Chioma di Ulivo- Courtyard Canopy

for:

California Polytechnic State University, San Luis Obispo

date:

Winter Quarter 2024

by:

Claudia Geist & Lilla Vigh

Faculty Advisor: Dr. Craig Baltimore, Ph.D., S.E.

Special Thank You To:

Shaina Dickie – 5th year Architectural Engineering Student

Samuel Lee – 4th year Architecture Student

Dave Kempken – *CAED Shop Manager*
Email: dkempken@calpoly.edu
Phone: (805) 756 - 2720

Tim Dieu – *Support Shop Technician*
Email: tdieu@calpoly.edu
Phone: (805) 756 - 2108

Vince Pauschek – *Support Shop Technician*
Email: vpausche@calpoly.edu
Phone: (805) 756 - 2156

Brenna Humphrey – *Walkthrough Productions*
Email: walkthroughproductions.com
Phone: (310) 663 – 7051

Samuel Venable – *Earth Systems*
Old Santa Fe Rd #8160,
San Luis Obispo, CA 93401
Phone: (805) 544 – 3276

Table of Contents

Nomenclature

GC_{pi}	Internal pressure coefficient
G_f	Gust-effect factor
K_d	Wind Directionality factor
K_e	Ground elevation factor
K_z	Velocity pressure coefficient
K_{zt}	Topographic factor
E	Shear modulus, *ksi*
I	Moment of inertia, *in^4*
H	Height of concrete column, *ft*
V_n	Nominal shear strength, *lb*
V_c	Nominal shear strength provided by concrete, *lb*
V_s	Nominal shear strength provided by shear reinforcement, *lb*
f_c	Compressive strength of concrete, *psi*
f_{ct}	Tensile strength of concrete, *psi*
ϕ	Strength reduction factor
Δ	Out-of-plane maximum displacement for column, *in*

1.0 Project Introduction

1.1 Purpose

The purpose of this senior project was to document existing conditions, design a roof structure, and build a quality diorama of the new structure which will be located adjacent to Engineering West Building 21 in the Hasslein Courtyard. The current canopy structure consists of concrete columns with an exposed concrete grade beam. Surrounding the column structure is a small patio area with a bench and an olive tree. This project aims to create a functional canopy space for the Architectural Engineering Department. The new canopy design should redirect the olives from accumulating on the floor and keep the small, enclosed section from flooding during heavy rain.

1.2 Introduction

In 2020, *Piazza di Ulivo* (“Olive Tree Square”) was initiated by Sophia Ha and David Colman in the Spring of 2020 as an effort to redesign the patio corner connected to the Engineering West ARCE offices (Ha and Colman). Through this project, surveys were conducted across students and faculty alike to determine the design needs and create a rough survey of the patio area. This project served as the shuttle point for this project, *Chioma di Ulivo* (“Olive Tree Canopy”), which was centered around developing the site’s existing conditions and a preliminary permit set for a new canopy configuration. One of the main engineering goals of this project is to explore hyperbolic paraboloid shells in the built environment. Through form finding and the use of the diorama, a hyperbolic canopy was born, with inverse trusses guiding round timber poles to conform to the paraboloid shape. In years prior, an old canopy structure was removed after the materials rotted, leaving the courtyard with five seemingly arbitrary columns and an unappealing bench. To this day, the ARCE courtyard lacks adequate shaded areas for outdoor gatherings, relaxation, learning space, and events. *Chioma di Ulivo* aims to create a space that students and faculty can enjoy while providing shade, beauty, and an indoor-outdoor experience.

A canopy made of 3” diameter timber poles will be used on the already existing inverted moment frames to cover the patio area. This canopy will have a hyperbolic paraboloid shape and be utilizing four of the five columns. The last columns will not be used as a connection point due to the olive tree extending too far out nearing to the column. The limited tolerance here makes the columns impractical without hurting the tree.

A new column is to be placed in the middle of the patio to work as a point of contact instead of the current fifth column as shown in Fig. 1.

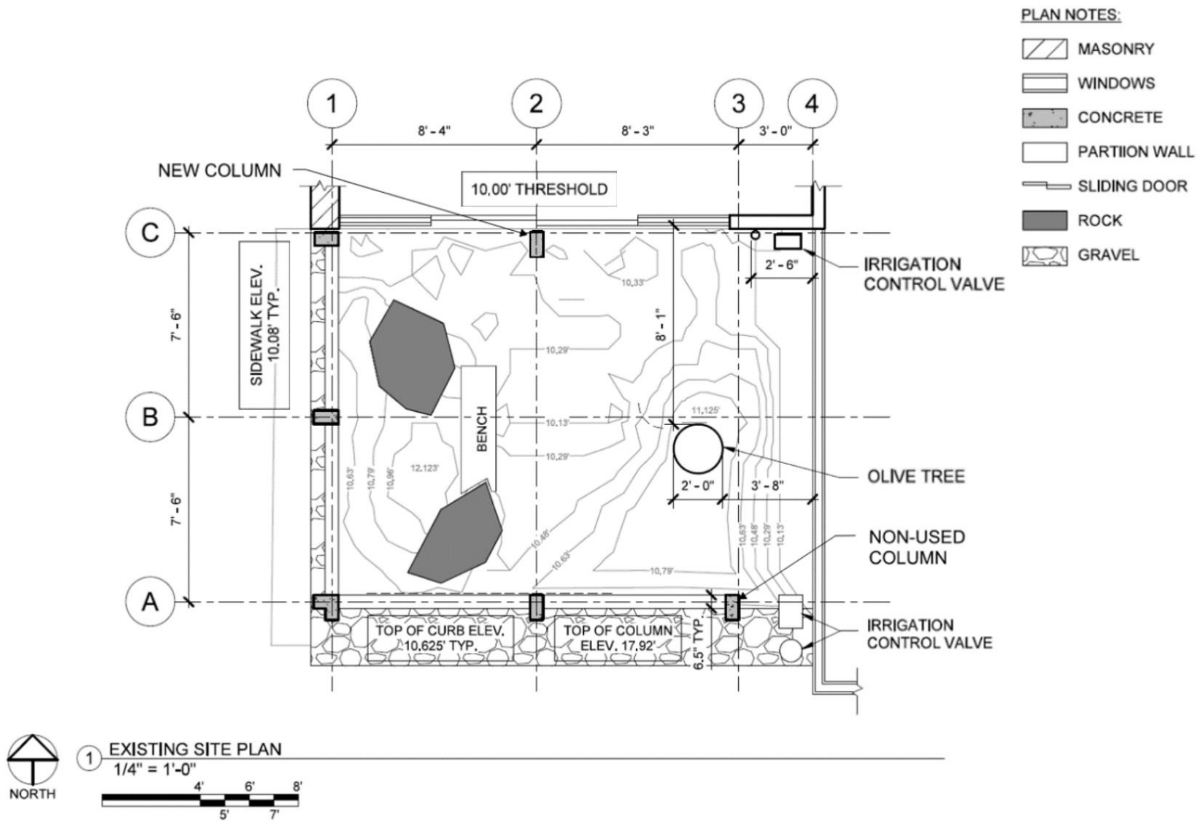


Fig. 1 Piazza di Ulivo- Existing Site Plan

1.3 Project Expectations

At the beginning of Fall Quarter 2023, the group consisted of two architectural engineering students and one landscape architect student. Lilla Vigh initiated the group and gathered the other two members before Spring Quarter started. The first week proved challenging with many conflicting schedules across the students and advisor. One proposed meeting time consisted of having meetings as early as 7:30 am or having the assigned consultant engineer and the landscape architect meet on separate days. A whole week was spent looking for a conventional meeting time that worked with everyone's schedule. Due to conflicting schedules, the landscape architect ended up dropping out of the project.

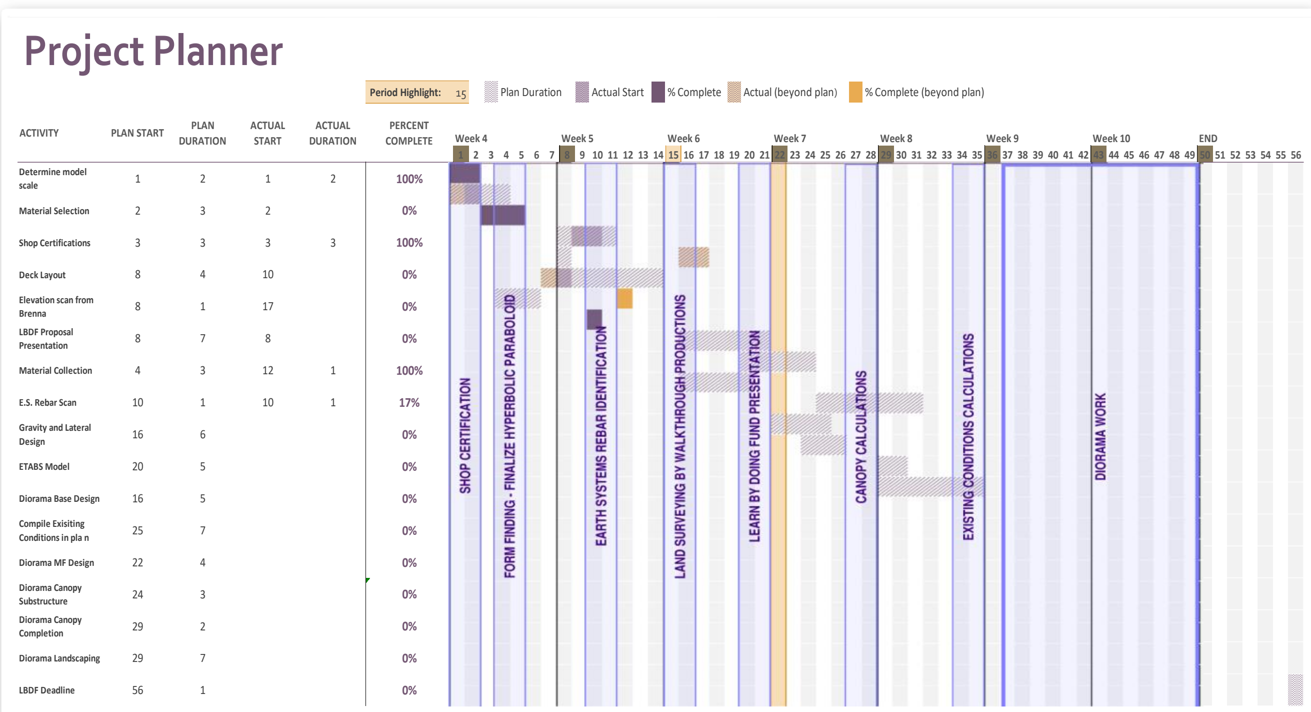
Choosing a proper meeting time for everyone involved in the project to meet was a demanding task. In real life projects, consulting engineers manage bigger groups and are constantly getting vital information from colleagues and even other companies. Staying organized and on track proved to be a major labor for the project to be successful. Much like this scenario, coordinating schedules with other team members can be a significant challenge due to conflicting commitments and priorities. Consulting Engineers have the task of scheduling meetings and communicating effectively with outside sources to gather the necessary information to finish the project at the promised deadline.

For this project, it was determined that Claudia Geist would serve as the primary consulting engineer, while Lilla Vigh would be the structural designer for the canopy structure. The project would be conducted in a mock-industry setting, with bi-weekly meetings with the project advisor.

1.4 Timeline

With *Piazza di Ulivo* initiated in Spring 2020, *Chioma di Ulivo* will be completed at the end of Winter Quarter 2024, with the project reporting and plan assembly occurring throughout Spring Quarter 2024. The CAED Student Scholar funds would be supporting the expenditures incurred during the diorama construction process, as well as providing the initial funding for the live canopy which is to be built by a future ARCE senior project group. This effort, *Costruzione di Piazza* ("Canopy build"), will be initiated as early as Spring Quarter 2024, or as late as Winter Quarter 2025.

With the scope of the project identified, a schedule was created to plan the future weeks of the project (see Fig. 2).



ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Determine model scale	1	2	1	2	100%
Material Selection	2	3	2		0%
Shop Certifications	3	3	3	3	100%
Deck Layout	8	4	10		0%
Elevation scan from Brenna	8	1	17		0%
LBDF Proposal Presentation	8	7	8		0%
Material Collection	4	3	12	1	100%
E.S. Rebar Scan	10	1	10	1	17%
Gravity and Lateral Design	16	6			0%
ETABS Model	20	5			0%
Diorama Base Design	16	5			0%
Compile Exisiting Conditions in pla n	25	7			0%
Diorama MF Design	22	4			0%
Diorama Canopy Substructure	24	3			0%
Diorama Canopy Completion	29	2			0%
Diorama Landscaping	29	7			0%
LBDF Deadline	56	1			0%

Fig. 2 Gantt chart for Chioma di Ulivo

2.0 Existing Conditions

2.1 Facilities Consultation

As a starting point, the facilities department of California Polytechnic State University was contacted to obtain plans for building 21, Engineering West. The first set of plans received from the department were the original plans dating back to the 1960's (Bowman). Such plans didn't have any information regarding the inverted moment frame. A subsequent visit to the facilities department was essential to obtain more plans with information regarding the structure.

Despite making a second trip to facilities, the subsequent plans had no useful information on the structure. Jesse Barron, Permit Manager from Facilities, offered his services to find the rebar in the moment frame. However, his services could not be used since Facilities will not be involved in the project.

2.2 Independent Surveying of Concrete Members

Without any useful information about the columns and beams, the next step was to do manual surveying. The height, width, and length of both the columns and the beams were measured with a simple measuring tape provided by Vince Pauschek from the High Bay Laboratory. The location of the tree was also measured with the intention of locating branches that could get in the way. The objective of these measurements was to build a roof without having to cut any branches off and possibly damage the tree.

The existing site plans per Fig. 1 did not have sufficient information on dimensions, rebar placement, and sizing. A more direct approach was needed to find the depth of the inverted moment frame, and the grade beam was excavated and surveyed to find the true depth and locate drainage holes. As shown in Fig. 4 the depths are different on each side of the patio. A hole was also discovered in the middle of the beam as shown in Fig. 3. By finding the drainage holes, the initial theory of this concrete structure acting as an inverted moment frame was disproven, and structurally this beam was identified as a grade beam providing stiffness.

Fig. 3 Excavation of grade beam on existing structure

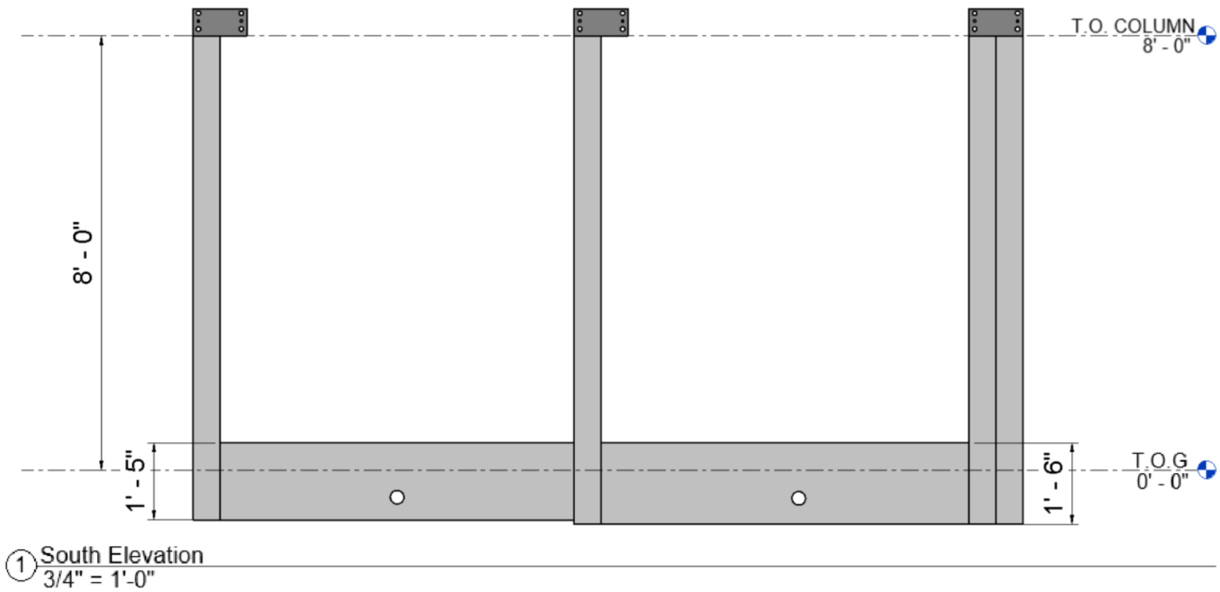


Fig. 4 South Elevation Existing Conditions

An additional piece of information missing from the structural plans was how deep the beams and columns ran. From Top of Grade, the columns measured 8’- 0” tall. The beams only showed 6 inches above the grade. On Friday 19th, a hole was dug using a shovel, provided once again by High Bay Laboratory, to find the depth of the beam. The beam adjacent to the masonry wall was determined to be 17 inches deep. Examining the exposed beam further showed a small hole of 3-inch diameter for drainage was discovered.

The process was repeated on the other side of the structure. An assumption was made of both sides of the structure having the depth. However, it was discovered to be 1.5 inches deeper due to the slope of the terrain.

Further measurements included sizes of the bricks and the grid lines pattern created on the floor, distances the walls are from the structure, and small details on the floor to model the diorama with more accurate detail.

After taking all the measurements, the structure was modeled using the Revit program as shown in Fig. 5.

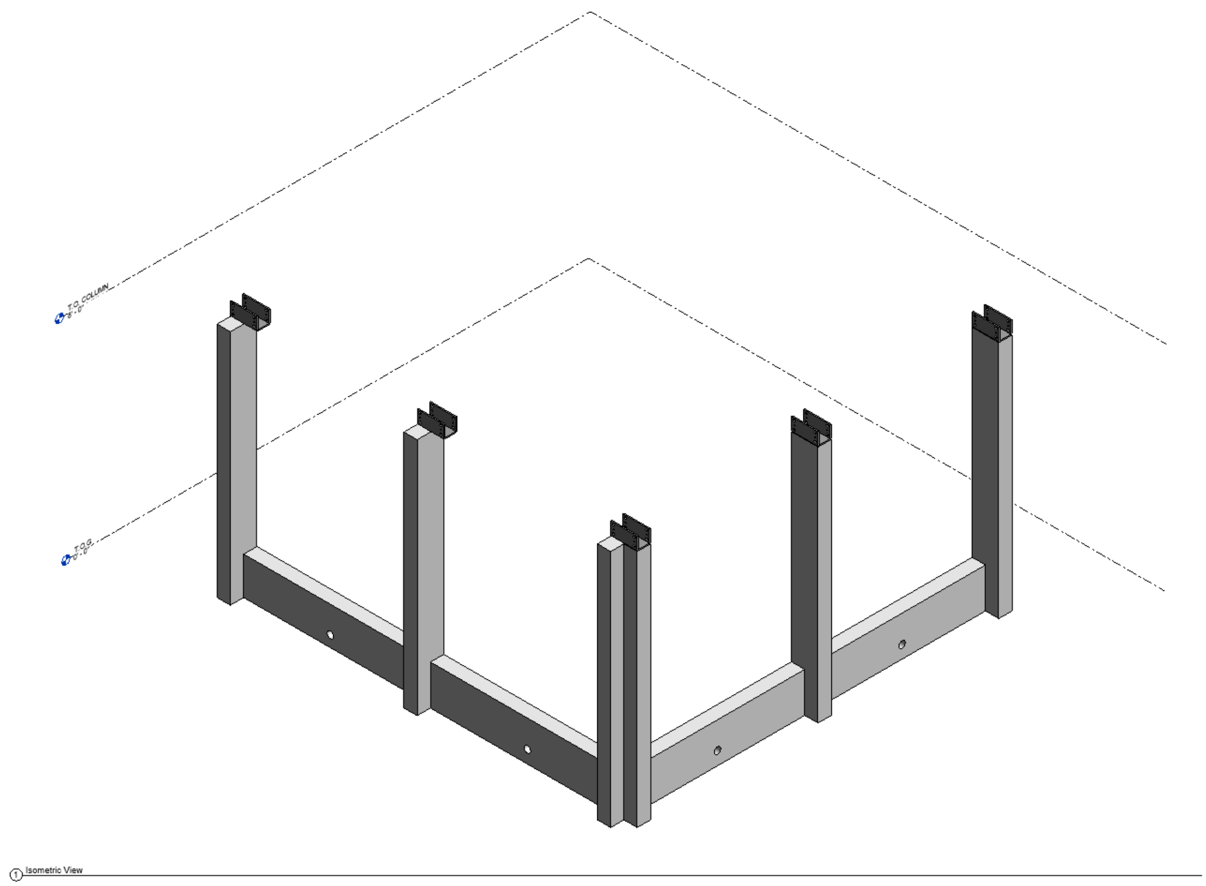


Fig. 5 Isometric View of Existing Conditions Chioma di Ulivo

2.3 Construction Management Department

Elevations of the site were obtained from *Piazza di Ulivo* per Fig. 1. This information had to be reevaluated before moving forward with the project. The Construction Management Department of California Polytechnic State University was contacted to acquire surveying equipment to be able to verify previous information. Heavy storms made surveying the site hard and was ultimately postponed. During this same time, Architectural Engineering Student Shaina Dickie presented the opportunity to work with Brenna Humphrey from Walkthrough Productions for a more sophisticated surveying opportunity. This is the route that was ultimately chosen for this project.

2.4 Walkthrough Productions

Brenna Humphrey, from Walkthrough Productions, was a guest speaker for the Winter Quarter Interdisciplinary Capstone Project ARCE 415 class. She showed the class a video about the company, the services they can provide, and the structural applications of their virtual walkthroughs (Humphrey). She disclosed how drones are used to take pictures and videos of project sites. The files are then uploaded to their program that allows them to establish precise dimensions and elevations without the need to physically measure anything. Pictures are also taken inside the buildings for the same purpose of measuring with the need to be present at the site. This is a very powerful program that helps lower unnecessary trips to the job site. For this project there were many trips to the structure to acquire more dimensions and even pictures to have a better idea of how to better model the structure. Saving time and money on trips can help move the project fast and lower the cost of labor.

Due to bad weather the topography survey had to be rescheduled several times, but ultimately a model view of the patio structure was developed.

2.5 Earth Systems

Without any proper information regarding the location of the rebar in the columns and beams, outside help was necessary. Dr. Baltimore suggested looking at local geotechnical engineers to help locate the placement of the rebar. A simple google search presented a company called Earth Systems located in San Luis Obispo, California. A visit to their firm was organized after sending a few emails through their websites contact information. During the meeting at Earth Systems, Professional Engineer Samuel Venable explained the work he does for the company. He further explained some of the projects the company has done and the ones he was part of. He gave a demonstration of the tools he uses to locate the rebar in concrete structures. The specific machine used for the demo is called an IDS GeoRadar C-Thrue GPR. This machine conducts a 2D reinforcement survey allowing the engineers to know where the rebar is placed inside the concrete (Venable).

The machine is a little yellow box with wheels, allowing it to move smoothly over the concrete member. A small screen displays the color gray when placed over concrete. While the machine is being moved over the member red lines appear. These red lines represent the rebar in the member. When the red lines appear a piece of chalk is used to make a mark representing the rebar.

After the demo was finished Earth Systems offered their services for free to help with this project. On February 7th the 2-D reinforcement survey was preformed and the spacing between rebar was established. Since the machine can only determine the distance between rebar and not the actual size, #4 longitudinal and transverse bars were assumed for future calculations. The final rebar spacing was determined to be #4 ties spaced 8 inches O.C., with ties spaced at 6 inches at the top and bottom of the column. In the column, two vertical bars were identified with 1.5 inches of clear cover. In the grade beam, it was identified that there may be one horizontal bar in the middle of the beam, but this was considered structurally negligible since the exact size and spacing could not be identified.

Fig. 6 Samuel Venable (Left) locating rebar in existing conditions with chalk

3.0 Roof Design

3.1 Hyperbolic Paraboloid Shells

With the initial conditions of the space established, the roof design was ready to be initiated. This was an opportunity to explore complex architectural canopy designs that went beyond simple deck designs. The starting point for this exploration was *SP 110: Hyperbolic Paraboloid Shells* by Jack Christiansen, evaluating different concrete shells such as gable, saddle, and umbrella. This text inspired the hyperbolic paraboloid shape for the canopy and demonstrated a variety of parabolic shapes and their significance in architectural history (Christiansen).

