# Table of Contents

Abstract........................................................................................................................................... ii

SECTION I: CONCEPT DESIGN
Literature Review......................................................................................................................... 1
Evaluation of Natural Light Penetration....................................................................................... 3
Hydroponic System Design.......................................................................................................... 5
Choice of Produce....................................................................................................................... 6
Material Considerations............................................................................................................. 7
Structural Design Considerations............................................................................................... 8
Economic Considerations........................................................................................................... 16

SECTION II: STRUCTURAL CALCULATIONS:
Structural Design Overview.......................................................................................................... S1
Loading.......................................................................................................................................... S3
Gravity System Design Calculations.......................................................................................... G1
Lateral System Design Calculations........................................................................................... L1
Foundation Design Calculations................................................................................................ F1
Connection Calculations........................................................................................................... C1

SECTION III: FUTURE DESIGNS
Analysis of Results..................................................................................................................... 17
Research Potential....................................................................................................................... 18
Conclusion................................................................................................................................. 20

SECTION IV: APPENDIX
Light Renderings......................................................................................................................... 21
Calculation Tools....................................................................................................................... 26
Sources......................................................................................................................................... 34
Miscellaneous Notes.................................................................................................................. mn-i
Abstract

Until recent years, vertical farming, or urban agriculture, has usually been referred to as more of a science fiction concept than a realistic means of production. However, it is becoming increasingly apparent that these urban crop-growing structures are not only technologically feasible, but efficient. These structures are entering the realm of economic feasibility as well, appearing in niche markets near large cities. Most of the facilities, however, are generally restricted in size to single-story buildings. The objective of this project was to design a multi story structure that would be well-equipped to house a large vertical farming operation. Some of the key aspects of the design are the use of natural light, structural stability, and minimizing the costs of construction. This report details the decision-making process behind the development of the structural design. Included are detailed explanations of the methods used to find an efficient configuration for the building that allows the maximum possible amount of natural light to be used by the facility. Significant deviations from traditional structural design were made when doing so would significantly increase the level of light allowed to be used inside the building. Details are included regarding the structural, economic, and technological challenges faced when coming up with this design. The results seem to indicate that an efficient structure is a plausible reality and could be implemented, and that this field contains a vast amount of research opportunities to come.
SECTION I

CONCEPT DESIGN
Literature Review

Farming is a practice that allows us as a society to produce enough food, and other products, to supply the demand of a vast number of people. With expanding population growth our farming practices have become extremely efficient and have expanded its own land use. With urban populations expanding there has been trouble to find and cultivate enough land to meet the ever growing demand that is occurring. On top of that transportation for a number of these products can get expensive as food is often grown far away from these urban areas. Vertical farming or indoor farming is a diverse field of technology that is used to produce food, drugs, and other products in, or near, urban environments and is one way we can tackle this growing problem (Mougeot, 2000).

Vertical farming comes in many different forms and many scholars have different ideas on how it should best be designed and implemented into these urban environments. Dr. Despommier of Columbia University believes that the ways indoor farming should be done is through tall multi-story structures. He claims that one vertical farm with an architectural footprint of one square city block and rising up to 30 stories could provide enough nutrition to comfortably accommodate the needs of 10,000 people with the currently available technologies (Despommier, 2013). However he believes that farming plants is the limit to his concept of vertical farming and that “Cattle, horses, sheep, goats, and other large farm animals seem to fall well outside the paradigm of vertical farming” (Despommier, 2013). Despommier overall believes that vertical farming is a part of handling these problems of land scarcity, food demand, and transportation. He wants the entire urban environment to be able to sustain itself on food, waste, and pollution management and thinks that vertical farming can have a huge impact on all of these areas (Despommier, 2014).

Although the people at Green Sense Farms are not as concerned with pollution or waste management effects of vertical farms could provide they are in agreement in that vertical farming is a stepping stone in indoor plant production. At Green Sense Farms they have taken indoor farming to the
operational level and have constructed a 30,000 square foot facility and designed with their own
technology. What makes this facility special is the use of a completely enclosed and controlled
environment. In this facility they use a powerful air recirculation system that filters the air, treats it for
microbes’ with UV radiation, and adds more CO$_2$ to allow for increased plant growth (Bhanoo, 2014).
This facility also treats its water the same way continuously checking its nutrients, pH and electro
conductivity for optimal plant absorption (Bhanoo, 2014). This facility is state-of-the-art but that is
because funded and backed by MIT and is in a unique position to make this technology open source, to
prototype rapidly (Bhanoo, 2014). Robert Colangelo, the president and founder of Green Sense Farms
has stated that “This facility is like a Ferrari racecar designed specifically to optimize leafy greens, if
we were to branch off into another direction we would have to redesign our system.” (Bhanoo, 2014).
This facility is on the leading edge of vertical/indoor farming technologies and is not a cost effective
solution or model quite yet with their experimental technologies.

Although technologies in other scholar’s facilities or designs are not put into practice to be
economically viable quite yet there are some structures that have begun its’ first attempt to make a
sustainable vertical farming operation. The Sky Greens facility in Singapore is the first commercial
vertical farm that was built and designed to begin to offset costs of importing vegetables (Shirk, 2015).
This system is a unique technology that slowly moves platforms dipping them into nutrient rich baths that
run off of less than $3 of electricity a month per tower (Shirk, 2015). This technology and facility is the
world’s first look at vertical farming on a commercial scale to see if it is an economically viable
concept. This is the goal to start creating facilities and try to find ways to make these concepts more and
more efficient to become viable enough to make a real impact in our upcoming problems of population
growth, land scarcity, food demand, and waste
Evaluation of Natural Light Penetration

Maximally efficient use of natural light is critical in the case of a multistory facility. The location of the building can greatly affect the patterns of light exposure on the interior. Depending on the site latitude on the planet, a design in one location may not necessarily work in another distant location. In the case of a temperate zone like San Luis Obispo, the facility is located far north of the Tropic of Cancer, which results in significant horizontal light exposure from the South, East, and West. As a result, the facility can grow crops in natural light on three sides of the building.

Since the sun’s rays are in motion and always at an angle at all times of the year, the level of light exposure on any given level will follow a general pattern of more light on the outside and gradually less in the interior areas. On a building with a side facing directly south, the area that receives full sunlight is at a 79 degree angle from the vertical, projected down from the floor above. The sun will hit that peak angle during the summer solstice, with the rest of the days having more horizontal penetration of sunlight into the interior of the structure.

Using the rendering tool in Revit 2015, the level of sunlight penetration into a model story in a building is measured by an approximated source of sunlight. The renderings were created by taking a rendered snapshot of the model for every hour of daylight on several days. The particular days studied were the summer and winter solstices, and the fall and spring equinoxes. For each day studied, a series of images was created from the horizontal penetration levels throughout the day, illustrating the areas exposed to natural light throughout the day. (see page )

This was taken a step further when the areas of natural light exposure were calculated mathematically. Using data from several Internet databases, the position of the sun was taken at 15 minute intervals throughout the day for several dates of interest. From there, formulas created in a Microsoft Excel spreadsheet were applied to generate the level of light penetration quickly. The levels of light exposure were calculated by hand from observation of the spreadsheet data.
For any given interval of time, there is a corresponding distance into the building that will be exposed to light for at least that amount of time. For example, a region with a 4 hour light rating would be exposed to a minimum of 4 hours of light throughout the day. However, some parts of the region would be exposed to direct sunlight for a significantly higher amount of time. Therefore, plants could be cycled through a region continuously such that the average level of light exposure would remain at 4 hours. The movement of plants would extend the amount of growable area inside the building.

This ideal depth to give an average exposure of 4 hours could be calculated with the data from the spreadsheet. Plotting the time on the x axis with the depth on the y axis and then using a curve fitting tool, a model equation was generated to approximate the data points. A simple integral with respect to x yields the total light exposure. The maximum depth at 4 hours is the average depth over the interval from 0 to 4 hours. This number varies depending the orientation of the building, the site location, and the time of year, which is why each day of the year yields a unique data set.

From the data, the question of building orientation and shape became apparent: south-facing or east/west-facing walls? South-facing walls dominate in the winter while walls facing in the other directions excel in summer months. Considering several days of the year as dates marking the beginning or end of a growing season, it was determined that east-west facing walls could be utilized for more growing seasons effectively, including the summer months where sunlight is more intense. There is still a portion of south-facing wall that can be used for growth as well.

The growth areas vary by season, with the ideal depth of the crop-raising system varying drastically between summer and winter. Each calendar year could be broken up into eight growing seasons of about 45 days each, with solstices and equinoxes defining most of the seasonal boundaries. Since the building is oriented with the primary growth zones facing east and west, the operation of the facility depends mostly on those areas. In the winter months, those faces of the building receive almost no consistent light, with effective depth as little as one foot on the winter solstice. It would probably be
more effective to simply have two off seasons that span from November 6th to February 4th than to attempt growing that small amount of produce. The south face of the building could still house a crop supply that is ample enough to continue operation in the winter months. During the seasons where southern light penetration is more effective than east and west combined, the corner bays on the southern end of the building could be reoriented to grow for south-facing crops instead of east-west even during regular growing seasons. Alternatively, having a single winter off-season centered on the winter solstice could yield seven growing seasons a year instead of six, with November and January growing seasons outputting relatively small but still worthwhile crop yields. Ultimately, this is a consideration that will ultimately be resolved when economics are brought into play at a later point.

**Hydroponic System Design**

The primary purpose of selecting a hydroponic system instead of in-house soil beds is to significantly reduce the overall weight of the structure. Achieving this sort of reduction in the need for heavier structural members over a large area would drastically reduce the amount of material used, and by extension, the overall cost of construction.

The basic design of the system depends on using PVC pipes spanning up to 30 feet to house the plants. Each pipe would have holes drilled at the top, typically spaced about 8 inches apart in order to allow ample growing space for the plants. The pipe would also serve as part of a distribution system that delivers nutrient-enhanced water to the plants. The spinach plants themselves would each be placed in a small, nutrient-rich container of soil that can be easily snapped into one of the holes on the PCV pipe. The container would also be porous in order to allow further absorption of nutrients flowing through the PVC pipe during operation. A typical pipe spanning 30 feet would support approximately 40 plants, and would be fitted into its place on a moving support system that allows the seed containers to be easily changed out after each growing season.
The ends of the pipes would be fitted into two different movable conveyor systems on each side of the pipe. Each pair of conveyors could house up to 50 pipes, depending on the ultimate light penetration into the building. These conveyors would be compact and framed onto light supports placed directly above the structural steel girders. Ideally, these conveyors would also contain small hoses that supply each pipe directly with water and nutrients, thus minimizing the need for a complex network of pipes connecting each pipe to a water source separately. Instead, the conveyor hoses would take water directly from the storage tanks housed in the core of the building.

For optimal efficiency throughout the year, the conveyor, support, and irrigation systems could be designed as a modular system with the ability to be easily assembled and disassembled. With the average light depth moving significantly every season, the conveyer modules would have to be capable of rapid reconfiguration by a crew of workers in just a day or two. Conveyors could be manufactured in eight or sixteen inch sections and linked together mechanically to create a system of any desired depth. This way, the target depth of light penetration would always be matched to the length of the conveyors. During the winter, when the east-west walls are in an off-season, the system could be quickly reconfigured to house more plants on the south-facing wall for a season or two. The output volume would not be as high, but it could be economically worthwhile to keep that portion of the building in operation during the winter off-season.

**Choice of Produce**

Spinach is the choice item for this project due to its fast harvest time, small size, and ability to flourish in partial shade. Most common species of this plant only require 3-4 hours of sunlight in order to effectively grow just as well as in full sunlight. Therefore, placing plants on the east-facing and west-facing sides of the building is a viable design despite the fact that those faces only receive roughly half the sunlight as an open space would.
Other crops with similar properties could also be grown in place of the spinach plants. The only required changes would be in the layout of the crop itself in order to optimize light exposure for that specific crop. Potential alternate crops to be used in the same system would include other leafy greens (cabbage, lettuce, etc.), legumes (peas, beans, etc.), and herbs (basil, rosemary, etc.). The only changes accompanying a change in crops would be altering the chemical composition of the nutrient solution fed to the plants. This would have an effectively negligible effect on the total weight inside the structure as long as the total water storage requirements did not exceed the designed capacity.

**Material Considerations**

Steel allows some of the smallest sections per unit strength and therefore the most light penetration, so the primary structural material will consist of hot rolled sections. Considering the humid nature of the indoor environment, the idea of coating the structural steel members in a corrosion-resistant material seems beneficial. The added weight to the structure is minimal, but the resulting extension of the building’s serviceable lifespan would be substantial. Significant portions of the building—such as the diaphragm trusses—can also be prefabricated in a shop and shipped out to the site, which yields both higher quality and lesser cost.

The decking system benefits the overall design of the facility if it allows light to penetrate through, extending downward for several floors. An open system such as premade steel or fiberglass grates would allow such penetration far more than a solid diaphragm like concrete or wood. Unlike residential or other building classes designed for constant use, this facility would only serve a small maintenance crew for planting, upkeep, and harvesting the crops. Therefore, an open system would not be a significant issue in terms of occupation. It is also lighter in weight when compared to solid diaphragm systems, so it would lessen the total weight of the structure.
**Structural Design Considerations**

The primary goals of the structural design are to achieve the maximum possible level of natural light exposure, to minimize use of materials, and to minimize the total cost of the facility.

The floor system is also intended to allow increased exposure to sunlight as it penetrates from the floors above. An open grate system was preferable to a traditional concrete and steel deck floor system, which blocks vertical light sources entirely. Among the options for an open system, both steel bar grating and Gator Deck fiberglass grating were considered.

**Gravity Beams and Girders**

The dead load was kept relatively light because of the lack of concrete decking throughout the building. The major contributors were the steel grate decking and the infrastructure holding up the rows of plants (which counts as dead load because it is to be anchored to the structure itself). The live load was assumed at 80 psf (corridor loading) for all areas due to the potential occupancy conditions. The usual occupancy would be only a handful of maintenance staff carrying light equipment, which only warrants a live load of up to 50 psf. The critical loading occurs either when a tour group passes through the building, or when additional workers are brought in during a harvest. The harvest condition also conflicts with the use of live load reduction as specified in ASCE 7-10. The live load reduction section assumes that large areas are seldom loaded to the absolute maximum capacity in every location, so reducing it is justified. Some exceptions are listed in which live load cannot be reduced in the case of very heavy loads, but corridor loading is not among them. However, a harvest day may actually bring live load conditions very close to that, which warrants restricted implementation of the live load reduction formula. Reduction was ultimately still used, but beams loaded to greater than 90 percent of full capacity were not used in the final design just in case the beams needed a bit of extra strength for a load that exceeded the condition prescribed by the live load reduction.
In the core bays, live load reduction was not used because it was expected that all of the large water tanks would be filled simultaneously. That scenario defeats the purpose of the live load reduction, which is why it was not justifiable to implement in the center of the building. The load condition is more akin to a storage area, which is an area that is not eligible for live load reduction in the code. The core bays were considered to have nonreducible live load, which made the beams considerably larger and deeper. This drops the ceiling clearance height in that area by a few inches, but does not obstruct the movement of people throughout that area or the natural light getting to the growth areas.

