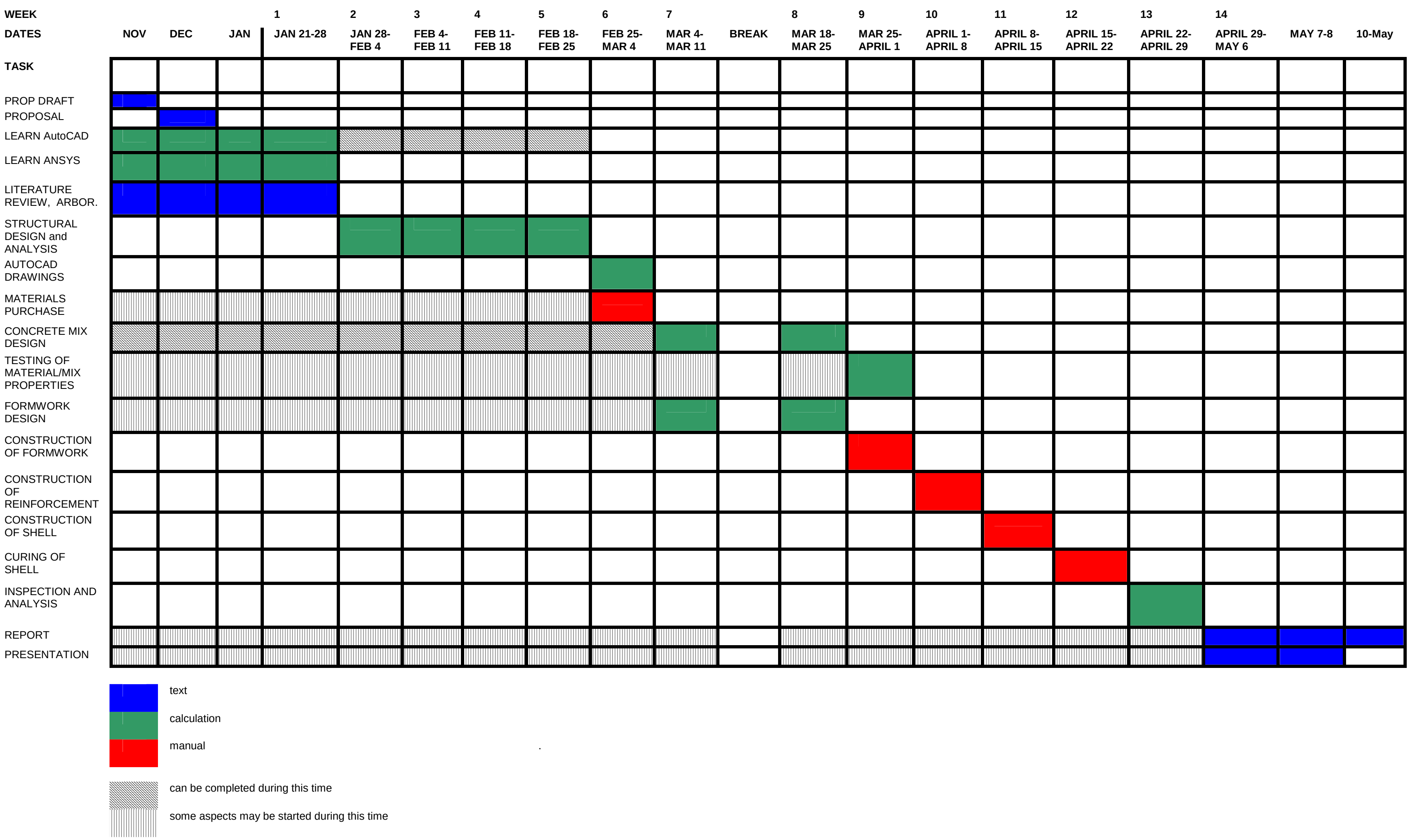
The project critical path and Gantt chart are located on the following pages respectively.

CRITICAL PATH



CRITICAL PATH IS HIGHLIGHTED WITH BOLD ARROWS

Gantt Chart for E90 Thin Shell Project



8 Source Listing

ACI. 318 Building Code and Commentary. Ch. 19 Shells and Folded Plate Members.

Billington, David. P. Thin Shell Concrete Structures, 2nd Edition. McGraw-Hill Book Company. USA. 1982

Faber, Colin. Candela: The Shell Builder. The Architectural Press. London. 1963.

Melaragno, Michele. An Introduction to Shell Structures: The Art and Science of Vaulting. Van Nostrand Reinhold. New York. 1991.

Penn State. Architectural Engineering Computer Lab Website. Paul Bowers and John Pillar. 2001. <http://www.arche.psu.edu/thinshells/module%20III/concrete_material.htm>.

Save La Concha. HOMECAMP.com. Lotta Livin'. <http://www.mondo-vegas.com/savelaconcha/architecture.php>.