3.2 Preliminary Form Considerations

Before the hyperbolic shape was determined, other potential shell shapes were considered. One of the ideas was done in collaboration with Samuel Lee, a 4th year Architecture Student from Cal Poly. In this design charette, markups were produced from a plan view of potential canopy designs (see Fig. 7). One of the main inspirations for this design was a steel canopy located on the northeast side of the Architecture Building (see Fig. 9). This folded shell design creates channels for water and olives to trickle down a series of gutter systems to provide shelter and easy clean up. The main issue with this design is the maintenance required to keep the gutter systems clean, as they would be filtering both olives and water and could become easily backed without regular maintenance. As this canopy would be residing on campus and be in correspondence with campus facilities and maintenance, this structural addition should not be producing greater hassle. Another fault in this design is it neglected the irregular branches coming from the tree, and therefore parts of the tree would be trimmed to work with the current design.

The biggest takeaway from the design charette was getting to brainstorm alongside an architect and understand the interests of each player in the design process. As an engineer, the design revolved around the limitations imposed by each material and member that would be needed to achieve the desired form. The architect’s priorities revolved around the experience and feeling evoked by the structure itself. Lee centered the design around circulation of the space, with great consideration for the different people that may interact with the space. For faculty, Lee aimed to remove any obstructions in the way of the window and sliding doors to ensure seamless movement from the indoor conference room and outdoor space. Another interaction facilitated by Lee’s design was the ability for maintenance to access equipment in the corner space of the site (see Fig. 7). The design ensures that the tree and the filtered olives would not impose greater obstruction on the pathway to the mechanical equipment. The design is also intended to redirect the viewer to the focal point of the canopy itself – the pinnacle of the folded shell structure – to deviate from the distraction of the equipment.

Working with an architect revealed architectural insights that would be applied later to the final design of the canopy. Circulation, visibility, and focal points were factors that the engineering design had to be considered in the final iteration.

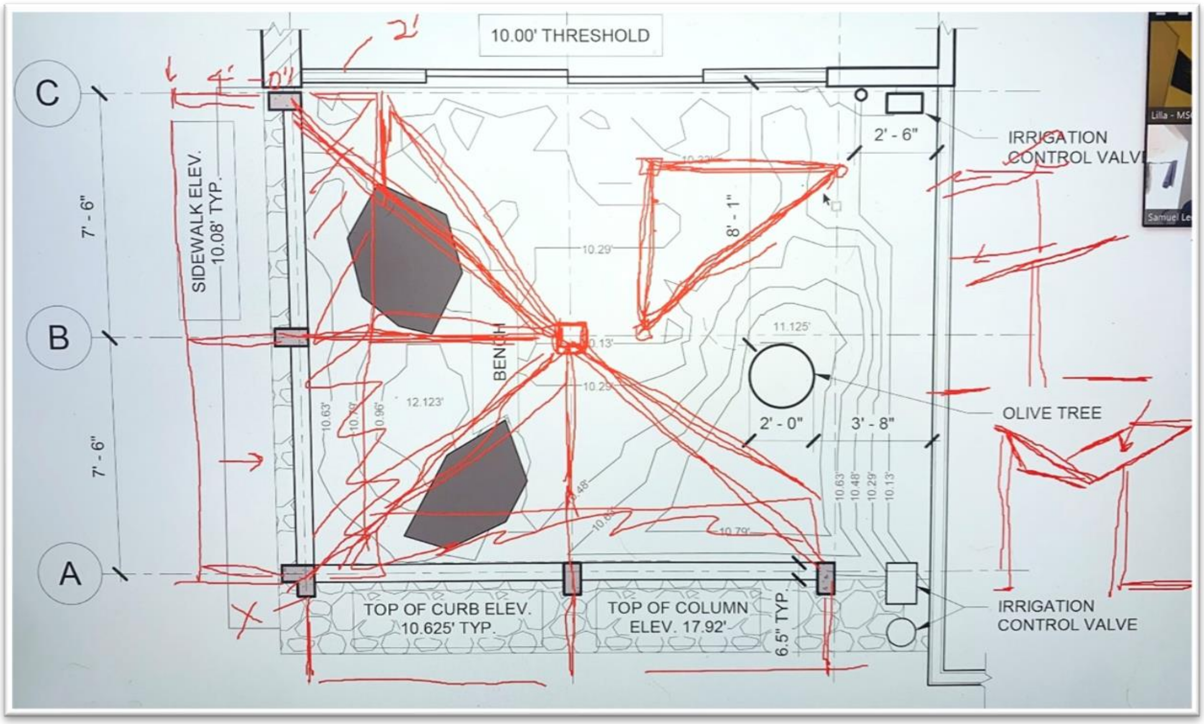


Fig. 7 Design Charrette Markups from Samuel Lee, 4th Year Architecture Student

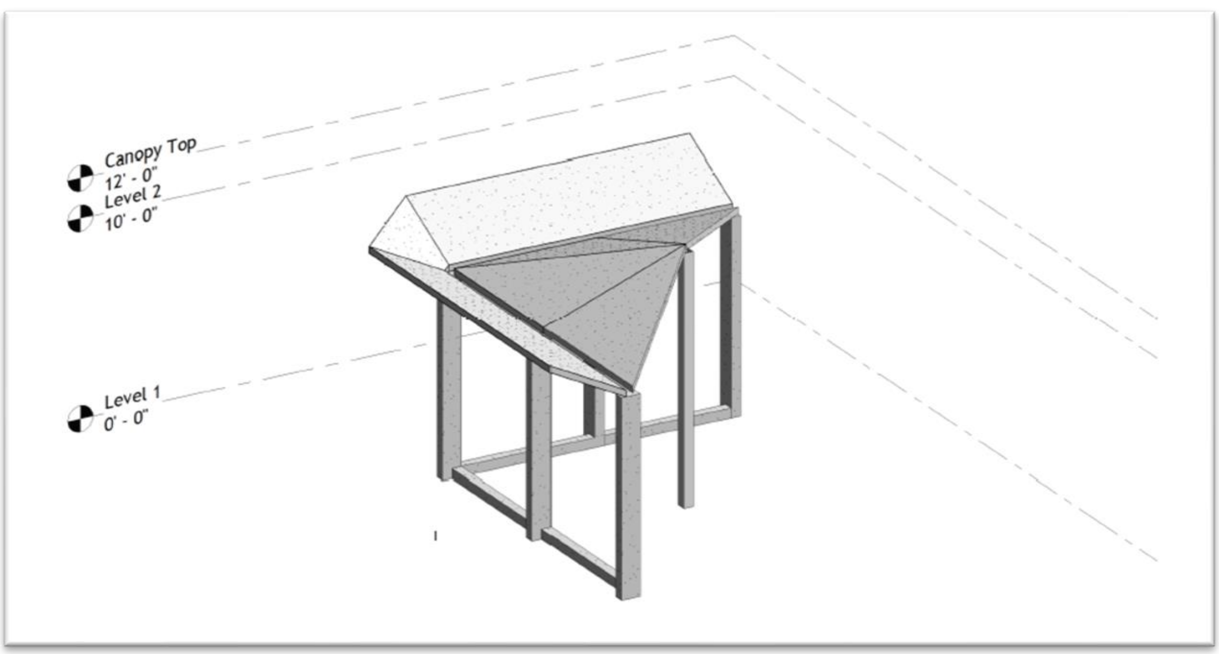


Fig. 8 Mock-up of explored folded shell model following design charrette

Fig. 9 Steel Canopy located near Architecture Bldg. 5

3.3 Materiality

As stated before, the primary constraint of a hyperbolic paraboloid is defining a curved, theoretical shape into structural members that are readily available and accessible. When considering the material for the canopy, accessibility and feasibility were the two greatest factors considered. When it comes to irregular shapes, concrete proves to be the most versatile material as it can be cast into any shape. Sourcing the concrete itself would be reasonable as the architectural engineering department sources concrete supplies for the ARCE 444-Reinforced Concrete Design lab. For this lab, there are also concrete mixers available that are accessible to students that could be utilized for this project. However, the formwork would prove to be the greatest limitation in this material approach. Given the footprint of the canopy (16’x20’), the formwork would be large and irregular. Creating a hyperbolic shape that is smooth, free of imperfections, and curved would be difficult to achieve from the formwork standpoint, and creating an even layer of concrete that wouldn't pool at either end of the formwork would be difficult to achieve. Transporting the final precast concrete would also be strenuous and require expensive machinery.

Steel proved to be a great alternative, as round steel pipes are readily available and come in a wide array of shapes and sizes. The main limitation of the steel members is the visual appeal, with the steel potentially disrupting the natural elements of the olive tree and surrounding landscaping in the courtyard.

Ultimately, timber poles were chosen as the final material for this project to best blend with the site of the canopy and allow for more feasible construction. To support the canopy, planar trusses will be utilized with dimensional lumber, and truss plates will be used to assemble the canopies. With timber poles, there are infinitesimal contact points for the round poles to make direct contact with the truss. The ends of the timber poles can be reduced to flat plates to rest directly on the truss. Timber poles are not as prevalent as dimensional lumber, but still available in the spans needed for footprint of the canopy.

3.4 Constructability

When considering constructability, paraboloid shells are desired because they can be mathematically broken down into repeated straight members to form a curve. In this case, by simply rotating a slender member along a central axis and repeating it, a curved surface can be produced (Christiansen). This idea became the foundation of the hyperbolic paraboloid design. The biggest constraint of the hyperbolic paraboloid shape isn't sourcing straight members, but rather it is determining how these members will be joined to the supporting framework. In the case of planar lumber, as the angle changes the member requires the support to constantly change elevations. Because dimensional lumber cannot be twisted, a stepped profile would be needed to accommodate these changes, as seen in Fig. 10(a) highlighted in yellow. Profiles like this are uncommon and difficult to source and would require custom profile engineering. The other option is to use a roof member that isn't planar but is round such as a timber pole, as per Fig. 10 (b). This means that at either end of the member, the support doesn't need to be modified in profile, rather the round nature of the pole will accommodate for these profile changes.

Determining the occupiable area for the canopy posed a challenge with a tree interjecting much of the site. One of the goals for this project was to impose the least amount of disruption to the existing site conditions, and that meant preserving the tree in its natural form. When it came to evaluating the usable space for the canopy, the elevations of several branches needed to be considered. The hyperbolic paraboloid shape had to conform to the elevations of existing branches, which meant certain paraboloid forms would not suffice. A form finding activity was necessary to determine the different shapes possible with the current approach.