**Columns**

The vertical loads going to the exterior columns are relatively light, and therefore demand lighter column sections. A typical W8 section used in compression has a width of about 8 inches, but HSS sections can be kept as narrow as 6 inches and still support the demand loads. Therefore, columns lining the perimeter of the building were designed as HSS 6x6 sections in order to boost the total net area of wall that allows light into the building. In the core of the building, where loads from the water storage area contribute to significantly heavier column loads, HSS sections would have to be much larger. For these areas, wide flange sections were used since HSS sections lose efficiency at higher levels of axial loading, and because light exposure in a storage and maintenance area is not as important.

**Roof Canopy**

At the highest level of the structure, natural light is effectively as abundant as it would be in an open area. This level would ideally house crop-growing systems in all areas, with water storage and maintenance areas kept at a minimum. The only structure needed above the floor level would be a lightweight canopy to enclose the area in order to regulate temperature and humidity in the facility. A traditional roof structure that consisted mostly of concrete over steel deck would block out much of the light that could potentially used to grow crops across the entire floor area of the uppermost floor. The structure would essentially be a traditional greenhouse housed on the top of the building. The walls and
roof would be composed of the same polyethylene panels that act as cladding in the rest of the building. In addition to allowing more light than a standard roof composed of concrete decking, it would also have a fraction of the weight. The roof would also not be expected to have any live load applied to it since the panels are not designed to support the load of workers servicing them from above. Instead, the roof panels could be serviced by removing them from below and performing maintenance on them at ground level.

The structural system supporting the panels would be a series of long-spanning, light steel beams. The primary beams would be spaced at 6'-8" and would be WT sections. The girders, too heavily loaded to use a light weight WT section, would most likely be double angles. Both section types allow the light panels to be easily and comfortably inserted into the space between steel beams. They could be easily placed and removed from that position, but still offer an effective form of insulation from the outside environment. This results in a design that is far lighter than traditional roof systems, is made of cheaper materials, and is only loaded heavily by wind pressures. The walls throughout the building could employ a similar system that would be designed for wind loads.

**Wind & Seismic**

The basic seismic parameters were analyzed for coordinates on Cal Poly property in the agricultural area. Specifically, the building’s model site is located northwest of the core of campus, across the street from the Cal Poly poultry unit near Highway 1. There are no known fault lines in the immediate vicinity, but the area is still a high seismic zone as expected in coastal California. The building was designed to a Seismic Design Category E.

Wind parameters were determined from basic conditions outlined in ASCE 7-10 for the same site. The area has moderately hilly terrain, occasional growths of trees, and several buildings in close proximity. With those obstructions in place, the building was assigned to wind exposure category C. Category D is usually reserved for areas with effectively no wind barriers such as large flat plains, or
areas on the ocean; category B mostly applies to tightly packed urban areas. The total wind speed on the leeward side was calculated to be 27 psf, a number used throughout the analysis of the diaphragm.

Wind controlled the overall lateral base shear in the east-west direction while seismic controlled in the north-south direction. Thus, the corresponding loading on the brace frames in each direction was based on those numbers. However, with the design of the diaphragm, the magnitude of the forces varied more subtly. In the case of seismic loading, a large fraction of the base shear was concentrated at the top floor, while wind load had a more equitable distribution to all the floors.

**Diaphragm**

Ordinarily, the floor system resting upon steel beams would be corrugated steel decking with a relatively thin layer of concrete on top. The concrete can adequately resist and transfer shear forces that come to it. This floor system functions easily as a diaphragm to resist lateral forces in any given story, but it does block out sunlight from above. An alternate floor system could effectively “recycle” light from near-overhead directions as it could extend downward through multiple floors. The open grate floor system does not provide a reliable system capable of functioning as a rigid diaphragm similar to concrete. A series of braces beneath the floor system would still provide ample light exposure to floors below, but would achieve a level of stiffness comparable to the traditional concrete diaphragm.

The diaphragm used in this design was the most non-conventional system in the entire building, considering that there was not a stable floor system in place to act as a truly rigid structure capable of transferring force to the places it was intended to go. Instead, a system of small, diagonal braces was put in place of a solid floor system to transfer loads laterally around each floor. The decision to use a design like this is consistent with one of the end goals of maximizing the exposure to natural exterior lighting, which is blocked by a solid floor system. An open truss would allow upwards of 90 percent of vertical light to penetrate through, with the only sources of opacity existing as either small angle sections or thin steel bars.
In the east-west direction, the method of analysis used relies on locating the single 30-foot span of truss with the highest stress level. The truss bearing that load is located in the far north bay, which is essentially a cantilever since it is not between two rows of collectors. On the short span of 30 feet, that single truss must bear the entire wind load striking the exterior since there is no way to distribute the load to multiple trusses. The windward pressure on that single truss far exceeds the total seismic or wind base shear distributed among six or more rows of truss throughout an entire floor. Therefore, analyzing that small truss and designing for that force across the entire diaphragm is conservative. Once the lateral wind loads are transmitted to the ends of the small span trusses, the girders in the east-west direction act as distributors, spreading the load out over several trusses. On that scale, all of the small trusses behave uniformly as a single diaphragm over the full span between the two rows of vertical brace frames.

In the north-south direction, seismic lateral force was the clear governing factor over wind, so base shear was distributed according to relative mass. Initially, the north-south spanning trusses were linked in two locations across the entire building at bays near the braced frames. This establishment of continuity across the whole structure justified calculating the lateral forces based on rigid diaphragm behavior. The segments of mass on the outside bays were effectively cantilevered outside of the braced frames surrounding the innermost row of bays. The resulting force from those outside areas would have to be concentrated on two short spans of truss in order to be transferred onto collectors on grid lines B and C.

The lateral trusses would be completed by utilizing the existing gravity system beams as the chords of each truss. The truss elements were initially placed so that every beam would be attached to some form of bracing, thus reducing the potential for lateral torsional buckling drastically. Reducing the unbraced length of each beam from 30 feet to 10 feet provided a source of bracing to strengthen the gravity system while outlining the design of the diaphragm. The original idea was to use channel sections as these short braces, but were discovered to have slenderness issues at smaller sizes. Single angle
sections were eventually selected as the short braces because they have a higher radius of gyration in both directions than a channel section at a small size, which eliminates the excessive slenderness and potential for compressive buckling.

The diagonal cross braces, measuring up to 12 feet in length, were also conceived of as channel sections originally, but were not efficient at that length due to slenderness issues. The single diagonal brace designed for in the initial analysis was eventually replaced with two diagonal cross braces in each bay, which would be designed simply as metal bars. Although nearly useless in compression, the bars had a strong tensile capacity and could carry the loads while retaining low weight and cross-sectional area. The change in design is justified by the existing single-brace calculations because only bars in tension would be considered viable carriers of load. The initial analyses showed all diagonal bars in compression, but simply switching the direction of loading would yield forces of the same magnitude in tension. Since the truss is symmetric and the number of bars in tension is identical regardless of force direction, the calculations are accurate in terms of the magnitude of tensile force resisted by the bars.

For the analysis of shear loads to the chords and collectors, wind and seismic were both in consideration. Wind may have governed net base shear on the entire building, but the distribution of seismic forces was more heavily concentrated at the upper levels of the building, which led to seismic force being the controlling factor in both directions for a single floor.

**Lateral System**

In order to maximize light penetration, the goal is to bring the lateral system inside as much as possible in order to avoid interference with the natural light penetration. Such systems considered included an interior core of concrete shearwalls, exterior and interior steel brace frames, and exterior moment frames. The design of the lateral force resisting system consists of balancing the light penetration issue and the torsion issue. Brace frames were ultimately selected as the system type, but their location was not conventional because placing them at the edges of the building would block out
more light. If located on the outside face of the building, the combination of larger gravity members, braces, and potentially large gusset plates would result in a significant reduction of natural light coming from the outside, with sometimes as much as 15% of the total window area compromised. Moreover, the presence of diagonal braces would introduce inconsistent light patterns that would reflect in the growth patterns of the crops. Such an unpredictable growth pattern would make maintenance and harvesting exceedingly difficult on the farmers operating the facility. For these reasons, the brace frame systems were brought away from the edges of the building to interior bays; the added complications of torsion and internal congestion were the consequences of switching to this design.

In the east-west direction, the rows of brace frames were simply moved from the northern and southern edges of the building to a location one grid line toward the center. The brace frames are perpendicular to the face of the building, thus causing minimal light interference. The braces spanning crop-growing areas are also oriented so the end near the wall is anchored at ceiling level, and the interior end at floor level. This was done to ensure that light entering the building at an angle was blocked out as little as possible. This does create an issue in which movement in the crop-growing areas is limited by the braces, which is resolved by corridors being routed through the central row of bays. The center bay would also have a brace across it, but there is still ample space for doorways allowing movement in that area. On the north side, the missing bay in the center would restrict movement to the far north bays, which is why a short balcony was inserted to allow that movement. The beam would be a W10x26 to match the typical growth bays, which is adequate because the balcony beam’s load demands are less than that of the beams in crop-growing areas. The balcony would be used as a corridor with a tributary area much smaller than that of W10x26 girders of the same span length. Additionally, it would not expected to house large water tanks or crops, leaving only the corridor live load, which is identical to the one assumed in the other areas, thus justifying the low load demands.
In the north-south direction, a similar action was taken to bring the brace frames inside the building to the core area, but doing so in this axis gave rise to another issue: torsion. With the frames placed in the central grid lines, the distance between them was reduced to 20 feet, or one third of the total building width. This design choice works because the building was designed to be highly symmetric on this axis anyway. Only the accidental torsion of five percent specified in the ASCE 7-10 contributed to the rigid diaphragm twisting. The effects of torsion in a level were actually kept relatively low. In terms of the brace layout itself, two braces per bay were designed similarly to a zipper frame, but without intermediate columns. This cuts down on slenderness of the braces in compression and increases redundancy of the lateral system in this direction.

**Foundations**

The only foundations required at first would be isolated footings at the base of the columns since there are no structural walls present in the design. The default system was considered to be a simple reinforced concrete pad footing beneath each column. The typical bearing pressures for soil per the CBC 2013 (identical to 2012 IBC) were used, with stiff soil being the assumed soil type. This worked for the exterior columns on the building, with square footings of side length 11 feet. The interior column footings however, would have required a side length of more than 20 feet. A deep-foundation solution such as a concrete caisson could be more effective in supporting the load, so that route was taken in the calculations. In the case of the building experiencing overturning forces, the deep foundations are also functional for tension resistance. A simple pad footing simply cannot provide this type of resistance, so deep foundations were used below any column where overturning was likely to occur. If buildings like this were to be actually constructed, an analysis by a geotechnical engineer would be valuable when designing facilities in excess of 5 stories such as this one.
Economic Considerations

Given the complex nature of the motion of sunlight throughout the day, it would be intuitive that an unusual shape would best optimize the building for light penetration. However, considering the nature of operating such a facility, keeping the building rectangular would make management and usage far more simple and streamlined. The rectangular bays allow the conveyor systems to be easily reconfigured for different growing seasons to maximize production. For example, southern exposure is more favorable during the winter, and therefore the corner bays should be oriented southward instead of east and west.

Additionally, some material choices such as fiberglass decking and polyethylene were chosen because of their economic advantages. Using a deck system made of a material that is already corrosion resistant in a humid environment is superior to painstakingly coating a vulnerable steel grate system in an anti-corrosion covering. The fiberglass does not have the spanning capabilities that steel does, but adding an extra beam per bay for support was economically favorable to the added labor costs of protecting the steel decking from corrosion. The center bays were an exception, however, because the fiberglass decking could not support the heavy load of water storage tanks. The polyethylene panels are economically favorable over glass because they are lighter, cheaper, and easier to replace. Further phases of projects like this will be subject to a wider range of options regarding the control of construction and operation costs in the facility.
SECTION II

STRUCTURAL CALCULATIONS
STRUCTURAL DESIGN OVERVIEW

Building Codes Considered
ASCE 7-10
CBC 2013
AISC Steel Design Manual, 14th Edition
ACI 318-04

Sds=0.791g
Sd1=0.450g
Soil Classification: D
Seismic Design Category: E

Basic Wind Speed: 110 MPH
Exposure Category: C

Materials
Wide Flange Steel Sections: ASTM A992 Steel (50 ksi)
Hollow Structural Sections: ASTM A500 Steel (46 ksi)
Single and Double Angle Sections: ASTM A36 (36 ksi)
WT Steel Sections: ASTM A36 (36 ksi)
Solid Steel Bars: ASTM A36 (36 ksi)
Normal Weight Concrete: 4 ksi
Reinforcing Steel: ASTM Gr. 60 (60 ksi)
Fiberglass Decking: Gator Deck T5020 Grade
Steel Decking: 15-W-2: 2-½” x 3/16”(15-2-103) Welded Steel Bar Grating
Report Title: Cal Poly Vertical Farm Project

Mon May 2, 2016 07:03:12 UTC

Building Code Reference Document: ASCE 7-10 Standard

(which utilizes USGS hazard data available in 2008)

Site Coordinates: 35.3128°N, 120.68°W

Site Soil Classification: Site Class D – “Stiff Soil”

Risk Category: I/II/III

USGS-Provided Output

\[
\begin{align*}
S_5 &= 1.133 \text{ g} & S_{MS} &= 1.186 \text{ g} & S_{DS} &= 0.791 \text{ g} \\
S_1 &= 0.430 \text{ g} & S_{M1} &= 0.676 \text{ g} & S_{D1} &= 0.450 \text{ g}
\end{align*}
\]

For information on how the SS and S1 values above have been calculated from probabilistic (risk-targeted) and deterministic ground motions in the direction of maximum horizontal response, please return to the application and select the “2009 NEHRP” building code reference document.

For PGA, T, Cr, and C1 values, please view the detailed report.

# Steel Bar Grating

## Welded

### 15/16" Center to Center of Bearing Bars

### LOADING & DEFLECTION TABLE

<table>
<thead>
<tr>
<th>Bar Size</th>
<th>Symbol</th>
<th>Approx.</th>
<th>Int. Mod.</th>
<th>SPAN (Length of Bearing Bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/4&quot; x 1/8&quot;</td>
<td>15-4-32</td>
<td>W 4.7</td>
<td>U 450</td>
<td>2588 200</td>
</tr>
<tr>
<td>3/4&quot; x 1/8&quot;</td>
<td>15-4-32</td>
<td>P 5.1</td>
<td>U 450</td>
<td>1555 223</td>
</tr>
<tr>
<td>3/4&quot; x 1/8&quot;</td>
<td>15-2-32</td>
<td>W 5.3</td>
<td>C 350</td>
<td>360 257</td>
</tr>
<tr>
<td>3/4&quot; x 1/8&quot;</td>
<td>15-4-33</td>
<td>W 6.9</td>
<td>U 675</td>
<td>432 300</td>
</tr>
<tr>
<td>3/4&quot; x 1/8&quot;</td>
<td>15-4-33</td>
<td>P 7.7</td>
<td>D 390</td>
<td>095 223</td>
</tr>
<tr>
<td>3/4&quot; x 1/8&quot;</td>
<td>15-2-33</td>
<td>W 7.5</td>
<td>C 350</td>
<td>540 436</td>
</tr>
<tr>
<td>1&quot; x 1/8&quot;</td>
<td>15-4-42</td>
<td>W 6.1</td>
<td>U 800</td>
<td>512 356</td>
</tr>
<tr>
<td>1&quot; x 1/8&quot;</td>
<td>15-4-42</td>
<td>P 6.5</td>
<td>D 074</td>
<td>116 168</td>
</tr>
<tr>
<td>1&quot; x 1/8&quot;</td>
<td>15-2-42</td>
<td>W 6.7</td>
<td>C 350</td>
<td>640 537</td>
</tr>
<tr>
<td>1&quot; x 1/8&quot;</td>
<td>15-4-43</td>
<td>W 8.9</td>
<td>U 1200</td>
<td>768 533</td>
</tr>
<tr>
<td>1&quot; x 1/8&quot;</td>
<td>15-4-43</td>
<td>P 9.8</td>
<td>D 074</td>
<td>116 168</td>
</tr>
<tr>
<td>1 1/4&quot; x 1/8&quot;</td>
<td>15-4-52</td>
<td>W 7.5</td>
<td>U 1250</td>
<td>800 556</td>
</tr>
<tr>
<td>1 1/4&quot; x 1/8&quot;</td>
<td>15-4-52</td>
<td>P 8.1</td>
<td>D 1250</td>
<td>1000 833</td>
</tr>
<tr>
<td>1 1/4&quot; x 1/8&quot;</td>
<td>15-4-53</td>
<td>W 11.0</td>
<td>U 1875</td>
<td>1200 833</td>
</tr>
<tr>
<td>1 1/4&quot; x 1/8&quot;</td>
<td>15-4-53</td>
<td>P 12.3</td>
<td>D 1875</td>
<td>1500 1051</td>
</tr>
<tr>
<td>1 1/4&quot; x 1/8&quot;</td>
<td>15-4-55</td>
<td>W 11.6</td>
<td>U 1875</td>
<td>1500 1207</td>
</tr>
<tr>
<td>1 1/2&quot; x 1/8&quot;</td>
<td>15-4-62</td>
<td>W 8.9</td>
<td>U 1800</td>
<td>1152 800</td>
</tr>
<tr>
<td>1 1/2&quot; x 1/8&quot;</td>
<td>15-4-62</td>
<td>P 9.4</td>
<td>U 1800</td>
<td>1440 1200</td>
</tr>
<tr>
<td>1 1/2&quot; x 1/8&quot;</td>
<td>15-4-63</td>
<td>W 10.9</td>
<td>D 040</td>
<td>062 089</td>
</tr>
<tr>
<td>1 1/2&quot; x 1/8&quot;</td>
<td>15-4-63</td>
<td>P 11.3</td>
<td>D 2700</td>
<td>1728 1200</td>
</tr>
<tr>
<td>1 1/2&quot; x 1/8&quot;</td>
<td>15-4-63</td>
<td>W 13.7</td>
<td>U 2700</td>
<td>1728 1200</td>
</tr>
<tr>
<td>1 1/2&quot; x 1/8&quot;</td>
<td>15-4-63</td>
<td>P 16.3</td>
<td>D 040</td>
<td>062 089</td>
</tr>
<tr>
<td>1 3/4&quot; x 1/8&quot;</td>
<td>15-4-73</td>
<td>U 15.2</td>
<td>D 3675</td>
<td>2332 1633</td>
</tr>
<tr>
<td>1 3/4&quot; x 1/8&quot;</td>
<td>15-4-73</td>
<td>P 18.6</td>
<td>D 3675</td>
<td>2332 1633</td>
</tr>
<tr>
<td>2&quot; x 1/8&quot;</td>
<td>15-4-83</td>
<td>W 17.3</td>
<td>U 4800</td>
<td>3072 2133</td>
</tr>
<tr>
<td>2&quot; x 1/8&quot;</td>
<td>15-4-83</td>
<td>P 18.9</td>
<td>C 3675</td>
<td>2940 2450</td>
</tr>
<tr>
<td>2&quot; x 1/8&quot;</td>
<td>15-4-83</td>
<td>W 19.7</td>
<td>U 4800</td>
<td>3840 3200</td>
</tr>
<tr>
<td>2&quot; x 1/8&quot;</td>
<td>15-4-93</td>
<td>W 20.5</td>
<td>D 030</td>
<td>047 067</td>
</tr>
<tr>
<td>2 1/4&quot; x 1/8&quot;</td>
<td>15-2-93</td>
<td>W 19.4</td>
<td>U 6075</td>
<td>3888 2700</td>
</tr>
<tr>
<td>2 1/4&quot; x 1/8&quot;</td>
<td>15-2-93</td>
<td>P 20.7</td>
<td>D 033</td>
<td>052 074</td>
</tr>
<tr>
<td>2 1/2&quot; x 1/8&quot;</td>
<td>15-2-103</td>
<td>W 21.4</td>
<td>U 7500</td>
<td>4800 3333</td>
</tr>
<tr>
<td>2 1/2&quot; x 1/8&quot;</td>
<td>15-2-103</td>
<td>P 22.7</td>
<td>D 030</td>
<td>047 067</td>
</tr>
<tr>
<td>2 1/2&quot; x 1/8&quot;</td>
<td>15-2-103</td>
<td>W 22.0</td>
<td>U 7500</td>
<td>6000 5000</td>
</tr>
<tr>
<td>2 1/2&quot; x 1/8&quot;</td>
<td>15-2-103</td>
<td>P 24.7</td>
<td>D 024</td>
<td>037 054</td>
</tr>
</tbody>
</table>

### Press-Locked

### 15/16" Center to Center of Bearing Bars

### General

Deflection: Spans and loads to the right of the bold line exceed 1/4" deflection for uniform load of 100 psf which provides safe pedestrian comfort. These can be exceeded for other types of loads with engineer’s approval.

Serrated Bars: For serrated grating, the depth of grating required for a specified load is 1/4" deeper than that shown in the table.

Material: ASTM A-569 standard

Load and deflections are theoretical and based on static loading.
## GATORDECK T-5020 – Load & Deflection Table

**LOAD = Lbs. / Sq. Ft.**

### CONCENTRATED LOAD

<table>
<thead>
<tr>
<th>SPAN INCHES</th>
<th>LOAD TYPE</th>
<th>LOAD FOR 0.25-inch deflection</th>
<th>LOAD FOR 0.375-inch deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>UL</td>
<td>500</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>500</td>
<td>0.021</td>
</tr>
<tr>
<td>30</td>
<td>UL</td>
<td>250</td>
<td>0.032</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>250</td>
<td>0.021</td>
</tr>
<tr>
<td>36</td>
<td>UL</td>
<td>100</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>100</td>
<td>0.014</td>
</tr>
<tr>
<td>42</td>
<td>UL</td>
<td>100</td>
<td>0.045</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>100</td>
<td>0.021</td>
</tr>
<tr>
<td>48</td>
<td>UL</td>
<td>100</td>
<td>0.080</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>100</td>
<td>0.032</td>
</tr>
<tr>
<td>54</td>
<td>UL</td>
<td>100</td>
<td>0.120</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>100</td>
<td>0.045</td>
</tr>
<tr>
<td>60</td>
<td>UL</td>
<td>75</td>
<td>0.146</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>100</td>
<td>0.062</td>
</tr>
<tr>
<td>66</td>
<td>UL</td>
<td>75</td>
<td>0.200</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>100</td>
<td>0.080</td>
</tr>
<tr>
<td>72</td>
<td>UL</td>
<td>75</td>
<td>0.281</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>100</td>
<td>0.103</td>
</tr>
<tr>
<td>78</td>
<td>UL</td>
<td>50</td>
<td>0.260</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>100</td>
<td>0.129</td>
</tr>
</tbody>
</table>
## Load Takeoffs

### EXTERIOR BAY LOAD TAKEOFF

<table>
<thead>
<tr>
<th>Area-Applied Loads (psf)</th>
<th>fiberglass decking</th>
<th>Application Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberglass Decking</td>
<td></td>
<td>3 Decking</td>
</tr>
<tr>
<td>Fireproofing</td>
<td></td>
<td>1 Decking</td>
</tr>
<tr>
<td>Corrosion Resistant</td>
<td></td>
<td>1 Decking</td>
</tr>
<tr>
<td>MEP</td>
<td></td>
<td>5 Decking</td>
</tr>
<tr>
<td>Misc</td>
<td></td>
<td>3 Decking</td>
</tr>
<tr>
<td>Beams</td>
<td></td>
<td>4.2 Beams</td>
</tr>
<tr>
<td>Cross Braces</td>
<td></td>
<td>1.4 Beams</td>
</tr>
<tr>
<td>Girders</td>
<td></td>
<td>4.7 Girders</td>
</tr>
<tr>
<td>Columns</td>
<td></td>
<td>4.7 Columns</td>
</tr>
</tbody>
</table>

### TOTALS (psf)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Deck</td>
<td>13</td>
</tr>
<tr>
<td>Beams</td>
<td>19.6</td>
</tr>
<tr>
<td>Girders</td>
<td>24.2</td>
</tr>
<tr>
<td>Columns</td>
<td>28</td>
</tr>
</tbody>
</table>

### Linearly-Applied Loads (plf)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC Pipe System</td>
<td>1</td>
</tr>
<tr>
<td>Spinach Biomass</td>
<td>1.2</td>
</tr>
<tr>
<td>Movable Rack System</td>
<td>60</td>
</tr>
<tr>
<td>Rack Support</td>
<td>25</td>
</tr>
<tr>
<td>Glass/Plastic Curtain Walls</td>
<td>21</td>
</tr>
</tbody>
</table>

### Live Load (psf)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80</td>
</tr>
<tr>
<td>Area-Applied Loads (psf)</td>
<td>metal decking</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Metal Decking</td>
<td>22 Decking</td>
</tr>
<tr>
<td>Fireproofing</td>
<td>1 Decking</td>
</tr>
<tr>
<td>Corrosion Resistant</td>
<td>1 Decking</td>
</tr>
<tr>
<td>MEP</td>
<td>8 Decking</td>
</tr>
<tr>
<td>Misc</td>
<td>3 Decking</td>
</tr>
<tr>
<td>Beams</td>
<td>3 Beams</td>
</tr>
<tr>
<td>Cross Braces</td>
<td>1.5 Beams</td>
</tr>
<tr>
<td>Girders</td>
<td>4.5 Girders</td>
</tr>
<tr>
<td>Columns</td>
<td>2 Columns</td>
</tr>
</tbody>
</table>

**TOTALS (psf)**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Deck</td>
<td>35</td>
</tr>
<tr>
<td>Beams</td>
<td>39.5</td>
</tr>
<tr>
<td>Girders</td>
<td>44</td>
</tr>
<tr>
<td>Columns</td>
<td>46</td>
</tr>
</tbody>
</table>

**Live Load (psf)**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Live Load</td>
<td>135</td>
</tr>
</tbody>
</table>
WALL WEIGHT

\[ W = (3 \text{pcf} \cdot 2^2) + (12' \cdot 59 \text{pcf} \cdot \frac{1}{12} \cdot \frac{1}{4}) = 21 \text{ plf} \]

Add to ext. bm. load as DL

GIRDER WEIGHT

CONVEYOR SYSTEM

CONVEYOR SUPPORT

PVC PIPE SYSTEM

wt. of pipes: \[ 0.5 + \left( \frac{0.3^2}{4} \cdot 10.4 \right) \div 1.2 \times 6 \rightarrow 12.24 \rightarrow 13 \text{ plf} \]

conveyor st: 3 layers \times 10 \text{ plf} \times 2 \text{ columns/girder} = 60 \text{ plf}

+ Support wt: 25 plf

98 plf added to girder as Dead Load

\[ 1.2 \times 74 = 88.8 \rightarrow \text{Add } 178 \text{ plf} \text{ factored DL} \]

TYPICAL LAYOUT/
**CORE BAYS**

Water storage live load:
- Assume water is stored in tanks no larger than 2' in diameter and no more than 6' in height.

Internal Volume = \( \pi \left( \frac{2}{2} \right)^2 \cdot 6 = 18.85 \text{ ft.}^3 \)

- Water weight = 62.4 psf \( \cdot \) 18.85 \( \text{ ft.}^3 = 1178 \text{ lb.} \)

Distribute to 2' \( \times \) 2' area: \( W = \frac{294 \text{ psf}}{4} \rightarrow \) Check locally

- Assume water tanks and other heavy objects cover a maximum of 25% of the total area inside the core bays

**AVERAGE LIVE LOAD**

\[ (30 \text{ psf} \times 0.75) + (294 \text{ psf} \times 0.25) = 134 \text{ psf} \]

Use 135 psf to design for beams, girders and columns.

**FOR SEISMIC WEIGHT, INCLUDE 25% OF WATER WEIGHT IN DEAD WEIGHT**

\[ 294 \times 0.25 \times 0.25 = 18.4 \text{ psf} \]

* Tanks will almost always have some water, and be contained to one location due to anchorage to the floor. Similar live load conditions in the code also specify provisions like this for heavy load cases such as library stacks.
LL = 80 pcf

DL = 15.2 pcf

TOTAL = 1.2 D + 1.6 L = 1.50 pcf

GATOR DECK (5.2 pcf)

C 3 x 6 system (1.4 pcf)

W10 x 26 (5.2 pcf)

\[ M_u = \frac{wL^2}{8} = \frac{750 \times 30^2}{8} = 84.4 k-ft \]

CAPACITY OF W10 x 26 @ 10' UNBRACED LENGTH = 84 k-ft \( \checkmark \)

(REF. AISC TABLE 3-10)

REACTIIONS (SYMMETRIC)

\[ R = \frac{\text{TOTAL LOAD}}{2} = 750 \text{ pcf} \times 30', \frac{1}{2} = 112.5 \text{k} \rightarrow \text{GRAVITY LOAD ON GIRDER/COLUMNS} \]

TYPICAL LOCATION

EDGE OF BLDG
\[ A_c \text{ (EXT. BM)} = \frac{1}{2} \left[ A_c \text{ (INT. BM)} \right] = \frac{1}{2} (5' \times 30') = \]

\[ : \quad W_{\text{ext}} = \frac{1}{2} \times 750 = 375 \text{ pFf} \]

\[ W_{\text{TOTAL}} = 375 + W_{\text{wall}} \]

\[ W_{\text{wall}} = \frac{6 \text{ pFf}}{\text{FUTURE SOLAR}} + \frac{(1.23 \text{ psf} \times 12^2)}{\text{WALL WT.}} = 21 \text{ pFf} \rightarrow 25 \text{ pFf factored} \]

\[ W_{\text{TOTAL}} = 375 + 25 = 400 \text{ pFf} \]

\[ M_w = \frac{wL^2}{8} = \frac{400 \times 30^2}{8} = 45 \text{ k-ft.} \quad L_b = 10' \]

---

**FOR BENDING, SELECT W8 x 21:** CAPACITY = \(67' \text{ k-ft. @ } L_b = 10'\)

*VALUES OBTAINED FROM AISC TABLE 3-10*

**REACTIONS**

\[ R = \frac{400 \text{ pFf} \times 30'}{1000} \cdot \frac{1}{2} = 6.0 \text{ k} \rightarrow \text{GRAVITY LOAD ON GIRDERS/COLUMNS} \]
Typical Core Beam

250 psf

1720 psf

\[ M_u = \frac{wl^2}{8} = \frac{1720 \cdot 30^2 \cdot \frac{1}{1000}}{8} = 193.5 \text{ k-ft.} \]

Select W16 x 40 for core beams.