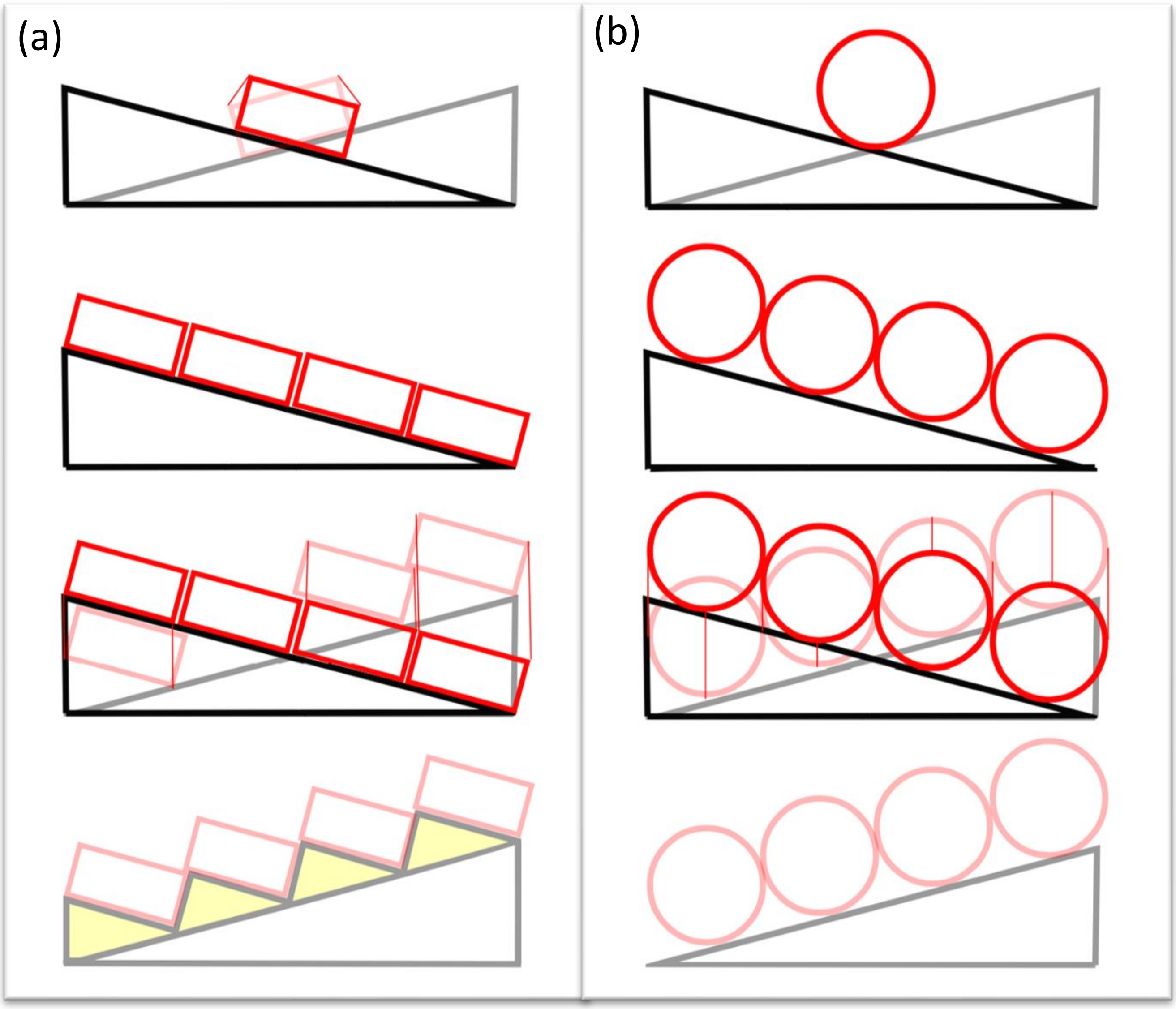


Fig. 10 Analysis of Dimensional (a) versus Circular (b) Member types relative to Inverted Trusses

3.5 Form Finding

To determine the feasibility of a hyperbolic shell, a modeling experiment was performed with 6" applicator sticks and twine (see Fig. 11). Curves are fundamentally composed of a series of repeated straight lines. A set of 80 sticks were connected using twine, resembling a bamboo placemat. This mat was then flexed in different ways to visualize the potential shapes that this repeated series would form.

Fig. 11 Mat Construction by Vigh

Following the experiment, the question arose of how this would mimic the constructability of the canopy? When considering construction materials, the closest material resembling an applicator stick would be logs or bamboo sticks, which are difficult to source for this project.

Through this form finding exercise, the final shape of the canopy was established, with two inverse trusses and an evolving canopy profile to follow the changes in elevation of each canopy (see Fig. 12). The applicator sticks proved to seamlessly align with the opposing grades of the opposite trusses, and this idea was to be further tested on the larger scale diorama.

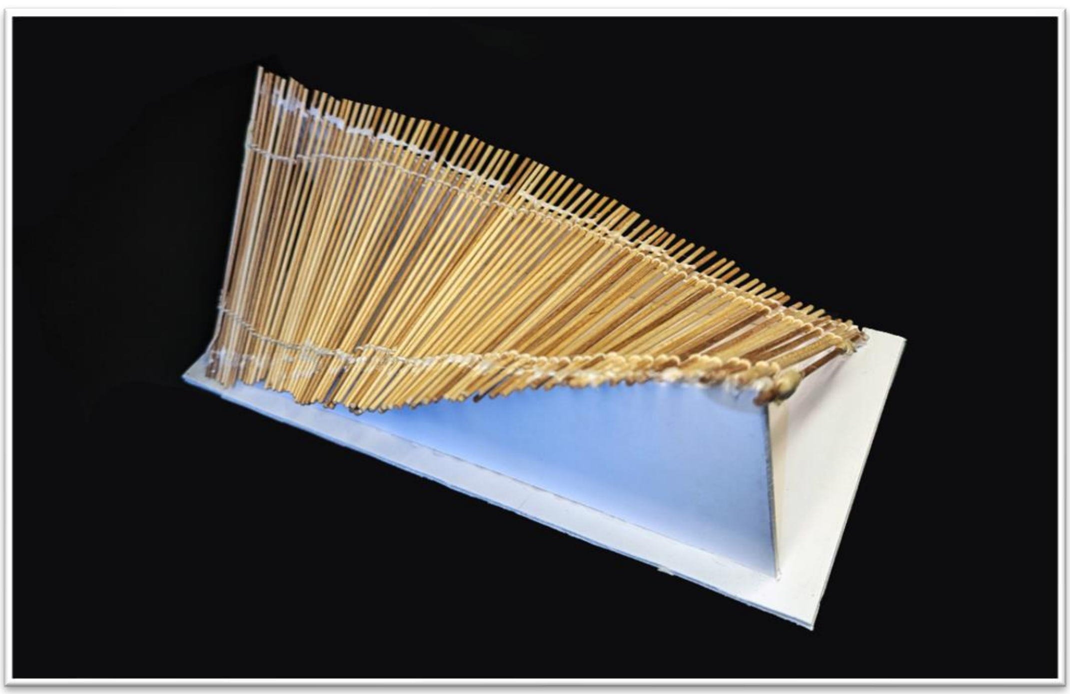


Fig. 12 Canopy Prototype Isometric View

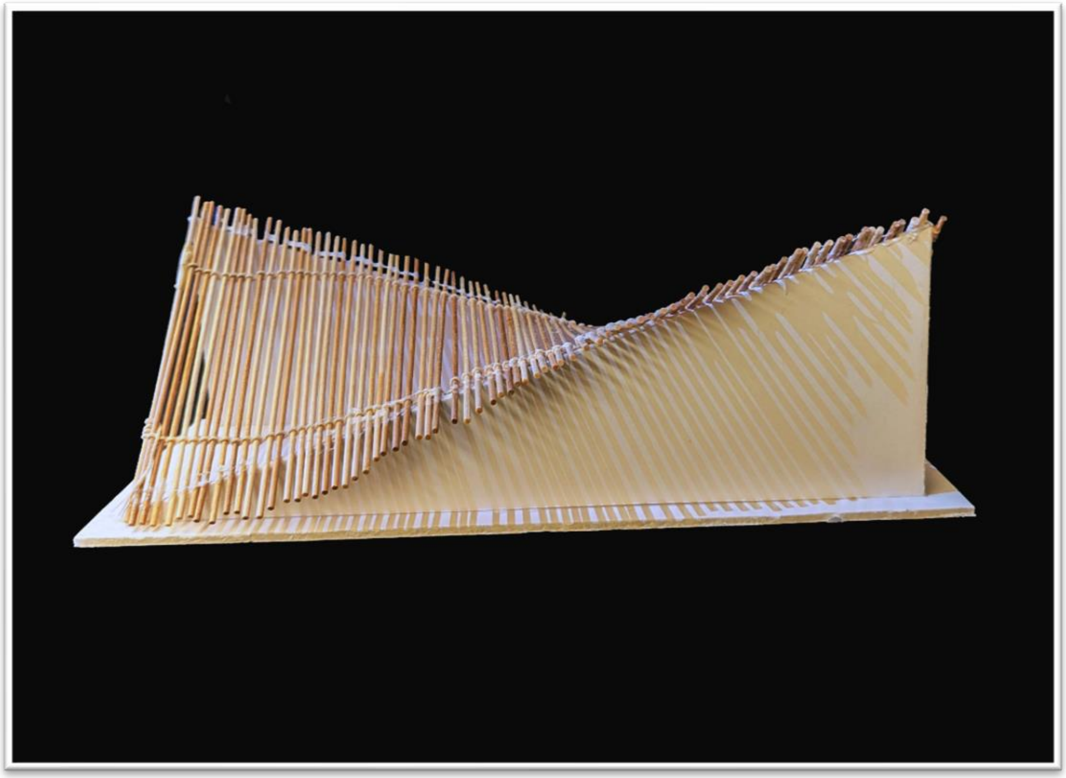


Fig. 13 Canopy Prototype East Elevation

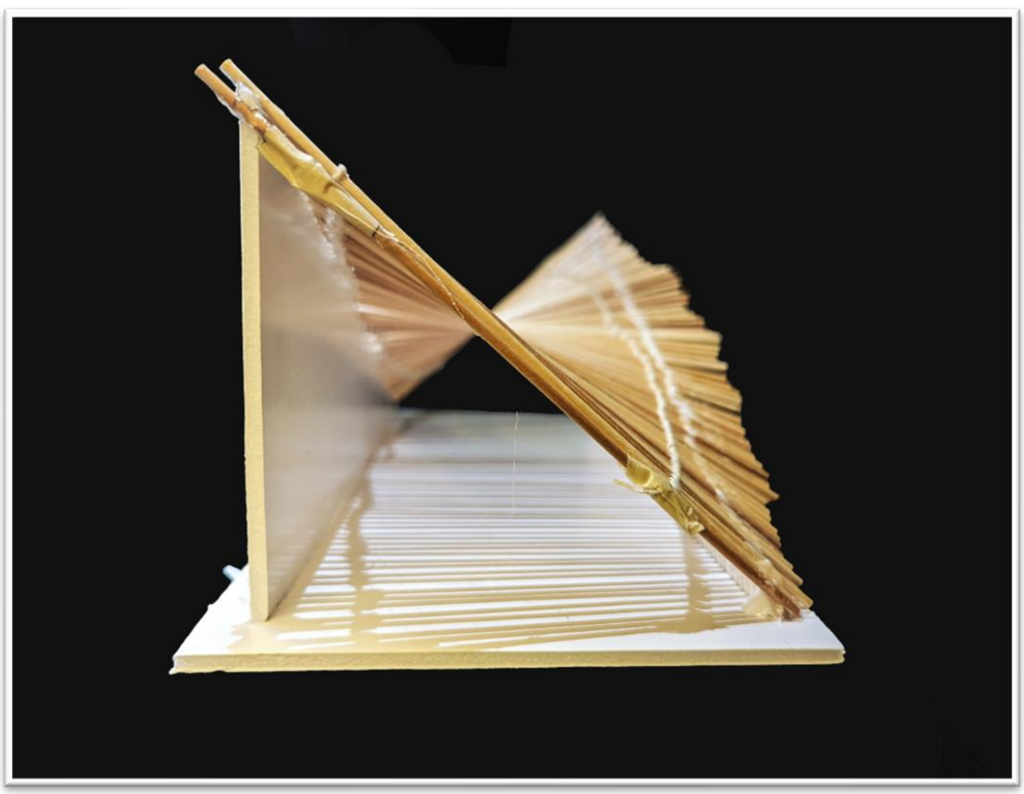


Fig. 14 Canopy Prototype South Elevation

3.6 Positive Slope Design Considerations

In order to finalize the height of the trusses in the design, the slope limitations had to be evaluated. The two defining factors in the height of the trusses were the olives and water, as snow and other roof loadings weren't necessary in the scope of this project. By determining the minimum slope requirements for water drainage and olive collection, the minimum truss height could be determined and evaluated with the existing conditions.

3.6.1 Olive Slope

To determine the necessary slope needed to ensure olives would roll off the roof, a small-scale experiment was conducted. There were several conditions tested in this experimentation, including drop height, olive configuration, and slope. The test was conducted using collected olives and a 2x4 wooden member to mimic the wooden roof members. For each test, it was noted whether the olive began rolling under the given parameters with a simple yes (Y) or no (N). Three different olives were collected for this experiment, varying in size, texture, and blemishes (see Fig. 15). Two drop heights were tested, one starting at rest on the slope (0 inches), and one dropped from a height of 6 inches to mimic an olive falling from the tree. It was observed that for the olives starting at rest, a steeper slope of 15 degrees was needed to fully clear all olives while only a slope of 10 degrees was needed to clear all olives when dropped from 6 inches. Two drop configurations were also observed per Fig. 16; Configuration A where the olive started parallel to the slope, and Configuration B where the olive started perpendicular to the slope. Configuration A proved more difficult for the olive to engage motion, and with an adequate slope to overcome the coefficient of friction, the olive was able to engage and would turn to the horizontal Configuration B and roll down the slope.