Capacity = 228 k-ft. per AISC Table 3-10

Shear force to girders

\[ R = 1720 \cdot 30 \cdot \frac{1}{2} \cdot \frac{1}{1000} = 25.8 \text{ k} \]

Typical Location

Hybrid loading: treat as core beam to be conservative.
Typ Ext Girder

118 psf added dead load
\[ L_b = 5' - 0'' \]

\[ \text{Peak } V = 34.9 \text{ k} \]

\[ \text{Peak } M = 228.5 \text{ k-ft} \]

**Live Load Reduction**

\[ K_{ll} = 2 \quad A_r = 600 \text{sf} \]

\[ L = L_0 \left( 25 \times \frac{15}{V_{M_{ll}} A_r} \right) = 54.6 \text{ psf} \]

\[ 1.2 (23.5) + 1.6 (34.3) = 115.5 \text{ k} \]

\[ 1.2 (23.5) + 1.6 (34.3) = 166.9 \text{ k-ft} \]

**Design Moment** : \[ M_n = 169 \text{ k-ft} \]

Select W 12 x 35 for girders in exterior bays to balance light weight with section depth capacity. @ \[ L_b = 5' = 192 \text{ k-ft} \]. Per AISC Table 3-10.

**Alternate Section Sizes**

<table>
<thead>
<tr>
<th>Section</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>W 14 x 30</td>
<td>177 k-ft **</td>
</tr>
<tr>
<td>W 10 x 39</td>
<td>175 k-ft **</td>
</tr>
<tr>
<td>W 10 x 45</td>
<td>206 k-ft</td>
</tr>
<tr>
<td>W 16 x 31</td>
<td>195 k-ft</td>
</tr>
</tbody>
</table>

**Notes**

*During a harvest time, the building may be fully occupied, which may exceed member capacity on reduced live load. Members at > 90% capacity are not 1st choice.*
Typical Girder Analysis

- \( L_b = 6.67' \)
- \( V_{max} = 51.6 \) k
- \( M_{max} = 344 \) k-ft.

Select W21 x 48, capacity: 390 k-ft.

Add girder self-weight, 48 psf:

\[
M = \frac{wL^2}{8} = \frac{48 \times 20^2}{8} = 24 \text{ k-ft.}
\]

Total \( M_{tot} = 344 + 24 = 368 \) k-ft. < 390 k-ft.

Typical Location
Spread water loads out over entire area.

\[
\left(135 \times 4 \text{ pbfys} \right) + \left(80 \times 13 \text{ rifs} \right) \div 17 = 93 \text{ psf} 
\text{ Avg. Live Load}
\]

\[1.2D + 1.6L = 1.2 \left(19.6\right) + 1.6\left(93\right) = 172.3 \text{ psf}\]

\[w = 172.3 \cdot 3.5 = 611.6 \text{ plf}\]

\[M_u = \frac{wL^2}{8} = \frac{611.6 \cdot 30^2}{8} = 96.9 \text{ k-ft.}\]

Select W12 x 26, Capacity = 114 k-ft. @ \(L_b = 10'\)

---

**Ext. Roof Beam**

\[w = \left(172.3 \cdot 2.5\right) + 25 = 455.8 \text{ plf}\]

\[M_u = \frac{wL^2}{8} = \frac{455.8 \cdot 30^2}{8} = 51.3 \text{ k-ft.}\]

Select W10 x 28, Capacity = 94 k-ft. @ \(L_b = 10'\)
1.2D + 1.6L = 1.2(24.2) + 1.6(93) = 177.8 psf

**Live Load Reduction**

\[ L = 93 \left( 0.25 + \frac{15}{\sqrt{600}} \right) = 80.2 \text{ psf} \]

\[ w = 157.4 \times 5 \times 15 = 11.81 \text{ k} \]

\[ 23.6k \quad 23.6k \quad 23.6k \]

\[ 35.4 \quad 35.4 \]

\[ 11.8 \]

\[ -11.8 \quad -35.4 \quad -35.4 \]

\[ 177 \quad 236 \quad 177 \]

\[ M = 236 \text{ k-ft.} \]

**SELECT W16 x 40, CAPACITY = 274 k-ft.**

*See p. 65 for detailed explanation of choice*
LIVE LOAD REDUCTION

\[ L = L_o \left( 1.25 - \frac{15}{A_{r}K_{lu}} \right) = 54.6 \text{ psf} \]

\[ K_{lu} = 4 \quad A_{r} = 300 \text{ sf} \]

EDGE OF BUILDING

\[ P_o = \left[ (1.2 \cdot 31) + (1.6 \cdot 54.6) \right] \cdot 10 \cdot 30 \cdot \frac{1}{1000} = 37.4 \text{ k / floor} \]

\[ (P_o \cdot 4) \text{ (normal flow)} + (2 \cdot P_o \text{ (top flow)}) = 6P_o = 225 \text{ k} \]

AXIAL LOADING

\[ k = 1.0 \quad L_o = 11' - 0'' \text{ max} \]

SELECT HSS 6\times6\times\frac{1}{2}

CAPACITY = 319 \text{ k} (AISC Table 4-4)

ABOVE COLUMN SPLICE

Total load \[ P_{total} = (2 \cdot P_o) = 4P_o = 150 \text{ k} \]

\[ k = 1.0 \quad L_o = 11' - 0'' \text{ max} \]

SELECT HSS 6\times6\times\frac{1}{4}

CAPACITY = 175 \text{ k} (AISC Table 4-4)
**Typ. Core Column**

**Live Load Reduction**

\[ K_c = 4 \quad A_c = 600 \, \text{sq ft} \]

\[ L = L_0 \left( 25 \div 12 \right) \]

\[ L = 117 \, \text{ft} \]

**Edge of Building**

\[ P_o = \left[ 1.2 \cdot 40 \div (1.6 \cdot 117) \right] \cdot 20' \cdot 30' \cdot \frac{1}{1000} = 101.2 \, k/\text{floor} \]

\[ 6P_o = 847 \, k \]

**Axial Loading**

\[ k = 1.0 \quad L_b = 11' - 0'' \, \text{max.} \]

Select W10 x 88 columns

Capacity = 973 k (Ref. AISC Table W-1)

**Above Column Splays**

Total load = \( P \cdot (2P_o) = 4P_o = 565 \, k \)

\[ k = 1.0 \quad L_b = 11' - 0'' \, \text{max.} \]

Select W10 x 54 columns

Capacity = 585 k (Ref. AISC Table W-1)

**Check L_b: 15' at Roof**

\[ P = \left[ 1.2 \cdot 3 + 1.6 \cdot (20) \right] \cdot 20' \cdot 30' \cdot \frac{1}{1000} = 21.4 \, k \]

W10 x 54 capacity @ \( L_b = 15' \): 495 k ✔
Assume no live load. Polyethylene panels cannot support human weight and would be serviced by removing panels from the floor below.

\[ D = 3 \text{ psf} \Rightarrow 1.4 \times D = 4.2 \text{ psf} \]

**BEAMS**

Try \[ W = 4 \times 6.5 \] \[ Z = 4.74 \text{ in}^3 \] Assume A36 steel

\[ M_n = 36 \text{ kips} \cdot \text{ft} \]

\[ M_n = 62.6 \text{ k-in.} = 5.22 \text{ k-ft.} \]

\[ \Phi M_n = 4.70 \text{ k-ft.} \]

\[ w_c = 4.2 \times 6.67 = 28 \text{ plf} \]

\[ M_u = \frac{w_c l^2}{8} = \frac{0.028 \times 30^2}{8} = 3.15 \text{ k-ft.} < 4.70 \text{ k} \]

**GIRDERS**

\[ 840 \text{ lb.} \]

\[ V_u = 0.84 \text{ k} \]

\[ M_u = 5.6 \text{ k-ft.} \]

Try \[ (2) L = 4 \times 3 = 5/16 \]

\[ Z = 1.28 \times 2 = 2.56 \text{ in}^3 \]

\[ M_n = 36.2 \text{ k-lb} \cdot \text{in.} = 7.68 \text{ k-ft.} \]

\[ \Phi M_n = 16.91 \text{ k-ft.} \]

\[ M_{u, \text{total}} = 5.6 \times \left( \frac{0.0072 \times 20^3}{8} \right) = 5.95 \text{ k-ft.} < 6.91 \text{ k-ft.} \]
SEISMIC LOADS

$S_{d5} = 0.791 \, g \quad S_{d1} = 0.450 \, g$

**Bldg. Total Seismic Weight**

\[
W_{floods} = 4 \left[ 28 \, \text{psf} \left( 30 \cdot 20 \cdot 13 \right) + 58.4 \, \text{psf} \left( 30 \cdot 20 \cdot 14 \right) \right] = 1434 \, k
\]

\[
W_{roof} = 2W_{floor} = 717.12
\]

\[
W_{canopy} = (180 \cdot 60) \cdot 3 \, \text{psf} = 32.4 \, k
\]

\[
W_{wall} = 1.25 \, \text{psf} \left[ (2780 + 60(320 - 60)) \right] = 550.65 \, k
\]

\[
W_{total} = 2234 \, k
\]

**Base Shear**

\[
C_5 = \frac{S_{d5}}{R/4} = \frac{0.791}{6/1.0} = 0.1318
\]

R = 6 (Ordinary Steel, Concentrically Braced Frame)

\[
V_b = C_5 \cdot W = 0.1318 \cdot 2234 = 295 \, k
\]

**Shear Distribution by Level**

\[
V_i = \frac{W_i \cdot h_i}{\sum W_i \cdot h_i} \cdot V_b \quad k = 1.0
\]

\[
V_2 = \frac{12 \cdot 371.2 \cdot V_b}{(12 \cdot 371.2) + (24 \cdot 571.2) + (36 \cdot 371.2) + (48 \cdot 371.2) + (60 \cdot 721.2) + (75 \cdot 371.2)} = 14.45k
\]

\[
V_3 = 28.9 \, k
\]

\[
V_4 = 43.35 \, k
\]

\[
V_5 = 57.31 \, k
\]

\[
V_6 = 141.36 \, k
\]

\[
V_7 = 9.12 \, k
\]
BUILDING FACE AREA

E/W: \(180 \times 69 = 12,420 \text{ sf} \)

N/S: \(60 \times 69 = 4,140 \text{ sf} \)

\(h_{\text{eff}} = 75 = \frac{h}{2} ; 75 - 6 = 69'\)

WIND PRESSURE PER ASCE 7-10

EXPOSURE C

BASE WIND SPEED: 110 MPH

\(K_d = 0.85\)

\(GCP_i = 0.18\)

\(K_{zt} = 1.0 \text{ due to lack of significant elevation changes near the site}\)

\(K_2 = 2.01 \left(\frac{75}{900}\right)^2 = 2.01 \left(\frac{75}{900}\right)^2 \times 9.5 = 1.191\)

\(q_z = 0.00256 \times K_2 \times K_{zt} \times K_0 \times V^2\)

\(= 0.00256 \times 1.191 \times 1.0 \times 0.85 \times 110^2 = 31.36 \text{ psf}\)

\(p = q \times GCP - q_i (GCP_i)\)

\(G = 0.85\)

\(C_p = 0.8 \text{ (windward)}, -0.5 \text{ (leeward)}\)

\(p_i = 31.36 (0.8)(0.85) - 31.36 (\pm 0.18) = 27.0 \text{ psf}\)

\(p_i = 31.36 (-0.5)(0.85) - 31.36 (\pm 0.18) = 19.0 \text{ psf}\)

BASE SHEAR

E/W: \(V_b = 12,420 (|p_i| + |p_i|), \frac{1}{1000} = 571.3 \text{ k}\)

N/S: \(V_b = 4,140 (|p_i| + |p_i|), \frac{1}{1000} = 190.4 \text{ k}\)

CONCLUSION:

WIND GOVERNS IN E/W DIRECTION, BUT SEISMIC GOVERNS IN THE N/S DIRECTION

*EXCEPTION: WHEN BASE SHEAR IS DISTRIBUTED BY LEVEL, SEISMIC GOVERNS AT THE TOP FLOOR

\(V_w = 180 \times 13.5 (27 + 16) \times \frac{1}{1000} = 111.8 \text{ k}\)

\(V_s = 141.4 \text{ k}\)
\[ x = 30' \\
\[ y = 85.588' = 85'7'' \]
\[ e_x = 0 + 5\% (60') = 3' \]
\[ e_y = 4.412 + 5\% (180') = 13.412' \]

\[ (l^2) \quad M_x = V_b e_x = 29.5 \cdot 3 = 88.5 \text{ k-ft} \]

\[ e(l) \quad M_y = V_b e_y = 571.3 \cdot 13.412 = 7662.9 \text{ k-ft} \]

**Torsional Force Distribution (N/S)**

\[ F_i = \frac{M_k \cdot l_i}{\Sigma k \cdot l_i^2} \]

**X-Direction**

\[ F_1 = \frac{M_x \cdot 3 \cdot 94.412}{(3 \cdot 94.412^2) + (3 \cdot 85.588^2) + (4 \cdot 10^2) \cdot 2} = \frac{296,663.9}{49,116.8} = 5.10 \text{ k} \]

\[ F_2 = \frac{M_x \cdot 3 \cdot 85.588}{49,116.8} = 4.63 \text{ k} \]

\[ F_3 = \frac{F_4}{49,116.8} = 0.72 \text{ k} \]
TORSIONAL ANALYSIS

E-W DIRECTION

\[ F_1 = \frac{M_y \cdot 3.94.912}{49.116.8} = 44.19 \text{k} \]
\[ F_2 = \frac{M_y \cdot 3.85.538}{49.116.8} = 40.06 \text{k} \]
\[ F_3 = F_4 = \frac{M_y \cdot 4.10}{49.116.8} = 6.24 \text{k} \]

SHEAR FORCE DISTRIBUTION

E-W DIRECTION:

\[ R_A = \frac{64.912}{120} \cdot V_b = 538.7 \text{k} \]
\[ R_B = \frac{55.538}{120} \cdot V_b = 264.6 \text{k} \]

N-S DIRECTION:

\[ R_A = R_B = \frac{V_b}{2} = 147.5 \text{k} \]

SUMMARY

<table>
<thead>
<tr>
<th></th>
<th>MAX. ( \nu ), directed</th>
<th>MAX. ( \nu ), torsal</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-S</td>
<td>147.5 k</td>
<td>5.10 k</td>
<td>152.6 k</td>
</tr>
<tr>
<td>E-W</td>
<td>308.7 k</td>
<td>441.19 k</td>
<td>350.9 k</td>
</tr>
</tbody>
</table>
C3 x 5
LATERAL TRUSSES

Windward face pressure

\[ V_b = 180 (6.75) (27 \text{ psf}) = 65.01 \text{ k} \]

365 psf = \( W_0 \) Max.