Fig. 15 Olive Specimens

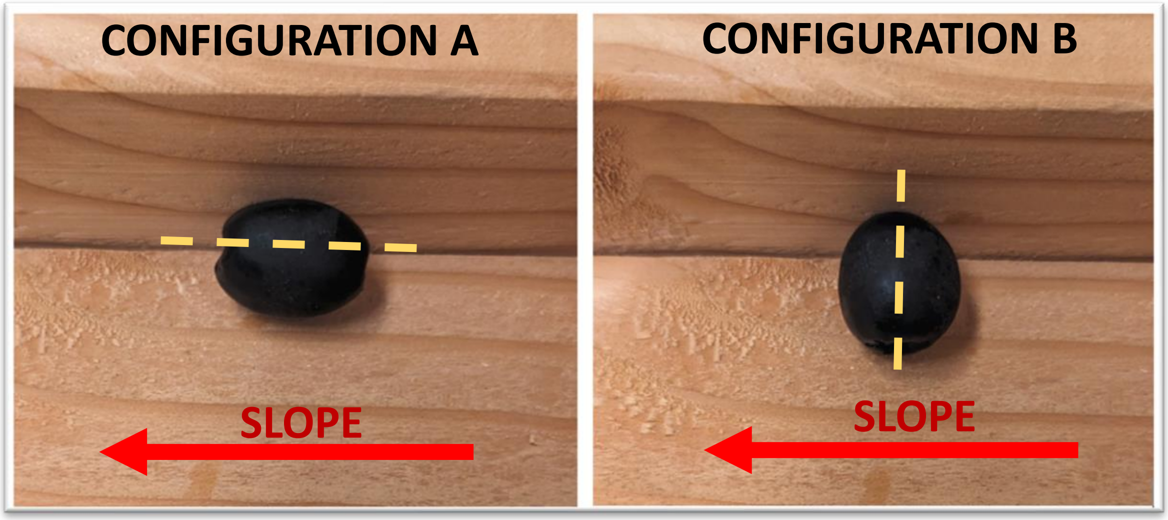


Fig. 16 Olive rolling configurations detailing the orientation relative to the slope

Table 1 Olive engagement across varying configurations, specimens, slopes, and drop height

SLOPE	DROP HEIGHT	Configuration A			Configuration B		
		OLIVE 1	OLIVE 2	OLIVE 3	OLIVE 1	OLIVE 2	OLIVE 3
2 degrees	0 in	N	N	N	Y	Y	Y
5 degrees	0 in	N	N	N	Y	Y	Y
10 degrees	0 in	N	N	N	Y	Y	Y
12 degrees	0 in	N	Y	N	Y	Y	Y
15 degrees	0 in	Y	Y	Y	Y	Y	Y
18 degrees	0 in	Y	Y	Y	Y	Y	Y
2 degrees	6 in	Y	N	Y	Y	Y	N
5 degrees	6 in	Y	Y	N	Y	N	Y
10 degrees	6 in	Y	Y	Y	Y	Y	Y
12 degrees	6 in	Y	Y	Y	Y	Y	Y
15 degrees	6 in	Y	Y	Y	Y	Y	Y
18 degrees	6 in	Y	Y	Y	Y	Y	Y

Through this experiment, it was observed that beyond 10 degrees at any configuration or drop height, each specimen was able to engage and successfully roll down the member (see Table 1). This slope consideration will be evaluated in the final design of the roof.

3.6.2 Water Slope

Per the 2024 IBC, it is started that that minimum design slope of built-up roofs is ¼ unit vertical per 12 units horizontal (2% slope) for drainage per section 1507.10.1. This is the minimum slope needed for flat roofs, and by designing a sloping roof against this condition, adequate drainage could be ensured. The olive slope experimentation proved to govern in this instance, as 10 degrees proved greater than a 2% slope.

4.0 Calculations

4.1 Wind Analysis

Chapter 27 in ASCE 7-16 was referenced to analyze the structure for wind loads and calculating the wind pressure. Table 27.2-1 was followed to determine MWFRS wind loads for open buildings.

The first step from the table is to determine the risk category. Structures are categorized according to the level of risk posed to human life. According to Table 1.5-1 this structure should be categorized as low risk to human life, therefore it should be granted Risk Category I. Step two determines the wind speed, V, according to the corresponding Risk Category. From Fig. 26.5-1 A the wind speed in San Luis Obispo was deemed 87 mph. Step three determines the load parameters: K_d, exposure category, K_{zt}, K_e, G_f, enclosure classification, and GC_{pi}.

K_d factor was found in Table 26.6-1. The structure was considered a triangular trussed tower allowing the K_d factor to be 0.85.

The exposure category was determined under Section 26.7 of the ASCE 7-16. The exposure category is defined as the upwind exposure for each wind direction considering the ground surface roughness, which is influenced by the natural topography, vegetation, and structures. Section 26.7.2 goes into detail. For this structure, the exposure category was Surface Roughness B due to the urban and suburban areas and the closeness of other structures.

K_{zt} factor which can be found in Section 26.8 in the ASCE 7-16 code. This factor is applied when wind speeds up due to sudden topography changes. Since the project site has no sudden elevation changes, K_{zt} was taken as 1.0.

The K_e factor was determined in Section 26.9. This factor can be taken as 1.0 since it is the most conservative approximation, and it is permitted in all cases.

G_f was determined in Section 26.11 and as this structure is rigid, the factor can be taken as 0.85.

The enclosure classification can be found in Section 26.12 of the ASCE 7-16. This structure was considered open.

GC_{pi} factor was found in Section 26.13 and Table 26.13-1. Having classified this structure as an open building, the code states GC_{pi} is negligible.

Step four determines the velocity pressure coefficient K_z and K_h using Table 26.10-1 in the ASCE 7-16 code. The height of the column plus the canopy was considered under 15 feet and as stated before with an exposure category B, the velocity pressure coefficient was 0.57.

Step five determines velocity pressure by using Equation 26.10-1 from ASCE 7-16,

$$q_z = 0.00256 K_z K_{zt} K_e V^2$$

where K_z is the velocity pressure exposure coefficient (dimensionless),

K_{zt} is the topographic factor (dimensionless),

K_d is the wind directionality factor (dimensionless),

K_e is the ground elevation factor (dimensionless),

V is the basic wind speed, in mi/hr,

q_z is the velocity pressure at height z.

Using the above equation and previously stated coefficients a value of 11.04 psi was calculated.

Step six determines the external pressure coefficient C_n, by using Fig. 27.3-4 for a monoslope roof open building. The slope of the truss was calculated by using the simple trigonometric tangent equation,

$$\tan\theta = \frac{opposite}{adjacent}.$$

where opposite side is the vertical length of 3 feet,

adjacent side is the horizontal length of 15 feet.

Given the structural slope evaluation from above, the limiting factor for the slope was the olive clearance, which through trials proved to be 10 degrees. After surveying the area, it was determined that a max truss height of 3 feet can be used to clear the surrounding branches. By using the above equation, the roof angle was determined to be 11.3 degrees. This slope corresponds to the minimum slope of 10 degrees needed per the olive slope. Interpolation was needed since the chart does not provide this option. As depicted in Table 2, Excel was used to interpolate between 7.5° and 15° for the 11.3° slope.

Table 2 Excel Interpolation

ROOF ANGLE	LOAD CASE	Wind Direction ɣ = 0				Wind Direction ɣ = 180			
		Clear Wind Flow		Obstructed Wind Flow		Clear Wind Flow		Obstructed Wind Flow	
		C_{NW}	C_{NL}	C_{NW}	C_{NL}	C_{NW}	C_{NL}	C_{NW}	C_{NL}
7.5°	**A**	-0.6	-1.0	-1.0	-1.5	0.9	1.5	-0.2	-1.2
15°		-0.9	-1.3	-1.1	-1.5	1.3	1.6	0.4	-1.1
7.5°	**B**	-1.4	0.0	-1.7	-0.8	1.6	0.3	0.8	-0.3
15°		-1.9	0.0	-2.1	-0.6	1.8	0.6	1.2	-0.3
11.3°	**A**	-0.75	-1.15	-1.05	-1.50	1.10	1.55	0.10	-1.15
11.3°	**B**	-1.65	0.00	-1.90	-0.70	1.70	0.45	1.00	-0.30

Step seven calculates wind pressure on each building surface for open buildings by using equation 27.3-2,

$$p = q_h K_d G C_N$$

where q_h is velocity pressure evaluated at mean roof height h, feet,

K_d is the wind directionality factor (dimensionless),

G is the gust-effect factor found in Section 26.11.1,

C_N is the net pressure coefficient found in Fig. 27.3-4.

Table 3 illustrates the values calculated from Fig. 27.3-4. It is important to note Load Case A represents the windward parapet pressure and Load Case B represents the leeward parapet pressure.

Table 3 Wind Pressure Calculation

WINDWARD LOAD CASE A (psf)								
	C_{NW}	C_{NL}	C_{NW}	C_{NL}	C_{NW}	C_{NL}	C_{NW}	C_{NL}
P_{11}	-6.00	-9.19	-8.38	-11.96	8.80	12.37	0.83	-9.17

LEEWARD LOAD CASE B (psf)								
	C_{NW}	C_{NL}	C_{NW}	C_{NL}	C_{NW}	C_{NL}	C_{NW}	C_{NL}
P_{11}	-13.19	0.00	-15.18	-5.57	13.57	3.61	8.00	-2.39

See Appendix ASCE 7-16 for Figures and Tables.

These values show that the design pressure for the windward case is 12.36 psf, while the leeward pressure is 15.18 psf.

4.2 Shear Check

The shear capacity and demand had to be calculated to analyze this structure further. For these calculations, #3 stirrups and #4 reinforcement rebar used were assumed, as well as a factored shear force of 200 lbs. All references for these calculations come from ACI 318 – 19 (22). The nominal shear strength provided by the concrete is found using Table 9.6.2.1 equation,

$$V_c = 2\sqrt{f'_c}b_w d$$

where f'_c is the specified concrete strength, psi,

b_w is the web width or diameter of circular section, in,

d is the distance from extreme compression fiber to centroid of longitudinal tension reinforcement, in.

The maximum shear strength provided by the shear reinforcement can be calculated using equation 22.5.1.2,

$$V_{s,MAX} = 8\sqrt{f'_c}b_w d.$$

These equations determined a value of 7,495 lbs. and 29,980 lbs. for the concrete shear strength and the shear reinforcement shear strength, respectively.

The summation of those two values allows a total of 37,475 lbs. for the nominal one-way shear strength at a section, V_n. The factored shear force divided by the shear factor of 0.75 gives a total of 266.7 lbs. which is much smaller compared to the nominal shear strength value.

A new steel shear strength can be calculated by using equation 22.5.8.5.3,

$$V_s = \frac{A_v f_{yt} d}{S}$$

where A_v is the area of shear reinforcement within spacing, in,

f_{yt} is specified yield strength of transverse reinforcement, psi,

d is the distance from extreme compression fiber to centroid of longitudinal tension reinforcement, in,

S is the spacing between shear reinforcement, in.

This computation gives a new steel shear reinforcement of 16,300 lbs.

The final step to analyze the shear reinforcement of the structure is to use the following equation and to check if its greater than the factored shear force at section,

$$\varphi V_n = \varphi(V_{s,new} + V_c).$$

Comparing the two values of 23,795 lbs. and 200 lbs. indicates ϕV_n is in fact lager than V_u.

4.3 Deflection Analysis

In order to test deflection, the concrete needed to be evaluated against cracked and uncracked section properties. First, the tensile strength of the concrete was assumed to be 10% of the compressive strength. Therefore, for an assumed concrete strength of f'_c = 3,000 psi, the tensile strength was computed with the following formula,

$$f_{ct} = 0.1 f'_c$$

where f_{ct} is the tensile strength of concrete, psi,

f'_c is the specified concrete strength, psi.

In this case, the tensile strength of the concrete was assumed to be 300 psi. The moment of inertia for weak axis bending of the column I_{yy} was computed with the following as,

$$I_{yy} = \frac{hb^3}{12}$$

where I_{yy} is the moment of inertia of section about vertical axis, in^4,

h is the height dimension of the rectangular column section, in,

b is the base dimension of the rectangular column section, in.

For the rectangular concrete column with 6.5” x 12”, the moment of inertia was computed as 274.6 in^4. This moment of inertia along with the tensile strength of concrete was used to determine the uncracked section threshold of the concrete columns. The stress equation considered in this evaluation in its base condition was,

$$\sigma = \frac{My}{I}$$

where σ is the bending stress, psi,

I is the moment of inertia of a section about centroidal axis, in^4,

M is the bending moment applied to structural member, lb-ft,

y is the distance from centroidal axis of gross section to extreme fiber, in,

This formula can be rewritten in terms of the tensile stress and the moment created by the applied horizontal force (V) times the height of the member (H):

$$f_{ct} = \frac{(VH)y}{I}$$

By inputting the 300 psi tensile strength of concrete for σ, 3.25 inches for the distance from the neutral axis in weak-axis bending, 8 feet for the height of the structure, and 274.6 in^4 for the moment of inertia, a max shear of 264 lbs. was computed. This value shows that the concrete can endure 264 lbs. of shear before cracking occurs in the member. In the design of the canopy structure, as long as this shear is not exceeded, the concrete can be considered under uncracked section properties. The value of the max uncracked shear strength coincides with the

With the section determined as uncracked, the deflection concrete columns can be analyzed under the following parameters,

$$\Delta = \frac{PH^3}{3E_cI} - \frac{1.2PH}{GA}$$

where Δ is the deflection of the member, in,

I is the moment of inertia of a section about centroidal axis, in^4,

E_c is the modulus of elasticity of concrete, ksi,

P is the applied axial load, kips,

H is the height of the member, in,

G is the shear modulus, approximated as 0.4E, ksi,

A is the cross-sectional area of the member, in^2, Before computing the deflection, a span-to-depth ratio was evaluated to determine what limit state governs the columns. In this case, the 8’ column with a 6” depth produced a ratio that largely exceeded 5, proving that the column was flexure governed. Therefore, the shear portion of the deflection formula could be neglected. To estimate the modulus of elasticity of concrete, the column was assumed to be normal-weight concrete with a compressive strength of 3000 psi. From ACI 318-19, section 19.2.2.1 was referenced to evaluate the modulus of elasticity using Equation 19.2.2.1.b,

$$E_c = 57{,}000\sqrt{f'_c}$$

where E_c is the modulus of elasticity of concrete, psi,

f'_c is the specified concrete strength, psi.

Using this equation, it was determined that the modulus of elasticity of concrete was 3,122 ksi. The predicted axial load for the structure was 0.900 kips, conservatively, to account for unexpected weight on the column. Using the deflection formula, the expected displacement of the structure under uncracked concrete conditions was 0.116 inches, which was deemed appropriate for the given structure.

5.0 Diorama Construction

5.1 Cost Analysis

The estimated budget for the project was approximately $380.00 for the diorama. This budget covers all diorama construction supplies and tools to build it. Funding sources for this project included industry donations, as well as a $400.00 grant from the College of Architecture and Environmental Design. This project received two industry donations which supported the diorama production and existing conditions evaluation. Earth Systems donated their rebar evaluation services to be able to locate the rebar in the existing concrete structures. Walkthrough Productions also donated their surveying services by measuring the topography of the area at no cost. The services are estimated to be at least $500 for the 3D imaging and $1000 for the rebar location services (Smith, "What to Keep in Mind").

Table 4 Quality Diorama Budget

DATE	EXPENDITURE	COST
2024-02-09	Hobby Lobby Diorama Supplies	$79.10
2024-02-13	Campus Book Store supplies	$19.57
2024-02-28	OSB, 2x3, Base Trim	$52.57
2024-03-08	Hobby Lobby Diorama Supplies	$11.95
2024-03-09	Hobby Lobby Diorama Supplies	$7.60
2024-03-10	Acrylic Craft Sheet	$20.84
2024-03-11	Campus Book Store supplies	$31.66
2024-03-12	Hobby Lobby Diorama Supplies	$29.45
2024-03-13	Dowels and Precast	$13.01
2024-03-13	Hobby Lobby Diorama Supplies	$9.22
----	Final Supplies to finish model	$100.00
2024-02-07	Earth Systems	(**DONATION**) $1000.00
2024-02-20	Walkthrough Productions	(**DONATION**) $500.00
NET COST		**$1874.97**
CAED College Support Grant		**$400.00**
KNA/RTM Senior Project Scholarship		**$1,500.00**

5.2 Material Collection

At the beginning of the diorama construction process a simple video search on how to make a diorama base tutorial was viewed for inspiration and clarity of where to start. The video used to learn how to build a base was, "How to make diorama base; Tutorial for beginners" by Fort Workshop. This video helped guide the preliminary material collection, advising to use a foam and PVA glue to build upon the base board of the diorama (Fort Workshop). The collected materials for the diorama were easy to find at local arts and crafts stores. The starting materials obtained were a small diorama kit, a bag of fine sand, a bag of small pebbles, a variety of glues, plaster, mod podge, different color paints, different size paint brushes, and hot glue sticks. A plywood board, 2x4 stud, and a 3 7/8-inch floor trim were purchased in a home improvement store. These materials were used to create the base and a platform for the diorama.

5.3 Shop Certifications

Before the diorama could be built, a certification needed to be acquired from Cal Poly's CAED Support Wood Shop. This certification allows students to use power tools and equipment. Certifications are usually done in the first year of the Architectural Engineering program; however, due to COVID-19 most students lack the certification. Transfer students are also not certified to use the shop, and it is not a part of their orientation to become certified. Both members of the Senior Project were unable to use the shop consequently both members had to get the shop certified.

Fig. 17 Geist using the miter saw at CAED Support Shop

The certification requires a 3-hour tutorial, given by the Red-Shirt students, of all the machines in the shop. These quizzes are to fortify all the information and to establish safety in the shop.

After the tutorial, a quiz on Canvas had to be completed. Questions involved how to use each machine, what materials were allowed with different tools, and tolerances of the materials. Each student finished the certification at separate times during Week Four of Winter Quarter. In the support shop, the studs, plywood sheet, and floor trims were cut to size.

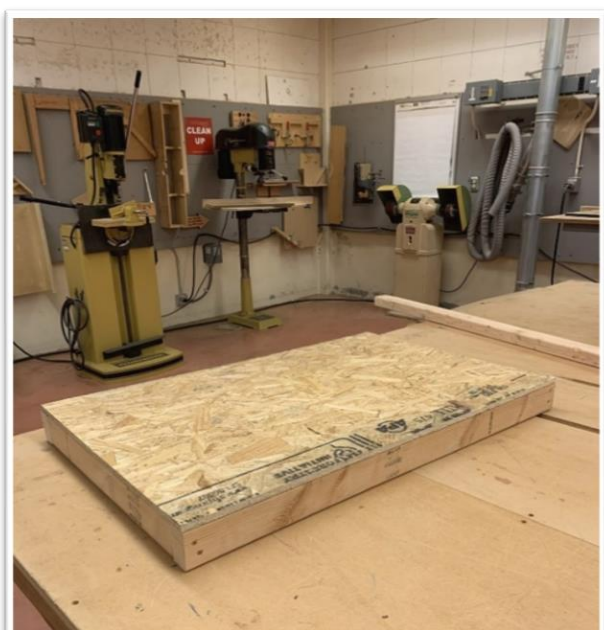


Fig. 18 Completed plywood base for Diorama

5.4 Construction Progress

5.4.1 Base Design

Different technics to build the base were tested. A hammer and nails were used first. However, such tools were inefficient to puncture the studs with the nails. A drill and screws were then used to properly secure the studs together with a length of 3 feet and width of 2 feet. A plywood sheet was added on top and was secured using a nail gun (see Fig. 18).

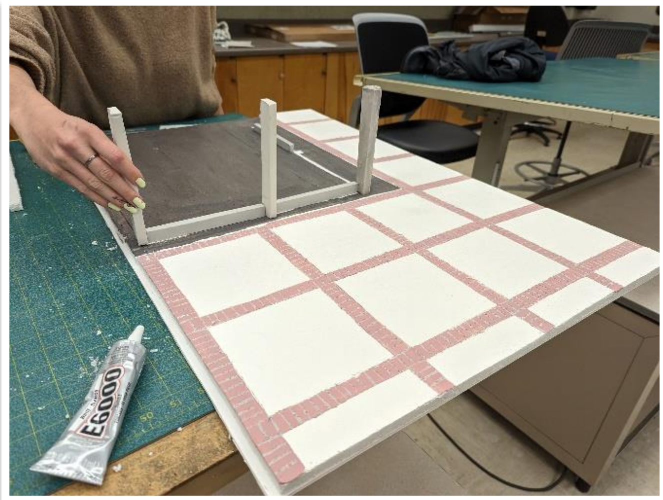


Fig. 19 Construction of Foam Board Base

After the base was finished a thin white foam board was used to create the floor of the diorama. Revit was used to correctly scale the courtyard to fit on the foam board. Different scales were tested on Revit to see what scale would allow the diorama to fit in a 3’ x 2’ x 2.33’ space in A-Lab of Engineering West. The scale that was settled on was 1” = 1’-0”.

The brick tile section on the courtyard was then sketched and imprinted on the foam board using a dull pencil. After the lines of the tiles were completed, the board was cut into individual sections having to puzzle piece section together and join them using spray adhesive and PVA glue. A thin layer of plaster was spread on the board to cover the texture of the foam to mimic the concrete ground. Indentations were made over the sketched lines to create an appearance of grout where the tiles met. After the plaster dried, the tiles were painted in colors to match the actual tiles on the courtyard (see Fig. 19).

The section that included the structure was then cut to size, glued, and using the same process as before added a thin layer of plaster. The plaster was painted in a color to match the soil of the site.

5.4.2 Concrete Column Design

Fig. 20 Bristol Paper Templates and Liners

To replicate the existing concrete columns, plaster was used and tinted with light gray acrylic paint to match the tone of the concrete. Small scale formwork was developed by making a flattened paper template of a single column and using this template to develop uniform patterns. Sample tests were performed on printer paper, Bristol paper, and cardboard, where puddles of plaster were placed on each material and allowed to cure. The plaster stuck to all materials, and therefore it was determined that plastic sheet protectors were needed as liners (see Fig. 20).

Fig. 21 Assembled Column Molds

When the plaster was cured, it emitted heat and developed condensation on the formwork. When the plaster set in the lining, the condensation remained within the lining, protecting the paper formwork from becoming exposed to the water and collapsing. Following trials with the different materials, ultimate Bristol paper was used to create molds. Each model was individually lined with the plastic sheet protecter and secured with masking tape for easy removal (see Fig. 21). The plaster mixture also needed to be modified to minimize leaking from the mold. Instead of a the recommended 2:3 ratio of water-to-plaster, a 1:2 ratio was used to create a slightly stiffer consistency that prevented leaks. After filling the molds, bridges of masking tape were laid across the top to combat bulging create an even column. The plaster was set after 30 minutes, but the columns were left overnight for a full cure.

5.4.3 Surrounding Walls and Tree

Branches were collected from the courtyard area which were used to model the olive tree in the middle of the canopy area. A mixture of brown paint, varnish, and Mod Podge was used to preserve the branches in the model. Sandpaper was used to create soft edges for the different branches to be joined together with hot glue. Globs of hot glue were applied to the model tree and concealed using the preservation mixture to mimic branch collars.

Initially, loose leaves were also collected from the courtyard that were going to be preserved for the leaves on the tree. However, these leaves proved to be too large for the model scale, and the preservation methods were too time consuming, and therefore this concept was abandoned. Artificial bouquet greenery was used instead and sourced from a craft store. This worked well with the hot glue, as it was able to securely fuse with the applied heat to the branches. Each cluster of leaves were individually applied to the tree and modeled closely to the live olive tree. Per the scale, the olives on the tree were negligible in the model.

To model the side walls of Engineering West, large poster boards were trimmed down to fit within the model scale. The East Wall was coated with a layer of blue paint, followed by a thin sheet of acetate to mimic the glossy sheen of the façade. Bristol paper was cut into thin strips and pained silver to mimic the trim of the openings and applied with super glue to the blue façade. For the North Wall, a thin layer of plaster was spread across the surface, and a rough edge of cardboard was used to texture the outer surface. Before the plaster cured, the edge of a sheet of cardstock was pressed along the left edge of the wall to create the impressions for the brick. This was then painted with the appropriate acrylic paint to mimic the red brick and cream outer wall.