Typical small span

- Check weak-axis bending in beam-chords
- For truss, model as point loads to A, C, E, G

Highest comp. force in C3 x 5: 8.16 k

Highest comp. force in W 8 x 21: 7.3 k

Highest torsion force in C3 x 5: 5.0 k
DIAPHRAGM DESIGN

END BAY SMALL SPAN

\[
\begin{align*}
3.85 k & \rightarrow 3.65 k & \rightarrow 3.65 k & \rightarrow 1.825 k \\
3.25 k & \rightarrow B & \rightarrow C & \rightarrow D \\
2.47 k & \rightarrow E & \rightarrow F & \rightarrow G
\end{align*}
\]

\text{Highest comp. force in C3x5: 20.4 k}
\text{Highest comp. force in W8 x 21: 32.85 k}

\[
\begin{align*}
20.4 k & \rightarrow C3x5 & \rightarrow 20.4 k \\
185 p/lf & \rightarrow 10.12" \\
52.56 k & \rightarrow W8 x 21 & \rightarrow 52.56 k \\
589 p/lf & \rightarrow 10'
\end{align*}
\]

LOAD COMBINATION

\[1.2D + 0.5L + 1.6 W\]
\[ V_{\text{floor}} = 141.4 \text{ k} \]

\[ V = C_s \cdot W_{\text{floor}} \cdot \frac{141.4}{295} \]

\[ V = [0.1318 \cdot (28.30 \cdot 20.6_{\text{bays}})] \cdot 6 \text{ floors} \cdot \frac{141.4}{295} = 32.21 \text{ k} \]

Distribute to 2 sets of trusses: \[ V_{\text{truss}} = 19.11 \text{ k} \]

\[ \mathbb{I} \]

\[ V_{\text{truss}} \]

Assume load splits evenly

\[ 6.37k \]

\[ 3.18k \]

\[ 10' + \text{HP} \]

\[ 5' \]

\[ P_{\text{max}} = 7.12 < 20.4 \]

Other braces govern design, use results from page L6 calculation
L = 11.18' = 134.2"
K = 1.0
r = .405"

L 4 x 4 x 7/16 \rightarrow 12.6 plf
HSS 3 x 3 x 3/86 \rightarrow 6.57 plf
Bars \rightarrow 5.5 plf
HSS 4 x 2\frac{1}{2} x 3/16 \rightarrow 6.37 plf

Use 1" Ø Bars in each direction (2 per bay)

\[ T_n = \left( \frac{1}{2} \right)^2 \pi \cdot 36 \text{ ksi} = 28.3k \]
\[ \phi T_n = 25.4k > 20.4k \checkmark \]

Weight = 5.5 plf \approx 5 plf (channels) \checkmark
- No need to recalculate weights
**W8x21 CAPACITY**

<table>
<thead>
<tr>
<th></th>
<th>DEMAND</th>
<th>CAPACITY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STRONG-AXIS BENDING</strong></td>
<td>20.8 k-ft.</td>
<td>61 k-ft.</td>
</tr>
<tr>
<td><strong>WEAK-AXIS BENDING</strong></td>
<td>7.3 k-ft.</td>
<td>21.3 k-ft.</td>
</tr>
<tr>
<td><strong>AXIAL COMPRESSION</strong></td>
<td>52.6 k</td>
<td>141.5 k</td>
</tr>
</tbody>
</table>

**Strong-Axis** \( M_u = \frac{wL^2}{8} = \frac{0.185 \cdot 50^2}{8} = 20.8 \text{ k-ft} \)

**Weak-Axis** \( M_u = \frac{wL^2}{8} = \frac{0.584 \cdot 10^2}{8} = 7.3 \text{ k-ft} \)

**COMPRESSION CAPACITY**

\[ L_y = 10', \quad K = 1.0, \quad r_y = 1.26 \text{ in}. \quad L_{xx} = 30', \quad r_x = 3.49 \text{ in}. \]

\[ \frac{KL_y}{r_y} = 10.9, \quad \frac{KL_x}{r_x} = 9.5 \]

\[ 4.71 \sqrt{E/F_y} = 4.71 \sqrt{29,000 / 50} = 113 > 103 \rightarrow F_{cr} = \left[ 0.658 \frac{F_{cr}}{F_y} \right] F_y \]

\[ F_e = \frac{F_y}{(KL_y)^2} = \frac{F_y \cdot 29,000}{10.5^2} = 26.9 \]

\[ F_{cr} = (0.658 \times 59% \times 50) = 22.97 \text{ ksi} \]

\[ \varnothing P_n = 0.9 (A \cdot F_{cr}) = 6.16 \times 22.97 = 141.5 \text{ k} \]

**WEAK-AXIS BENDING CAPACITY**

\[ L_y = 10', \quad Z_y = 5.68 \text{ in}^3 \]

\[ M_y = M_{po} = F_y Z_y = 5.68 \times 50 = 285 \text{ k-in}. = 23.7 \text{ k-lb/ft} \]

\[ \varnothing M_n = 21.3 \text{ k-ft}. \quad \text{(REF. AISC TABLE 3-4)} \]

**COMBINED FORCES**

\[ \frac{P_n}{(\varnothing M_n)} + \left( \frac{M_{ux}}{(\varnothing M_{ux})} + \frac{M_{uy}}{(\varnothing M_{uy})} \right) \leq 1.0 \]

\[ 52.6 \quad \left( \frac{73}{141.5} + \frac{20.8}{61} \right) \leq 1.0 \]

\[ 0.979 < 1.0 \checkmark \]

**W8x21 IS ADEQUATE**
**WOX26 CAPACITY**

<table>
<thead>
<tr>
<th>Strong-Axis Bending</th>
<th>Demand</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>51.3 k-ft.</td>
<td>51.3 k-ft.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weak-Axis Bending</th>
<th>7.3 k-ft.</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Axial Compression</th>
<th>52.6 k-ft.</th>
</tr>
</thead>
</table>

**Compression Capacity**

\[
L_y = 10', f_y = 1.33 \text{ in.} \quad L_x = 30', r_x = 4.27 \text{ in.} \quad K = 1.0
\]

\[
K = \frac{90.2}{r_x} = 84.3
\]

\[
F_{cy} = \frac{29,000 \cdot 17^2}{90.2^2} = 35.2
\]

\[
F_{cr} = (0.658 \cdot 50/38.2) \cdot 50 = 27.6 \text{ ksi}
\]

\[
\phi P_n = 0.9 \cdot 27.6 \cdot 7.61 = 188.9 k
\]

**Weak-Axis Bending Capacity**

\[
Z_y = 7.5 \text{ in.}^3
\]

\[
M_y = M_p = 7.5 \cdot 50 = 375 \text{ k-in.} = 31.25 \text{ k-ft.}
\]

\[
L_p = 1.76 r_x \sqrt{\frac{F_{cy}}{F_{cr}}} = 1.76 \cdot 4.27 \sqrt{\frac{29,000}{50}} = 181 \text{ in.} = 15.08' > 10' \quad \checkmark
\]

\[
\phi M_n = 28.9 \text{ k-ft.} \quad \text{(Ref. AISC Table 3-4)}
\]

**Combined Forces**

\[
\frac{P_n}{\phi P_n} + \frac{8}{9} \left( \frac{M_{ax}}{\phi M_{ax}} + \frac{M_{ay}}{\phi M_{ay}} \right) \leq 1.0
\]

\[
\frac{52.6}{188.9} + \frac{8}{9} \left( \frac{7.3}{28.1} + \frac{51.3}{94} \right) = 0.991 \leq 1.0 \quad \checkmark
\]

**WOX26 IS ADEQUATE**
**Diaphragm Chords**

**East-West (E/W)**

\[ \Sigma M_R = 60C - (786 \cdot 60 \cdot 30) = 0 \]

\[ T = 23.58k \]

\[ C = 23.58k \]

Check W8x21 Compression Demand @ Center of:

\[ 8.16 + 23.58 = 31.74k < 32.85k \text{ (governing)} \]

Ref. P. L4

Ref. P. L5

**North-South (N/S)**

\[ \Sigma M_R = 120C - (2.36 \cdot 30 \cdot 15) = 0 \]

\[ C = 8.85k \]

\[ T = 8.85k \]

Check 8.85k added on W10x26 Girders

→ See next page
E/W

\[ \sqrt{V_{\text{max}}} = 141.4 \left( \frac{350.9}{306.7} \right) = 161.8 \text{ k} \]

60' * Scaled effect of torsion, Ref. P. L3

\[ \frac{161.8}{60} = 2.7 \text{ klf} \]

CHECK +54 k added on W10x26 girders

\[ K = 1.0 \quad L = 20' \quad r_x = 4.35'' \rightarrow \frac{KL}{r} = 55 \]

\[ F_e = \frac{W^2 \cdot 29.0000}{55^2} = 94 \]

\[ F_{cr} = \left( 0.658 \cdot 90/100 \right) \cdot 50 = 40 \text{ ksi} \]

\[ \phi P_n = 0.9 \cdot 40 \cdot 7.61 \text{ in}^2 = 274 \text{ k} \]

COMBINED FORCES

\[ \frac{55}{274} + \left( 33 \cdot \frac{3}{116} \right) = 0.875 < 1.0 \checkmark \]

W10x26 is adequate as a collector.

CHECK W21x48

\[ K = 1.0 \quad L = 20' \quad r_x = 8.24'' \quad \frac{KL}{r} = 29 \quad F_{cr} = 47 \text{ ksi} \]

\[ \phi P_n = 0.9 \cdot 47 \cdot 14.1 = 596 \text{ k} \]

COMBINED FORCES

\[ \frac{55}{2596} + \frac{346.1}{396} = 0.934 < 1.0 \checkmark \]

W21x48 is adequate as a collector.
\[ V_{\text{max}} = 141.4 \left( \frac{152.6}{147.5} \right) = 146.3 \text{ k} \]  

Scaled effect of torsion, Ref. P. L3

\[ \frac{146.3}{180} = 0.81 \text{ klf} \]

CHECK 61k ADDED ON W16 x 40

\[ K = 1.0 \quad L = 30' \quad R_x = 6.96 \text{ in.} \quad \Rightarrow \frac{KL}{R_x} = 52 \]

\[ F_e = \frac{\pi^2 \times 29,000}{52^2} = 107 \quad F_{cr} = (0.658 \times 50) \times 0.50 = 15.37 \text{ ksi} \]

\[ \phi_P = 0.9 \times 15.37 \times 11.8 = 163 \text{ k} \]

**COMBINED LOADING**

\[ \frac{61}{163} + \left( \frac{198.7}{228} \right) \frac{3}{9} = 0.95 < 1.0 \checkmark \]

**W16 x 40 IS ADEQUATE AS A COLLECTOR**
N-S BF ANALYSIS

\[ V_b = 152.6 \text{ k} \]

\[ L_{brace} = 19.2' \]

Overturn: \[ F_p = \frac{V_b}{L} = \frac{152.6 \cdot 12}{60} = 30.5 \text{ k} \]

\[ \sqrt{15^2 + 12^2} = 19.2' \]

\[ F_{brace} = 38.15 \cdot \frac{19.2}{15} = 48.8 \text{ k} \]

For preliminary design, select HSS 4\(\frac{1}{2}\) x 4\(\frac{1}{2}\) x 5/16
Capacity = 53.0 k

See RISA 2D results on next page for detailed story drift analysis (p. L112)

- Story drift is adequate
RISA 2D ANALYSIS NORTH-SOUTH

**JOINT DEFLECTIONS**

<table>
<thead>
<tr>
<th>LC</th>
<th>Joint Label</th>
<th>X [in]</th>
<th>Y [in]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>N2</td>
<td>.285</td>
<td>-.078</td>
</tr>
<tr>
<td>1</td>
<td>N3</td>
<td>.55</td>
<td>-.144</td>
</tr>
<tr>
<td>1</td>
<td>N4</td>
<td>.806</td>
<td>-.196</td>
</tr>
<tr>
<td>1</td>
<td>N5</td>
<td>1.047</td>
<td>-.235</td>
</tr>
<tr>
<td>1</td>
<td>N6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>N7</td>
<td>.269</td>
<td>-.094</td>
</tr>
<tr>
<td>1</td>
<td>N8</td>
<td>.52</td>
<td>-.169</td>
</tr>
<tr>
<td>1</td>
<td>N9</td>
<td>.761</td>
<td>-.226</td>
</tr>
<tr>
<td>1</td>
<td>N10</td>
<td>.986</td>
<td>-.263</td>
</tr>
<tr>
<td>1</td>
<td>N11</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>N12</td>
<td>.25</td>
<td>-.079</td>
</tr>
<tr>
<td>1</td>
<td>N13</td>
<td>.489</td>
<td>-.149</td>
</tr>
<tr>
<td>1</td>
<td>N14</td>
<td>.717</td>
<td>-.21</td>
</tr>
<tr>
<td>1</td>
<td>N15</td>
<td>.921</td>
<td>-.259</td>
</tr>
<tr>
<td>1</td>
<td>N16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>N17</td>
<td>.239</td>
<td>-.116</td>
</tr>
<tr>
<td>1</td>
<td>N18</td>
<td>.47</td>
<td>-.213</td>
</tr>
<tr>
<td>1</td>
<td>N19</td>
<td>.685</td>
<td>-.291</td>
</tr>
<tr>
<td>1</td>
<td>N20</td>
<td>.872</td>
<td>-.35</td>
</tr>
<tr>
<td>1</td>
<td>N21</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>N22</td>
<td>.239</td>
<td>-.143</td>
</tr>
<tr>
<td>1</td>
<td>N23</td>
<td>.467</td>
<td>-.257</td>
</tr>
<tr>
<td>1</td>
<td>N24</td>
<td>.675</td>
<td>-.344</td>
</tr>
<tr>
<td>1</td>
<td>N25</td>
<td>.847</td>
<td>-.404</td>
</tr>
<tr>
<td>Member Label</td>
<td>Sec</td>
<td>Axial[k]</td>
<td>Shear[k]</td>
</tr>
<tr>
<td>--------------</td>
<td>-----</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>N26</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>N27</td>
<td>.242</td>
<td>-.095</td>
<td></td>
</tr>
<tr>
<td>N28</td>
<td>.466</td>
<td>-.171</td>
<td></td>
</tr>
<tr>
<td>N29</td>
<td>.675</td>
<td>-.228</td>
<td></td>
</tr>
<tr>
<td>N30</td>
<td>.845</td>
<td>-.266</td>
<td></td>
</tr>
<tr>
<td>N31</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>N32</td>
<td>.243</td>
<td>-.081</td>
<td></td>
</tr>
<tr>
<td>N33</td>
<td>.466</td>
<td>-.149</td>
<td></td>
</tr>
<tr>
<td>N34</td>
<td>.675</td>
<td>-.203</td>
<td></td>
</tr>
<tr>
<td>N35</td>
<td>.845</td>
<td>-.244</td>
<td></td>
</tr>
<tr>
<td>N36</td>
<td>1.598</td>
<td>-.285</td>
<td></td>
</tr>
<tr>
<td>N37</td>
<td>1.208</td>
<td>-.285</td>
<td></td>
</tr>
<tr>
<td>N38</td>
<td>1.371</td>
<td>-.294</td>
<td></td>
</tr>
<tr>
<td>N39</td>
<td>1.147</td>
<td>-.294</td>
<td></td>
</tr>
<tr>
<td>N40</td>
<td>1.155</td>
<td>-.317</td>
<td></td>
</tr>
<tr>
<td>N41</td>
<td>1.077</td>
<td>-.313</td>
<td></td>
</tr>
<tr>
<td>N42</td>
<td>1.004</td>
<td>-.412</td>
<td></td>
</tr>
<tr>
<td>N43</td>
<td>1.071</td>
<td>-.412</td>
<td></td>
</tr>
<tr>
<td>N44</td>
<td>.957</td>
<td>-.466</td>
<td></td>
</tr>
<tr>
<td>N45</td>
<td>1.065</td>
<td>-.466</td>
<td></td>
</tr>
<tr>
<td>N46</td>
<td>.955</td>
<td>-.297</td>
<td></td>
</tr>
<tr>
<td>N47</td>
<td>1.064</td>
<td>-.297</td>
<td></td>
</tr>
<tr>
<td>N48</td>
<td>.955</td>
<td>-.293</td>
<td></td>
</tr>
<tr>
<td>N49</td>
<td>1.063</td>
<td>-.293</td>
<td></td>
</tr>
<tr>
<td>N50</td>
<td>1.074</td>
<td>-.308</td>
<td></td>
</tr>
<tr>
<td>N51</td>
<td>1.068</td>
<td>-.425</td>
<td></td>
</tr>
<tr>
<td>N52</td>
<td>1.05</td>
<td>-.3</td>
<td></td>
</tr>
<tr>
<td>N53</td>
<td>.958</td>
<td>-.363</td>
<td></td>
</tr>
<tr>
<td>N54</td>
<td>.871</td>
<td>-.237</td>
<td></td>
</tr>
<tr>
<td>N55</td>
<td>.835</td>
<td>-.317</td>
<td></td>
</tr>
<tr>
<td>N56</td>
<td>.67</td>
<td>-.176</td>
<td></td>
</tr>
<tr>
<td>N57</td>
<td>.649</td>
<td>-.24</td>
<td></td>
</tr>
<tr>
<td>N58</td>
<td>.445</td>
<td>-.098</td>
<td></td>
</tr>
<tr>
<td>N59</td>
<td>.434</td>
<td>-.139</td>
<td></td>
</tr>
<tr>
<td>N60</td>
<td>.206</td>
<td>-.01</td>
<td></td>
</tr>
<tr>
<td>N61</td>
<td>.201</td>
<td>-.012</td>
<td></td>
</tr>
</tbody>
</table>

MEMBER FORCES
<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>-90.805 -.028 .127</td>
</tr>
<tr>
<td>5</td>
<td>-90.805 -.028 .005</td>
</tr>
<tr>
<td>1</td>
<td>M92 1 98.301 .003 .055</td>
</tr>
<tr>
<td>2</td>
<td>98.301 .003 .043</td>
</tr>
<tr>
<td>3</td>
<td>98.301 .003 .03</td>
</tr>
<tr>
<td>4</td>
<td>98.301 .003 .018</td>
</tr>
<tr>
<td>5</td>
<td>98.301 .003 .006</td>
</tr>
<tr>
<td>1</td>
<td>M93 1 -88.026 .013 .006</td>
</tr>
<tr>
<td>2</td>
<td>-88.026 .013 -.056</td>
</tr>
<tr>
<td>3</td>
<td>-88.026 .013 -.118</td>
</tr>
<tr>
<td>4</td>
<td>-88.026 .013 -.18</td>
</tr>
<tr>
<td>5</td>
<td>-88.026 .013 -.242</td>
</tr>
<tr>
<td>1</td>
<td>M94 1 96.559 .003 .064</td>
</tr>
<tr>
<td>2</td>
<td>96.559 .003 .048</td>
</tr>
<tr>
<td>3</td>
<td>96.559 .003 .032</td>
</tr>
<tr>
<td>4</td>
<td>96.559 .003 .016</td>
</tr>
<tr>
<td>5</td>
<td>96.559 .003 0</td>
</tr>
<tr>
<td>1</td>
<td>M105A 1 159.783 .196 0</td>
</tr>
<tr>
<td>2</td>
<td>159.783 .196 -.588</td>
</tr>
<tr>
<td>3</td>
<td>159.783 .196 -1.176</td>
</tr>
<tr>
<td>4</td>
<td>159.783 .196 -1.765</td>
</tr>
<tr>
<td>5</td>
<td>159.783 .196 -2.353</td>
</tr>
<tr>
<td>1</td>
<td>M110A 1 .018 -.22 -3.004</td>
</tr>
<tr>
<td>2</td>
<td>.018 -.22 -2.18</td>
</tr>
<tr>
<td>3</td>
<td>.018 -.22 -1.357</td>
</tr>
<tr>
<td>4</td>
<td>.018 -.22 -.533</td>
</tr>
<tr>
<td>5</td>
<td>.018 -.22 .291</td>
</tr>
</tbody>
</table>

All critical members are under capacity
Begin by taking braces to yield/buckling strength:

- HSS 4½ x 4½ x 9/16 @ 52 k (buckling)
- HSS 4½ x 4½ x 9/16 @ 194 k (tensile yield)

**Test Beam for 193 k axial load**

Test Minor Column for 88k axial load

**Test Column for 121 k added axial load**

**COLUMN STRENGTH CHECK: W10 x 88**

\[
\frac{1.00 + 0.51 + 0.10}{1.0} = \frac{1.00 + 0.51 + 0.10}{1.00} = \frac{1.61}{1.00} = 1.61
\]

\[
P_u = 498.4 k
\]

\[
\varphi P_n = 973 k \quad \text{✓}
\]

**CHECK W10 x 54**

\[
\varphi P_n = 564 k \quad \text{✓}
\]
CHECK W16x40 STRENGTH

\[ P_u = 193 \text{k} \]
\[ M_u = \frac{193.9 + 0.4}{2} = 139 \text{ k-ft} \]
\[ \phi M_u = 22.8 \text{ k-ft} \]
\[ \frac{Kl}{r} = 76.4 \rightarrow F_\theta = \frac{29,000 \cdot 11^2}{76.4^2} = 49 \]
\[ F_{cr} = (0.658 \cdot 50) \cdot 50 = 32.6 \text{ ksi} \]
\[ P_n = A \cdot F_{cr} = 11.8 \cdot 32.6 = 384.9 \text{ k} \]
\[ \phi P_n = 346.4 \text{ k} \]

COMBINED LOADING

\[ \frac{P_u}{\phi P_n} + \frac{8 M_u}{9 \phi M_u} = 1.10 > 1.0 \rightarrow \text{Try W16x50} \]
\[ P_n = 14.7 \cdot 32.6 = 431.3 \text{ k} \rightarrow \phi P_n = 431.3 \text{ k} \]
\[ \frac{P_u}{\phi P_n} + \frac{8 M_u}{9 \phi M_u} = 0.989 < 1.0 \checkmark \]

CHANGE TO W16x57 FOR ADDITIONAL STRENGTH

SIZE MINOR COLUMN

\[ P_u = 88 \text{k} \]

SELECT HSS 4x4x\( \frac{3}{8} \), CAPACITY = 104 k \checkmark

REF. AISC TABLE 4-4
\[ F_{\text{max}} = \frac{117}{\cos \theta} = 117 \left( \frac{23.32}{20} \right) = 136 \text{k} \]

\[ L = 23.32' \]

SELECT HSS 6\times6\times5/8 FOR PRELIMINARY DESIGN
CAPACITY = 150 k @ 24' in compression (Ref. AISC Table 4-16)

SEE RISA 2D RESULTS ON NEXT PAGE FOR DETAILED STORY DRIFT ANALYSIS (p. L15)

- Story drift is adequate.
- Outside columns changed to HSS 6\times6\times5/8
- Outside foundations are now drilled caissons
### Joint Deflections

<table>
<thead>
<tr>
<th>LC</th>
<th>Joint Label</th>
<th>X [in]</th>
<th>Y [in]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>N2</td>
<td>.21</td>
<td>.05</td>
</tr>
<tr>
<td>1</td>
<td>N3</td>
<td>.512</td>
<td>.064</td>
</tr>
<tr>
<td>1</td>
<td>N4</td>
<td>.777</td>
<td>.058</td>
</tr>
<tr>
<td>1</td>
<td>N5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>N6</td>
<td>.175</td>
<td>-.177</td>
</tr>
<tr>
<td>1</td>
<td>N7</td>
<td>.424</td>
<td>-.322</td>
</tr>
<tr>
<td>1</td>
<td>N8</td>
<td>.673</td>
<td>-.43</td>
</tr>
<tr>
<td>1</td>
<td>N9</td>
<td>1.01</td>
<td>.045</td>
</tr>
<tr>
<td>1</td>
<td>N10</td>
<td>.894</td>
<td>-.503</td>
</tr>
<tr>
<td>1</td>
<td>N11</td>
<td>1.216</td>
<td>.025</td>
</tr>
<tr>
<td>1</td>
<td>N12</td>
<td>1.489</td>
<td>.045</td>
</tr>
<tr>
<td>1</td>
<td>N14</td>
<td>1.098</td>
<td>-.582</td>
</tr>
<tr>
<td>1</td>
<td>N15</td>
<td>1.208</td>
<td>-.587</td>
</tr>
<tr>
<td>1</td>
<td>N17</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>N18</td>
<td>.29</td>
<td>-.107</td>
</tr>
<tr>
<td>1</td>
<td>N19</td>
<td>.549</td>
<td>-.194</td>
</tr>
<tr>
<td>1</td>
<td>N20</td>
<td>.784</td>
<td>-.265</td>
</tr>
<tr>
<td>1</td>
<td>N21</td>
<td>.99</td>
<td>-.321</td>
</tr>
</tbody>
</table>
Based on data from this model, make the following structural changes:

- Change Exterior columns to HSS 6x6x5/8 (Capacity= 360k)
- Change Exterior foundations to drilled caissons similar to interior foundations
HSS 6 x 6 x 5/32, CAPACITY = 484 k (tension)

Test Beam for 311 k axial load
Test Column for 249 k axial load

COLUMN

\[
\left[ 1.0 (40) + 0.5 (117) + (0.25)_{03} (40) \right] \times 6 \times 10^{-3} \times \frac{1}{1000} + 249 = P_u
\]

\[ P_u = 437.7 k \]

\[ \phi P_u = 360 k \times \]

CHANGE TO HSS 7 x 7 x 5/32, FULL HEIGHT (CAPACITY = 470 k)

REF. AISC TABLE 4-4

CHECK BEAM

\[ \phi P_u = 596 k \] (REF. R. L9 FOR CALCULATION)

\[ \phi M_n = 390 k-ft. \]

\[ P_u = 311 k \]

\[ M_u = 156 k-ft. \]

COMBINED LOADING.

\[
\frac{P_u}{\phi P_u} + \frac{8 M_u}{9 \phi M_n} = 0.877 < 1.0 \checkmark
\]

W21 x 48 IS ADEQUATE
EXT. MOMENT IN CONNECTION (GRAVITY)

- Check shear tab thickness
- Check bolt strength
- Check for block shear tearout
- Check welds to girders

(2) 9/8" A325 BOLTS

BOLTS

Strength of (1) A325 Bolt: 12.4 k > 11.25 k /√

ELONGATION

Start w/ 3/8" Thick Steel A36 Plate

\[ E_{rx} = 9'' \rightarrow M_{max} = 11.25 k \cdot 9'' = 102 \text{ k-in.} \]

\[ Z_R = \frac{b h^3}{k_l} = \frac{3/8 \cdot 6^3}{4} = 3.375 \text{ in.}^3 \]

\[ M_{n} = Z_{r} F_{v} = 3.375 \cdot 36 = 121.5 \text{ k-in.} \rightarrow \phi_{min} = 109 \text{ k-in.} /√ \]

BLOCK SHEAR

\[ A_{nu} = \left[ 15" \cdot \left( 1.5 \cdot \frac{1}{16} \right) \right] \cdot \frac{3}{8} = 1.30 \text{ in.}^2 \]

\[ A_{nt} = \left( \frac{1}{2} - \frac{1}{6} \right) \cdot \frac{3}{8} = 0.433 \text{ in.}^2 \]

\[ R_n = 0.6 F_u A_{nu} + 0.5 F_u A_{nt} = 70.4 k \]

\[ \phi = 0.75 \]

\[ \phi R_n = 46.2 k \left/ 11.25 k \right/√ \]

WELDS

Use 70 ksi welds, 3/16" (F_{ty} = 70 ksi)

\[ A_w = 1 \cdot \frac{3}{16}" \]

\[ \frac{1.25}{0.75} = 1.67 \cdot R_{max} \]

\[ R_n = 0.6 \cdot 70 \cdot \left( \frac{1}{2} \cdot \frac{3}{16} \right) \cdot 1 = 15 \quad (\text{Ref. A325 Formulas 8-1}) \]

\[ 5.56 \cdot \phi = 15 \]

\[ \phi_{min} = 2.69" \]

\[ \text{Use } \frac{3}{16}" \cdot 3" \quad \text{70 ksi WELDS} \]
EXT. GIRDER-COLUMN CONNECTION (GRAVITY)

SEE PREVIOUS PAGE FOR CONNECTION DETAIL

Strength of (2) A325 Bolts: 24.8 k > 18.1 k ✓

BOLTS

BENDING

Start with ½" Thick A36 Steel Plate  e_{max} = 4"

M_u = 18.1 \times 4^2 = 72.4 k-in.