Fig. 22 Tree and Wall Assembly on Diorama

Plexiglass was used as the windowpanes and sliding glass door. Each glass pane was scored and cut to fit the openings, and silver Bristol board strips were used to outline each pane. Plexiglass was thicker and stiffer than other clear materials, allowing it to hold its shape well within the openings of the wall. Acetate sheets were better suited for the East Wall texture as it was thinner and easy to apply to the existing wall base.

5.4.4 Finishing Touches

To complete the model, spray glue was used to apply dried leaves, wood pieces, and sand to the base of the model to reflect landscaping of the canopy area. Mica powder and other dried pigments were used to add dimension to the natural area. Using the faux greenery from the original model craft kit, a bush was constructed into a small piece of Styrofoam that was later secured to the main model with white PVA glue.

Spray glue was used to attach the base to the rest of the model and was further secured with a nail gun. To neaten the perimeter of the model, a prefabricated wood trim was applied to the base of the model. A-line cuts were performed to ensure the trim pieces fit together. Wood glue was applied as the initial tack to the base, followed by brad nails that were applied with the nail gun.

These finishing touches completed the final diorama for *Chioma di Ulivo*, which was placed in A-Lab of Engineering West upon completion.

Fig. 23 Completed Chioma di Ulivo Diorama

Fig. 24 Completed Chioma di Ulivo Diorama Front View

Fig. 25 Completed Chioma di Ulivo Diorama in A-Lab of Engineering West

6.0 Conclusion

Chioma di Ulivo proved successful as it created an environment that is useful for both students and faculty alike, encouraged usage and engagement in an indoor-outdoor space. Using different slope analyses, a successful olive filtration system was identified and applied to the canopy design, ensuring most olives could clear the canopy system. This space promoted architectural objectives such as circulation, aesthetics, and accessibility for facilities.

To mobilize *Chioma di Ulivio* into its next phase, *Costruzione di Piazza*, a current team of ARCE students have begun the process of permitting and further adapting the structural design for the final construction of the canopy. This team will finalize the live canopy by Spring 2025.

The proposed small canopy structure project offers an opportunity to transform the Architectural Engineering Courtyard into a vibrant and inviting outdoor space. By providing shade and shelter, it will enhance the comfort and enjoyment of students while complementing the natural beauty of the surroundings.

7.0 References

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7.1 Annotated Bibliography

Christiansen, Jack, editor. "SP-110: Hyperbolic Paraboloid Shells*." ACI Symposium Publication,* vol. 110, 1 Nov. 1988, https://doi.org/10.14359/14143.

The purpose of this book is to review the theory, materiality, cost, and construction of hyperbolic paraboloid shell structures. This text is motivated by the work of Felix Candela, a Spanish Mexican architect who majorly contributed to the development of thin, concrete shells. The work was done in conjunction with both ACI and ASCE, showing its credibility and providing reasonable restraint to the work done. The work utilizes citations of real-world design samples and analyzes the effectiveness of the shell design and uses these examples in the development of shell theory. The book was published in 1988, which may present dated code claims regarding concrete analysis, as the concrete code recycles about every 3 years. The chapters in the book are developed by ACI Committee 334, who specialized on individual data sets and techniques for each chapter, over a 10-year research effort.

Fort Workshop. "How to Make Diorama Base | Tutorial for Beginners." *YouTube*, 26 May 2022, www.youtube.com/watch?v=S11YSlD4_B4&t=183s.

Fort Workshop was founded in 2017 and specializes in prefabricated models and the mechanics behind model making. They are based in Ukraine and provide house a marketplace for prefabricated model kits, as well as house premiere equipment and adhesives needed for model making. The purpose of this source is to illustrate the different materials needed to create a topographic diorama base for model makers that are new to this practice. Fort Workshop is credible as they are aware of model chemistry and what techniques are needed to build a realistic diorama, and this video puts those practices into action.

8.0 Appendix

8.1 ASCE 7 – 16

Table 27.2 -1: Steps to Determine MWFRS Wind Loads for Enclosed, Partially Enclosed, and Open Buildings

Step 1: Determine Risk Category of building; see Table 1.5-1.
Step 2: Determine the basic wind speed, V, for the applicable Risk Category; see Figs. 26.5-1 and 26.5-2.
Step 3: Determine wind load parameters:

- Wind directionality factor, K_d; see Section 26.6 and Table 26.6-1.
- Exposure category; see Section 26.7.
- Topographic factor, K_{zt}; see Section 26.8 and table in Fig. 26.8-1.
- Ground elevation factor, K_e; see Section 26.9
- Gust-effect factor, G or G_f; see Section 26.11.
- Enclosure classification; see Section 26.12.
- Internal pressure coefficient, (GC_{pi}); see Section 26.13 and Table 26.13-1.

Step 4: Determine velocity pressure exposure coefficient, K_z or K_h; see Table 26.10-1.
Step 5: Determine velocity pressure q_z or q_h, Eq. (26.10-1).
Step 6: Determine external pressure coefficient, C_p or C_N:

- Fig. 27.3-1 for walls and flat, gable, hip, monoslope, or mansard roofs.
- Fig. 27.3-2 for domed roofs.
- Fig. 27.3-3 for arched roofs.
- Fig. 27.3-4 for monoslope roof, open building.
- Fig. 27.3-5 for pitched roof, open building.
- Fig. 27.3-6 for troughed roof, open building.
- Fig. 27.3-7 for along-ridge/valley wind load case for monoslope, pitched, or troughed roof, open building.

Step 7: Calculate wind pressure, p, on each building surface:

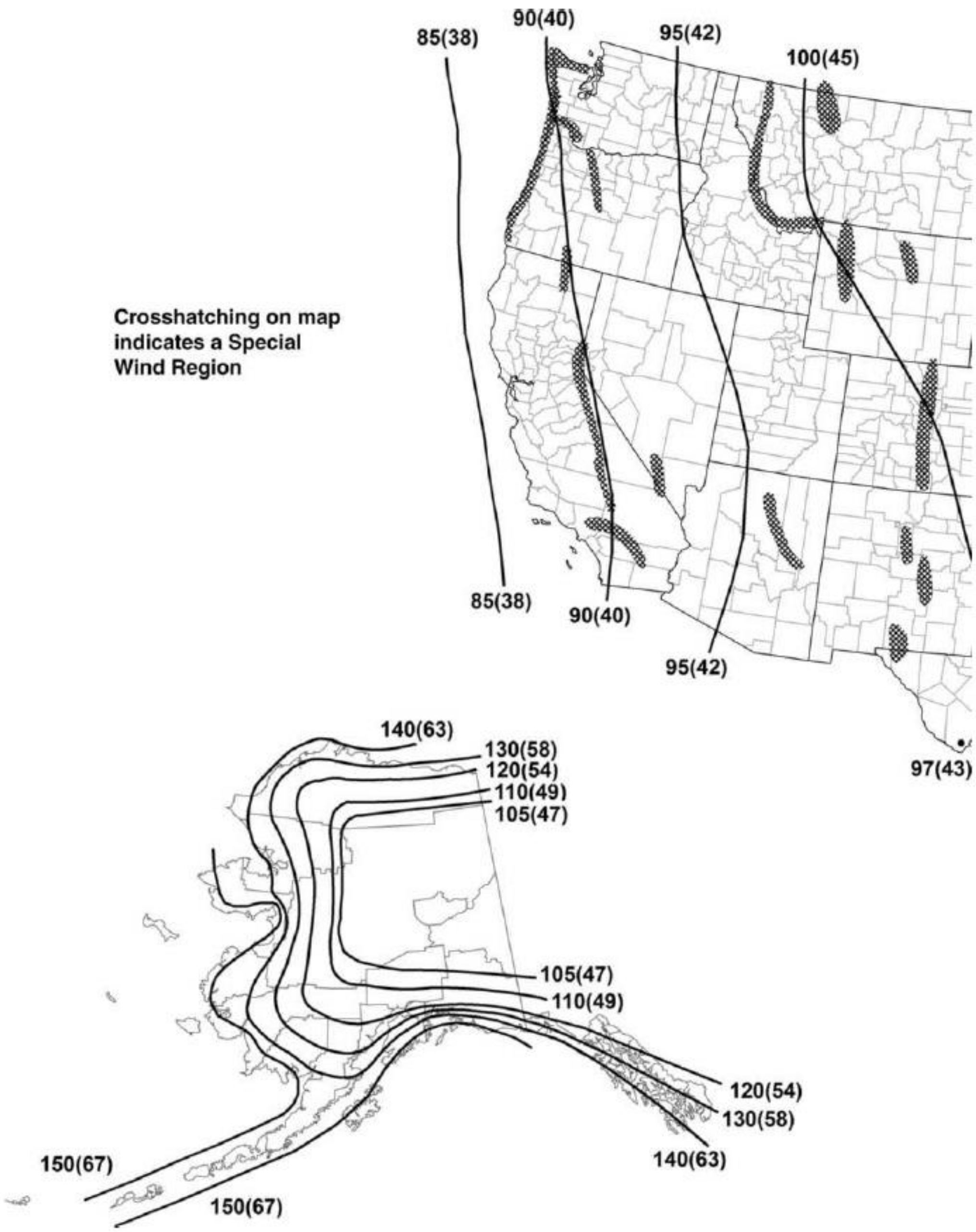
- Eq. (27.3-1) for rigid and flexible buildings.
- Eq. (27.3-2) for open buildings.

Table 1.5-1 Risk Category of Buildings and Other Structures for Flood, Wind, Snow, Earthquake, and Ice Loads

Use or Occupancy of Buildings and Structures	Risk Category
Buildings and other structures that represent low risk to human life in the event of failure	I
All buildings and other structures except those listed in Risk Categories I, III, and IV	II
Buildings and other structures, the failure of which could pose a substantial risk to human life	III
Buildings and other structures, not included in Risk Category IV, with potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure	
Buildings and other structures not included in Risk Category IV (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, hazardous waste, or explosives) containing toxic or explosive substances where the quantity of the material exceeds a threshold quantity established by the Authority Having Jurisdiction and is sufficient to pose a threat to the public if released[a]	
Buildings and other structures designated as essential facilities	IV
Buildings and other structures, the failure of which could pose a substantial hazard to the community Buildings and other structures (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, or hazardous waste) containing sufficient quantities of highly toxic substances where the quantity of the material exceeds a threshold quantity established by the Authority Having Jurisdiction and is sufficient to pose a threat to the public if released[a]	
Buildings and other structures required to maintain the functionality of other Risk Category IV structures	

[a]Buildings and other structures containing toxic, highly toxic, or explosive substances shall be eligible for classification to a lower Risk Category if it can be demonstrated to the satisfaction of the Authority Having Jurisdiction by a hazard assessment as described in Section 1.5.3 that a release of the substances is commensurate with the risk associated with that Risk Category.

FIGURE 26.5-1A Basic Wind Speeds for Risk Category I Buildings and Other Structures



Notes

1. Values are nominal design 3-s gust wind speeds in mi/h (m/s) at 33 ft (10 m) above ground for Exposure Category C.
2. Linear interpolation is permitted between contours. Point values are provided to aid with interpolation.
3. Islands, coastal areas, and land boundaries outside the last contour shall use the last wind speed contour.
4. Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions.
5. Wind speeds correspond to approximately a 15% probability of exceedance in 50 years (Annual Exceedance Probability = 0.00333, MRI = 300 years).
6. Location-specific basic wind speeds shall be permitted to be determined using www.atcouncil.org/windspeed.

Table 26.6-1 Wind Directionality Factor, K_d

Structure Type	Directionality Factor K_d
Buildings	
Main Wind Force Resisting System	0.85
Components and Cladding	0.85
Arched Roofs	0.85
Circular Domes	1.0[a]
Chimneys, Tanks, and Similar Structures	
Square	0.90
Hexagonal	0.95
Octagonal	1.0[a]
Round	1.0[a]
Solid Freestanding Walls, Roof Top Equipment, and Solid Freestanding and Attached Signs	0.85
Open Signs and Single-Plane Open Frames	0.85
Trussed Towers	
Triangular, square, or rectangular	0.85
All other cross sections	0.95

[a]Directionality factor $K_d = 0.95$ shall be permitted for round or octagonal structures with nonaxisymmetric structural systems.