Z_R = \frac{bh^2}{4} = \frac{1/2 \times 6^2}{4} = 4.5 \text{ in.}^2

M_n = 4.5 \times 36 = 162 k-in. \Rightarrow \varnothing M_n = 145.8 k-in. > 72.4 k-in. ✓

\varnothing R_n = 46.2 k \times \left(\frac{1/2}{2/3}\right) = 61.6 k > 18.1 k ✓

\Rightarrow FROM PREVIOUS PAGE

\varnothing R_n = 46.2 k \times \left(\frac{1/2}{2/3}\right) = 61.6 k > 18.1 k ✓

\Rightarrow FROM PREVIOUS PAGE, 5.568 \ell = \frac{18.15}{75} = 24.1 k

\ell_{min} = 4.33"

USE 3/16" x 5" 70 ksi WELDS
INT. BEAM - GIRDER CONNECTION (GRAVITY)

\[ e_{\text{max}} = 8" \]

\[ 25.8k \]

(3) \( \frac{3}{8} " \) A325 BOLTS

\[ \text{Strength of A325 Bolt (8\%) = 12.4k} \]

\[ 12.4 \cdot 2 = 37.2k > 25.8k \]

PLATE BENDING

Start with \( \frac{1}{2} " \) Thick Steel A36 Plate

\[ M_u = 8 \cdot 25.8k = 206.4 \text{ k-in.} \]

\[ Z_k = \frac{1.11^2}{4} = 0.592 \text{ in.}^3 \]

\[ M_n = Z_fy = 10.13 \cdot 36 = 364.5 \text{ k-in.} \Rightarrow M_n = 328 \text{ k-in. > 206.4 k-in.} \]

BLACK SHEAR

\[ A_{nv} = \left[ 7.5 - (2.5 \cdot \frac{11}{16}) \right] \frac{1}{2} = 2.89 \text{ in.}^2 \]

\[ A_{nt} = (1\frac{1}{2} - \frac{11}{16}) \frac{1}{2} = 0.578 \text{ in.}^2 \]

\[ R_n = 0.6 F_y A_{nv} + 0.85 F_s A_{nt} = 134.1 \text{ k} \]

\[ \text{or} = \frac{0.6 F_y A_{nv} + 0.85 F_s A_{nt}}{114.5 \text{ k}} \]

\[ R_n = 85.9k > 25.8k \]

WELDS

\[ R_n = \frac{25.8}{75} = 34.4k \]

\[ R_n = 0.6 (70) \left( \frac{12}{16} \right) \left( \frac{1}{16} \right) l = 34.4 \]

\[ l_{\text{min}} = 6.18" \]

USE \( \frac{3}{16} " \times 7" \) 70 ksi WELDS
**INT. GIRDER-COLUMN CONNECTION (GRAVITY)**

\[ e_{\text{max}} = 9'' \]

\[ 151.6k \]

**BOLTS**

Strength of (1) 5/8" A325 Bolt: 12.4 k

\[ 12.4 \times 5 = 62 \text{k} > 51.6 \text{k} \quad \checkmark \]

**BENDING**

Start w/ 1/2" Thick Steel A36 Plate

\[ M_n = 9.151.6 = 464.4 \text{k-in} \]

\[ Z_k = \frac{bh^2}{4} = \frac{0.5 \times 15^2}{4} = 28.125 \text{ in}^3 \]

\[ M_n = Z_kF_y = 28.125 \times 36 = 1012.5 \text{k-in.} \quad \rightarrow \quad \phi M_n = 0.911.3 \text{k-in.} > 464.4 \text{k-in.} \quad \checkmark \]

**BLOCK SHEAR**

\[ A_{nv} = [13.5 - (4.5 \times \frac{1}{16})] \times \frac{1}{2} = 5.2 \text{ in}^2 \]

\[ A_{nt} = (1.5 - \frac{1}{2}) \times \frac{1}{2} = 0.578 \text{ in}^2 \]

\[ R_n = 0.6F_u A_{nv} + U_{bs} F_u A_{nt} = 214.5 \text{k} \]

OR: \[ 0.6F_y A_{qu} + U_{bs} F_u A_{nt} = 179.3 \text{k} \]

\[ \phi R_n = 134.5 \text{k} > 51.6 \text{k} \]

**WELDS**

\[ R_n = 0.6 (70) \left( \frac{\sqrt{2}}{2} \right) (\frac{1}{16}) l_{\text{min}} = R_{n_{\text{max}}} \]

\[ R_{n_{\text{max}}} = \frac{51.6}{0.75} = 68.8 \]

\[ l_{\text{min}} = 12.355'' \]

USE 3/16" x 13" 70 ksi WELDS
Gusset Plate Design (E-W Braces)

Limit state: yielding of A36 Plate > Yielding of brace

\[
\tan 20^\circ = \frac{x}{12} = 0.364 \\
x = 4.367'' \\
l = 10 + 2x = 18.73'' \\
A_l = 18.73''
\]

\[p_u = 1.1 \quad p_{br} = 1.1 (484) = 532.4 \text{ k} \]

\[532.4 \text{ k} = (18.73'' \cdot 36 \text{ ksi} \cdot 0.9) \]

\[t = 0.876'' \text{ min. } \rightarrow \text{ Use min. } 1'' \text{ thick plate} \]

WELDS

\[-F_x = 1.1 \cdot 484 \cdot \frac{20}{23.5} = 457 \text{ k} \quad \frac{457}{0.75} = 609 \text{ k} = p_{max} \]

\[609 = 0.6 (70) \left(\frac{\sqrt{2}}{2}\right) \left(\frac{3}{4}\right) l \cdot (2 \text{ sides}) \]

\[l_{min} = 13.67'' \rightarrow \text{ Use } \frac{3}{4}'' \times 14'' \text{ welds each side} \]

\[-F_y = 1.1 \cdot 484 \cdot \frac{12}{23.5} = 274 \quad \frac{274}{0.75} = 365.6 \text{ k} \]

\[365.6 = 0.6 (70) \left(\frac{\sqrt{2}}{2}\right) \left(\frac{3}{4}\right) l \cdot (2) \]

\[l_{min} = 8.21'' \rightarrow \text{ Use } \frac{3}{4}'' \times 9'' \text{ welds each side} \]

\[-F_{br} = 1.1 \cdot 484 = 532.4 \text{ k} \quad \frac{532}{0.75} = 709.7 \text{ k} \]

\[709.7 = 0.6 (70) \left(\frac{\sqrt{2}}{2}\right) \left(\frac{3}{4}\right) l \cdot (4) \]

\[l_{min} = 7.96'' \rightarrow \text{ Use } \frac{3}{4}'' \times 9'' \text{ welds all sides} \]

Block Shear Tearout

\[\phi p_u = 0.75 [(0.56.24) + (1.0 \cdot 0.58.6)] = 649.3 \text{ k} > 532 \text{ k} \]
GUSSET PLATE DESIGN (MID BEAM)

HSS 4 1/2 x 4 1/2 x 5/16

194 k max.

\[ \theta = 10 + 12 \tan 20^\circ \cdot 12 \tan 40^\circ = 24.4'' \]

\[ A_r = 24.4 \text{ in.} \quad (\text{start w/ t = 1/2''}) \]

\[ P_u = 1.1 \cdot (194) = 213.4 k \]

\[ 24.4 \cdot 0.5 \cdot 36 \cdot 0.09 = 39.53 k \gtrless 213.4 k \checkmark \]

WELDS

\[ F_x = 1.1 \cdot 194 \cdot \frac{15}{14.2} = 166.6 k \quad \text{Start w/ 15'' of 1/2'' weld each side} \]

\[ F_y = 1.1 \cdot 194 \cdot \frac{12}{14.2} = 133.3 k \]

\[ F_{exx} = 0.6 \left( 70 \left( \frac{\sqrt{3}}{2} \right) \left( \frac{1}{2} \right) \left( 12 \times 2 \text{ sides} \right) \right) = 445.4 k \quad \text{either direction} \]

\[ \Phi F_{exx} = 334.1 k \]

COMBINED LOADING:

\[ \frac{166.6}{334} + \frac{133.3}{334} = 0.898 < 1.0 \checkmark \]

Use 1/2'' x 15'' 70 ksi WELDS EACH SIDE

BLOCK SHEAR TEAROUT

\[ \Phi R_n = 0.75 \left[ (12 \cdot 36 \cdot 0.6) + (58 \cdot 1.0 \cdot 3) \right] = 324.9 k \gtrless 213.4 k \checkmark \]
COLUMN SPlice AT 4TH FLOOR (HSS)

HSS 6 x 6 x 1/4

5/8" A325 BOLTS

1/2" A36 PLATE

HSS 6 x 6 x 1/2

\[ \phi P_n = 175 \text{k} \]

PLATE

Bolt Group Capacity:

**BLOCK SHEAR TEAROUT**

\[ A_{nv} = \left[ 4.5 - (1.5 \cdot \frac{3}{16}) \right] \cdot 4 \cdot \frac{1}{2} = 7.6 \text{in.}^2 \]

\[ A_{nt} = (3 - \frac{4}{16}) \cdot \frac{1}{2} \cdot 2 = 2.31 \text{in.}^2 \]

\[ R_n = 0.6 \cdot F_u \cdot A_{nt} + U_b \cdot F_y \cdot A_{nt} = 398 \text{k} \]

\[ R_n = 0.6 \cdot F_y \cdot A_{gu} + U_b \cdot F_u \cdot A_{nt} = 328 \text{k} \leftarrow \]

\[ \phi R_n = 246 \text{k} > 175 \text{k} \checkmark \]

**HSS BOLT GROUP TEAROUT**

\[ A_{nv} = 3.8 \text{in.}^2 \]

\[ A_{nt} = 1.16 \text{in.}^2 \]

\[ R_n = 0.6 \cdot F_u \cdot A_{nt} + U_b \cdot F_y \cdot A_{nt} = 254 \text{k} \]

\[ R_n = 0.6 \cdot F_y \cdot A_{nt} + U_b \cdot F_u \cdot A_{nt} = 209 \text{k} \leftarrow \]

\[ \phi R_n = 157 \text{k} < 175 \text{k} \times \]

Locate 1st bolt 2" from edge of HSS

\[ A_{nv} = 3.8 \left( \frac{5}{4} \right) = 4.72 \text{in.}^2 \]

\[ A_{gu} = 5" \]

\[ R_n = 0.6 \cdot F_y \cdot A_{gu} + U_b \cdot F_u \cdot A_{nt} = 287 \text{k} \]

\[ \phi R_n = 215 \text{k} > 175 \text{k} \checkmark \]
DIAPHRAGM BRACE CONNECTIONS (WELDED)

\[ \frac{3}{8}" \text{ WELD ALL AROUND (70 ksi)} \quad \text{MAX. DEMAND} = 20.4 \text{k} \]

\[ l = C = 2 \pi r = \frac{3}{8} \pi \approx 2.75" \cdot 1.1 (\text{angled}) = 3.025" \]

\[ R_n = 70 \left( \frac{\sqrt{3}}{2} \right) \left( \frac{3}{16} \right) (3.025) = 2.81 \text{k} \]

\[ \Phi R_n = 0.75 \cdot 2.81 \text{k} = 2.105 \text{k} \quad > 20.4 \text{k} \quad \checkmark \]

---

DIAPHRAGM ANGLE SECTION BRACES

\[ W3 \times 21 \text{ MIN.} \quad e_{\text{max}} = 8" \]

\[ 5/8" A325 \text{ BOLT (Capacity} = 12.4 \text{ k}) \]

---

BLOCK SHEAR TEAROUT

\[ A_{nv} = 2 \cdot (\frac{3}{8})^2 \cdot 1.5 = 1.125 \text{ in.}^2 \quad A_{nt} = \frac{3}{8} \cdot \frac{3}{16} = 0.258 \text{ in.}^2 \]

\[ R_n = 0.6 F_u A_{nv} + U_{bs} F_u A_{nt} = 54 \text{k} \]

\[ R_n = 0.6 F_y A_{gy} + U_{bs} F_u A_{nt} \leq 39 \text{k} \]

\[ \Phi R_n = 29.4 \text{k} \quad > 11 \text{k} \quad \checkmark \]
Assume Soil Type D per 2013 CBC Table 1806.2
\( \rho = 2000 \text{ psf} \)

\[ \frac{225k}{\rho} = 112.5 \text{ sf} \rightarrow b = 10.61' \]

**USE 11' SQ. CONC. FTG.**

**CHECK BENDING**

\[ M_u = \frac{2000 \text{ psf} \cdot 0.5' \cdot 5'}{2} = 550 \text{ k-ft} = 60 \text{ k-in.} \]

\[ d = 12 - 3 - \frac{0.5}{2} - 0.5 = 8' \]

\[ A_{sfy} = 0.85 \text{ f} \cdot \alpha \cdot \text{ a} \]

\[ 0.2 \cdot 60 = 0.85 \cdot 0.6 \cdot \text{ a} \]

\[ \text{ a = 0.58 ft} \]

\[ M_n = A_{sfy} \left( d - \frac{\alpha}{2} \right) = 0.2 \cdot 60 \left( 8 - \frac{0.58}{2} \right) = 922 \text{ k-in.} \]

\[ c = \frac{a}{0.85} = 0.692 \quad \frac{c}{d} = 0.086 \rightarrow \phi = 0.9 \]

\[ \phi M_n = 82 \text{ k-in.} > 60 \text{ k-in.} \checkmark \]

**USE #4 BARS @ 6" OC EACH WAY**
\[ \rho = 2000 \text{ psf} \]

\[ \frac{347,000}{2000} = 423.5 \rightarrow 20.6' \text{ sq. ft.} \rightarrow \text{Try 3' Ø Caisson} \]

\[ Q_{ult} = \beta P_v A_{scl} + q_b A_{base} \quad (\text{Sand}) \]

\[ \alpha = 0.25 \quad \text{Per CBC 2013 Table 1806.2} \]

\[ P_v = 150 \text{ psf/ft. Per CBC 2013 Table 1806.2} \]

\[ Q_{allow} = \frac{Q_{ult}}{2.0} = 847 \]

\[ Q_{ult} = 169.4 k = \left(\frac{150 - d}{2}\right) \left(3 \pi d^2\right) + 2000 \left(\pi \cdot 1.5^2\right) \]

\[ 169.4 k = 706.7 \quad d^2 \]

\[ d = 48.78' \]

\[ 48.78 + 5 + 3 = 56.78 \]

**USE 60' DEEP 3' Ø CAISSONS WITH REINF. SHOWN BELOW**

\[ 12 \times 1.0 \times 12 \text{ in.}^3 > 1.0\% \text{ MINIMUM} \]

**REQUIRED BY ACI 318**
SECTION III

FUTURE DESIGNS
Analysis of Results

The overall design of the facility largely hinged on allowing natural light to extend deep into the building on every floor. Everything in the structural and architectural design are centered on optimizing that factor in order to maximize the production of crops. The result was a long, slender rectangular building with broad walls of clear windows on all sides. The building is structurally feasible and even lighter than a typical office or residential building of the same size. The lack of a heavy concrete decking system both allowed more light in and reduced the overall weight of the structure.