26.7.2 Surface Roughness Categories

26.7 EXPOSURE

For each wind direction considered, the upwind exposure shall be based on ground surface roughness that is determined from natural topography, vegetation, and constructed facilities.

26.7.1 Wind Directions and Sectors. For each selected wind direction at which the wind loads are to be determined, the exposure of the building or structure shall be determined for the two upwind sectors extending 45° on either side of the selected wind direction. The exposure in these two sectors shall be determined in accordance with Sections 26.7.2 and 26.7.3, and the exposure the use of which would result in the highest wind loads shall be used to represent the winds from that direction.

26.7.2 Surface Roughness Categories. A ground surface roughness within each 45° sector shall be determined for a distance upwind of the site, as defined in Section 26.7.3, from the categories defined in the following text, for the purpose of assigning an exposure category as defined in Section 26.7.3.

Surface Roughness B: Urban and suburban areas, wooded areas, or other terrain with numerous, closely spaced obstructions that have the size of single-family dwellings or larger.

Surface Roughness C: Open terrain with scattered obstructions that have heights generally less than 30 ft (9.1 m). This category includes flat, open country and grasslands.

Surface Roughness D: Flat, unobstructed areas and water surfaces. This category includes smooth mud flats, salt flats, and unbroken ice.

26.8 Topographic Effects

26.8.1 Wind Speed-Up over Hills, Ridges, and Escarpments. Wind speed-up effects at isolated hills, ridges, and escarpments constituting abrupt changes in the general topography, located in any exposure category, shall be included in the determination of the wind loads when site conditions and locations of buildings and other structures meet all of the following conditions:

1. The hill, ridge, or escarpment is isolated and unobstructed upwind by other similar topographic features of comparable height for 100 times the height of the topographic feature ($100H$) or 2 mi (3.22 km), whichever is less. This distance shall be measured horizontally from the point at which the height H of the hill, ridge, or escarpment is determined.
2. The hill, ridge, or escarpment protrudes above the height of upwind terrain features within a 2-mi (3.22-km) radius in any quadrant by a factor of 2 or more.
3. The building or other structure is located as shown in Fig. 26.8-1 in the upper one-half of a hill or ridge or near the crest of an escarpment.
4. $H/L_h \geq 0.2$.
5. H is greater than or equal to 15 ft (4.5 m) for Exposure C and D and 60 ft (18 m) for Exposure B.

26.9 Ground Elevation Factor

The ground elevation factor to adjust for air density, K_e, shall be determined in accordance with Table 26.9-1. It is permitted to take $K_e = 1$ for all elevations.

26.11 Gust Effects

26.11.1 Gust-Effect Factor. The gust-effect factor for a rigid building or other structure is permitted to be taken as 0.85.

26.12 Enclosure Classification

26.12.1 General. For the purpose of determining internal pressure coefficients, all buildings shall be classified as enclosed, partially enclosed, partially open, or open as defined in Section 26.2.

26.12.2 Openings. A determination shall be made of the amount of openings in the building envelope for use in determining the enclosure classification. To make this determination, each building wall shall be assumed as the windward wall for consideration of the amount of openings present with respect to the remaining building envelope.

26.12.3 Protection of Glazed Openings. Glazed openings in Risk Category II, III, or IV buildings located in hurricane-prone regions shall be protected as specified in this section.

26.13 Internal Pressure Coefficients

Internal pressure coefficients, (GC_{pi}), shall be determined from Table 26.13-1 based on building enclosure classifications determined from Section 26.12.

Table 26.13-1 Main Wind Force Resisting System and Components and Cladding (All Heights): Internal Pressure Coefficient, (GCpi), for Enclosed, Partially Enclosed, Partially Open, and Open Buildings (Walls and Roof)

Enclosure Classification	Criteria for Enclosure Classification	Internal Pressure	Internal Pressure Coefficient, (GC_{pi})
Enclosed buildings	A_o is less than the smaller of $0.01A_g$ or 4 sq ft (0.37 m) and $A_{oi}/A_{gi} \leq 0.2$	Moderate	+0.18 −0.18
Partially enclosed buildings	$A_o > 1.1A_{oi}$ and $A_o >$ the lesser of $0.01A_g$ or 4 sq ft (0.37 m) and $A_{oi}/A_{gi} \leq 0.2$	High	+0.55 −0.55
Partially open buildings	A building that does not comply with Enclosed, Partially Enclosed, or Open classifications	Moderate	+0.18 −0.18
Open buildings	Each wall is at least 80% open	Negligible	0.00

Notes
1. Plus and minus signs signify pressures acting toward and away from the internal surfaces, respectively.
2. Values of (GC_{pi}) shall be used with q_z or q_h as specified.
3. Two cases shall be considered to determine the critical load requirements for the appropriate condition:
   a. A positive value of (GC_{pi}) applied to all internal surfaces, or
   b. A negative value of (GC_{pi}) applied to all internal surfaces.

Table 26.10-1 Velocity Pressure Exposure Coefficients, K_h and K_z

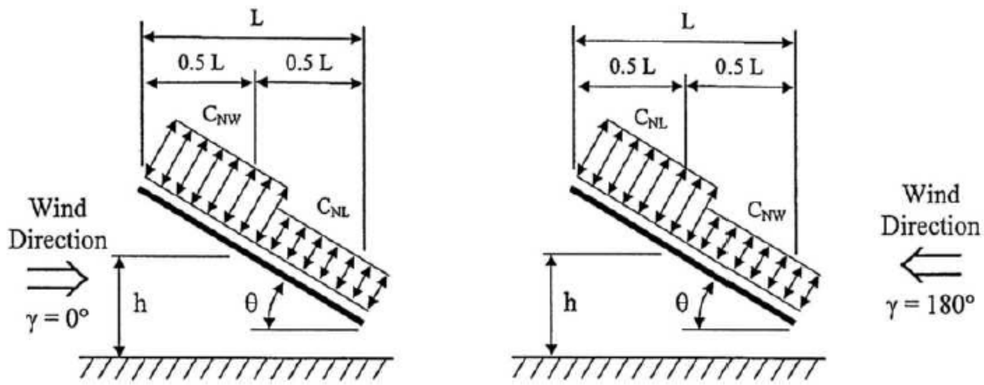
Height above Ground Level, *z*		Exposure		
ft	m	B	C	D
0–15	0–4.6	0.57 (0.70)[a]	0.85	1.03
20	6.1	0.62 (0.70)[a]	0.90	1.08
25	7.6	0.66 (0.70)[a]	0.94	1.12
30	9.1	0.70	0.98	1.16
40	12.2	0.76	1.04	1.22
50	15.2	0.81	1.09	1.27
60	18.0	0.85	1.13	1.31
70	21.3	0.89	1.17	1.34
80	24.4	0.93	1.21	1.38
90	27.4	0.96	1.24	1.40
100	30.5	0.99	1.26	1.43
120	36.6	1.04	1.31	1.48
140	42.7	1.09	1.36	1.52
160	48.8	1.13	1.39	1.55
180	54.9	1.17	1.43	1.58
200	61.0	1.20	1.46	1.61
250	76.2	1.28	1.53	1.68
300	91.4	1.35	1.59	1.73
350	106.7	1.41	1.64	1.78
400	121.9	1.47	1.69	1.82
450	137.2	1.52	1.73	1.86
500	152.4	1.56	1.77	1.89

[a]Use 0.70 in Chapter 28, Exposure B, when $z < 30$ ft (9.1 m).

Notes
1. The velocity pressure exposure coefficient K_z may be determined from the following formula:
   For 15 ft (4.6 m) $\leq z \leq z_g$ $\quad K_z = 2.01(z/z_g)^{2/\alpha}$
   For $z <$ 15 ft (4.6 m) $\quad K_z = 2.01(15/z_g)^{2/\alpha}$
2. α and z_g are tabulated in Table 26.11-1.
3. Linear interpolation for intermediate values of height z is acceptable.
4. Exposure categories are defined in Section 26.7.

FIGURE 27.3-4 Main Wind Force Resisting System, Part 1 (0.25 ≤ h⁄L ≤ 1.0): Net Pressure Coefficient, CN, for Open Buildings with Monoslope Free Roofs, θ≤45°, γ=0°, 180°)

Diagrams



Notation

L = Horizontal dimension of roof, measured in the along-wind direction, ft (m).
h = Mean roof height, ft (m).
γ = Direction of wind, degrees.
θ = Angle of plane of roof from horizontal, degrees.

Net Pressure Coefficient, C_N

		Wind Direction, $\gamma = 0°$				Wind Direction, $\gamma = 180°$			
		Clear Wind Flow		Obstructed Wind Flow		Clear Wind Flow		Obstructed Wind Flow	
Roof Angle, θ	Load Case	C_{NW}	C_{NL}	C_{NW}	C_{NL}	C_{NW}	C_{NL}	C_{NW}	C_{NL}
0°	A	1.2	0.3	−0.5	−1.2	1.2	0.3	−0.5	−1.2
	B	−1.1	−0.1	−1.1	−0.6	−1.1	−0.1	−1.1	−0.6
7.5°	A	−0.6	−1.0	−1.0	−1.5	0.9	1.5	−0.2	−1.2
	B	−1.4	0.0	−1.7	−0.8	1.6	0.3	0.8	−0.3
15°	A	−0.9	−1.3	−1.1	−1.5	1.3	1.6	0.4	−1.1
	B	−1.9	0.0	−2.1	−0.6	1.8	0.6	1.2	−0.3
22.5°	A	−1.5	−1.6	−1.5	−1.7	1.7	1.8	0.5	−1.0
	B	−2.4	−0.3	−2.3	−0.9	2.2	0.7	1.3	0.0
30°	A	−1.8	−1.8	−1.5	−1.8	2.1	2.1	0.6	−1.0
	B	−2.5	−0.5	−2.3	−1.1	2.6	1.0	1.6	0.1
37.5°	A	−1.8	−1.8	−1.5	−1.8	2.1	2.2	0.7	−0.9
	B	−2.4	−0.6	−2.2	−1.1	2.7	1.1	1.9	0.3
45°	A	−1.6	−1.8	−1.3	−1.8	2.2	2.5	0.8	−0.9
	B	−2.3	−0.7	−1.9	−1.2	2.6	1.4	2.1	0.4

Notes

1. C_{NW} and C_{NL} denote net pressures (contributions from top and bottom surfaces) for windward and leeward half of roof surfaces, respectively.
2. Clear wind flow denotes relatively unobstructed wind flow with blockage less than or equal to 50%. Obstructed wind flow denotes objects below roof inhibiting wind flow (>50% blockage).
3. For values of θ between 7.5° and 45°, linear interpolation is permitted. For values of θ less than 7.5°, use load coefficients for 0°.
4. Plus and minus signs signify pressures acting toward and away from the top roof surface, respectively.
5. All load cases shown for each roof angle shall be investigated.

8.2 2018 International Building Code

Chapter 15 – Roof Assemblies and Rooftop Structures

1504.4 Ballasted low-slope roof systems.

Ballasted lowslope (roof slope < 2:12) single-ply roof system coverings installed in accordance with Sections 1507.12 and 1507.13 shall be designed in accordance with Section 1504.8 and ANSI/SPRI RP-4.

1507.12 Thermoset single-ply roofing.

The installation of thermoset single-ply roofing shall comply with the provisions of this section.

1507.12.1 Slope.

Thermoset single-ply membrane roofs shall have a design slope of not less than one-fourth unit vertical in 12 units horizontal (2-percent slope) for drainage.

1507.12.2 Material standards. P

Thermoset single-ply roof coverings shall comply with ASTM D4637 or ASTM D5019.

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1507.12.3 Ballasted thermoset low-slope roofs.

Ballasted thermoset low-slope roofs (roof slope < 2:12) shall be installed in accordance with this section and Section 1504.4. Stone used as ballast shall comply with ASTM D448 or ASTM D7655.

1507.13 Thermoplastic single-ply roofing.

The installation of thermoplastic single-ply roofing shall comply with the provisions of this section.

1507.13.1 Slope.

Thermoplastic single-ply membrane roofs shall have a design slope of not less than one-fourth unit vertical in 12 units horizontal (2-percent slope).