Geography plays a major role in the dynamics of natural light, effectively dictating the orientation of the building. In low-latitude regions ranging from the tropics all the way to middle temperate zones, sunlight enters the building more effectively from the east and west than from the southern face. Although the numbers would change with any change in latitude relative to San Luis Obispo, the major axis orientation would be the same for most regions.

Economically, it was no secret that the cost of construction would be the dominant barrier to creating a facility like this. The ability of the facility to produce in a cost-effective manner competes against the existing environment in the area. An extremely fertile area like California would likely see poor results when compared to existing farmland because the natural soil is immensely productive already. The only element of California granting an advantage to vertical farms is the high price of land in many areas. A vertical farm could occupy a much smaller physical land area than a traditional farm, thus increasing the efficiency of the space per square foot.

The design would be more viable in regions where traditional farming on a large scale is inefficient or not even an option. Such areas would include desert regions where water is scarce. An enclosed facility with little to no openings for water to evaporate from it would be highly capable of containing and reusing its water supply. An open-air farm in an arid environment would be susceptible to
losing much of the water used on it to evaporation, which drives up the already high cost of fresh water in these regions. Another climate in which vertical farming could flourish would be the lands near the poles which are subject to regular freezing temperatures. The harsh outside environment is unfavorable to most crops due to snow, low temperatures, and permafrost conditions in the soil. A contained and heated facility would be far more productive because it has the ability to raise crops at nearly any time of year instead of the short summer growing season. This particular design also works because the natural light from the south would extend deep into the building. An immense south-facing facility could be the most viable design type for these regions. Urban environments are also locations that become favorable to vertical farms, gaining their economic advantage by cutting down on transportation costs from traditional farms located up to several hundred miles away. Land prices in downtown areas would probably be too expensive for vertical farms, but neighborhoods on the outskirts of cities that house mostly industrial buildings and warehouses could be a relatively cheap site location. The crops’ journey from farm to market would typically be less than ten miles instead of hundreds, thus slashing transportation costs and even bringing tourist attractions to the first cities that build these facilities.

**Research Potential**

The patterns and techniques used in the design of this facility come from a largely untapped well of potential research opportunities. The Student Experimental Fields near the Rodeo Arena at the Cal Poly campus offer an easy opportunity to begin that research. There is plenty of open space for testing scale-model versions of the design that are exposed to the actual climate conditions of the area. Future students could use the research area to conduct tests regarding natural lighting conditions, story height, different building systems, different architectural designs, and more. Additional laboratory tests could be conducted to optimize the performance of the conveyor systems, irrigation systems, and possibly the introduction of digital monitoring of the crops and machines. The expansion of research in this field
could potentially encompass dozens of majors at Cal Poly, with much left to be discovered by pioneering research.

One of the most readily testable experiments arising from this project is the corroboration of growth patterns under obscured natural light. A model story could be created by sowing a plot of spinach seeds in a predefined area and building an opaque cover directly above it to mimic the story above. That cover could be as simple as a series of plywood planks on 2x2 posts that matches the crop area below. An ordinary, unobstructed plot of spinach plants could be grown nearby and used as a control group. From there, the results would ideally show the point at which spinach plants stop growing effectively in the building. That would be the limit of natural light penetration for the building.

The results of the model story experiment open up several more directions in which research can go. For example, a similar experiment could also introduce a third group that employs the use of conveyor systems in order to empirically measure the extension of natural light depth that they provide. The use of artificial light supplements and hybrid lighting could also be explored with the use of LED components in the darker regions of the buildings. The artificial lighting could be powered by the external solar panels allowed in the original design, which would offset the long-term cost of electricity.

Another branch of structural engineering could potentially adopt projects of this type in the way of integrating them into existing buildings. A retrofit project could attempt to house the necessary growth systems in a building initially designed for other purposes. Future ARCE students could draw upon this design in order to find ways of incorporating it into a mixed-use structure.

Much design work is still needed in order to bring the theorized conveyor systems into reality. Departments such as Mechanical and Electrical Engineering could find research potential in this area. The largest challenge would most likely be the integration of an irrigation system into the conveyors, linking hoses and water-tight connections to the moving components. A modular design in which systems can easily change size or configuration would be a significant advantage for the overall function of the
facility. However, this would be difficult to integrate with the irrigation system and would require extensive design work. Despite the amount of work required, the conveyors described in this project are likely a feasible concept and could be implemented into structures in the future.

Furthermore, the design could be put up to real-world conditions not initially considered in the design model. For example, the actual peak amount of sunlight energy and heat does not occur precisely in a cardinal direction, but at an angle somewhere in the southwest quadrant. Models could be created to isolate that angle, and then another iteration of design could have the building oriented toward that angle. This opens up a series of experimental architectural designs that could be developed in order to find configurations that maximize natural light exposure.

**Conclusion**

Although the economic willpower to invest in a large-scale structure like this has yet to come, the design does have potential applications that are worth the input of resources. The first regions of the world to invest in this type of design would be the regions in which traditional farming is inefficient or even unfeasible. Such areas include deserts plagued by drought, land area near the poles that experience permafrost conditions, and major cities with little to no arable farmland nearby. Vertical farming gains its advantages in these regions by offering immense productivity relative to the alternative, or by saving shipping costs from a distant location. The technological ability to create an efficient facility is already available. The world is now ready for the rise of the vertical farm.
PART IV

APPENDIX
Light Renderings

The following images were obtained using the rendering tool in Revit 2015. A model story measuring 20 feet by 50 feet with a ceiling 10 feet directly above was created in the program and illuminated with a light source designed to approximate the sun’s position at a given time of day. The sample shown here is the lighting throughout the day of June 20th, the summer solstice, in San Luis Obispo, CA.
SLO Summer Solstice, 8:00 AM
SLO Summer Solstice, 8:30 AM
SLO Summer Solstice, 9:00 AM
SLO Summer Solstice, 9:30 AM
SLO Summer Solstice: 10:00 AM
SLO Summer Solstice, 9:00 AM
Calculation Tools

The following are outputs from the Excel spreadsheet used to generate the values for total light penetration. Amount of depth assumes a 10 foot clear story height with regard to day and time is calculated and plotted with time intervals of 15 minutes. Values in the 4 left columns are from outside sources and describe the sun’s position. The 4 columns on the right calculate the extent of natural light penetration on each face of the building. Each location and day of the year will yield a unique data set. The following is a sample output from the SLO Summer Solstice from sunrise to sunset.

<table>
<thead>
<tr>
<th>Elevation</th>
<th>Azimuth</th>
<th>Elev (Rd)</th>
<th>Az (Rd)</th>
<th>North Light Penn</th>
<th>South Light Penn</th>
<th>East Light Penn</th>
<th>West Light Penn</th>
</tr>
</thead>
<tbody>
<tr>
<td>-25.23</td>
<td>29.38</td>
<td>-0.44035</td>
<td>0.512777</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-23.66</td>
<td>32.73</td>
<td>-0.41294</td>
<td>0.571246</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-21.93</td>
<td>35.96</td>
<td>-0.38275</td>
<td>0.62762</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-20.07</td>
<td>39.06</td>
<td>-0.35029</td>
<td>0.681725</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-18.09</td>
<td>42.03</td>
<td>-0.31573</td>
<td>0.733561</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-15.99</td>
<td>44.87</td>
<td>-0.27908</td>
<td>0.783129</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-13.79</td>
<td>47.6</td>
<td>-0.24068</td>
<td>0.830776</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-11.49</td>
<td>50.21</td>
<td>-0.20054</td>
<td>0.876329</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-9.11</td>
<td>52.72</td>
<td>-0.159</td>
<td>0.920137</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-6.64</td>
<td>55.14</td>
<td>-0.11589</td>
<td>0.962374</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-3.95</td>
<td>57.46</td>
<td>-0.06894</td>
<td>1.002865</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-0.74</td>
<td>59.7</td>
<td>-0.01292</td>
<td>1.041961</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.62</td>
<td>61.87</td>
<td>0.028274</td>
<td>1.079834</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4.2</td>
<td>63.97</td>
<td>0.073304</td>
<td>1.116486</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6.91</td>
<td>66.01</td>
<td>0.120602</td>
<td>1.152091</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9.69</td>
<td>68.01</td>
<td>0.169122</td>
<td>1.186997</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>12.53</td>
<td>69.96</td>
<td>0.21869</td>
<td>1.221031</td>
<td>15.4189098</td>
<td>0</td>
<td>42.27132076</td>
<td>0</td>
</tr>
<tr>
<td>15.41</td>
<td>71.88</td>
<td>0.268955</td>
<td>1.254542</td>
<td>11.28339001</td>
<td>0</td>
<td>34.48085822</td>
<td>0</td>
</tr>
<tr>
<td>18.32</td>
<td>73.77</td>
<td>0.319744</td>
<td>1.287528</td>
<td>8.441229652</td>
<td>0</td>
<td>28.99825855</td>
<td>0</td>
</tr>
<tr>
<td>21.27</td>
<td>75.65</td>
<td>0.371231</td>
<td>1.32034</td>
<td>6.366732469</td>
<td>0</td>
<td>24.88695801</td>
<td>0</td>
</tr>
<tr>
<td>24.24</td>
<td>77.52</td>
<td>0.423067</td>
<td>1.352978</td>
<td>4.799452974</td>
<td>0</td>
<td>21.68477733</td>
<td>0</td>
</tr>
<tr>
<td>Value</td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>27.23</td>
<td>79.39</td>
<td>0.475253</td>
<td>1.385616</td>
<td>3.578035337</td>
<td>0</td>
<td>19.1006461</td>
<td>0</td>
</tr>
<tr>
<td>30.25</td>
<td>81.27</td>
<td>0.527962</td>
<td>1.418428</td>
<td>2.602587242</td>
<td>0</td>
<td>16.94864538</td>
<td>0</td>
</tr>
<tr>
<td>33.28</td>
<td>83.18</td>
<td>0.580845</td>
<td>1.451764</td>
<td>1.80918101</td>
<td>0</td>
<td>15.12734846</td>
<td>0</td>
</tr>
<tr>
<td>36.32</td>
<td>85.13</td>
<td>0.633903</td>
<td>1.485798</td>
<td>1.154863656</td>
<td>0</td>
<td>13.55430242</td>
<td>0</td>
</tr>
<tr>
<td>39.37</td>
<td>87.14</td>
<td>0.687136</td>
<td>1.520879</td>
<td>0.608089153</td>
<td>0</td>
<td>12.17203912</td>
<td>0</td>
</tr>
<tr>
<td>42.43</td>
<td>89.22</td>
<td>0.740543</td>
<td>1.557181</td>
<td>0.148926376</td>
<td>0</td>
<td>10.93888853</td>
<td>0</td>
</tr>
<tr>
<td>45.48</td>
<td>91.4</td>
<td>0.793775</td>
<td>1.59523</td>
<td>0</td>
<td>0.240262166</td>
<td>9.830913922</td>
<td>0</td>
</tr>
<tr>
<td>48.54</td>
<td>93.72</td>
<td>0.847182</td>
<td>1.635721</td>
<td>0</td>
<td>0.573208782</td>
<td>8.816211771</td>
<td>0</td>
</tr>
<tr>
<td>51.59</td>
<td>96.2</td>
<td>0.900415</td>
<td>1.679005</td>
<td>0</td>
<td>0.856299912</td>
<td>7.882380216</td>
<td>0</td>
</tr>
<tr>
<td>54.62</td>
<td>98.9</td>
<td>0.953298</td>
<td>1.726129</td>
<td>0</td>
<td>1.098657858</td>
<td>7.015886921</td>
<td>0</td>
</tr>
<tr>
<td>57.63</td>
<td>101.89</td>
<td>1.005832</td>
<td>1.778314</td>
<td>0</td>
<td>1.306016325</td>
<td>6.202860529</td>
<td>0</td>
</tr>
<tr>
<td>60.6</td>
<td>105.25</td>
<td>1.057669</td>
<td>1.836957</td>
<td>0</td>
<td>1.482106598</td>
<td>5.436306905</td>
<td>0</td>
</tr>
<tr>
<td>63.53</td>
<td>109.13</td>
<td>1.108807</td>
<td>1.904676</td>
<td>0</td>
<td>1.63177551</td>
<td>4.704321013</td>
<td>0</td>
</tr>
<tr>
<td>66.38</td>
<td>113.68</td>
<td>1.158549</td>
<td>1.984089</td>
<td>0</td>
<td>1.756343214</td>
<td>4.004860711</td>
<td>0</td>
</tr>
<tr>
<td>69.12</td>
<td>119.18</td>
<td>1.206371</td>
<td>2.080082</td>
<td>0</td>
<td>1.859845668</td>
<td>3.330532279</td>
<td>0</td>
</tr>
<tr>
<td>71.7</td>
<td>125.97</td>
<td>1.2514</td>
<td>2.198589</td>
<td>0</td>
<td>1.942518142</td>
<td>2.676593306</td>
<td>0</td>
</tr>
<tr>
<td>74.04</td>
<td>134.56</td>
<td>1.292241</td>
<td>2.348513</td>
<td>0</td>
<td>2.006672371</td>
<td>2.037731791</td>
<td>0</td>
</tr>
<tr>
<td>76.01</td>
<td>145.5</td>
<td>1.326624</td>
<td>2.539452</td>
<td>0</td>
<td>2.0532583</td>
<td>1.41165082</td>
<td>0</td>
</tr>
<tr>
<td>77.43</td>
<td>159.17</td>
<td>1.351407</td>
<td>2.778038</td>
<td>0</td>
<td>2.084039776</td>
<td>0.792901021</td>
<td>0</td>
</tr>
<tr>
<td>78.12</td>
<td>175.14</td>
<td>1.36345</td>
<td>3.056767</td>
<td>0</td>
<td>2.096133471</td>
<td>0.178227853</td>
<td>0</td>
</tr>
<tr>
<td>77.93</td>
<td>191.75</td>
<td>1.360134</td>
<td>3.346666</td>
<td>0</td>
<td>2.093542774</td>
<td>0</td>
<td>0.435457025</td>
</tr>
<tr>
<td>76.92</td>
<td>206.89</td>
<td>1.342506</td>
<td>3.610909</td>
<td>0</td>
<td>2.072192495</td>
<td>0</td>
<td>1.050826803</td>
</tr>
<tr>
<td>75.24</td>
<td>219.41</td>
<td>1.313185</td>
<td>3.829424</td>
<td>0</td>
<td>2.035600397</td>
<td>0</td>
<td>1.672652288</td>
</tr>
<tr>
<td>73.09</td>
<td>229.3</td>
<td>1.27566</td>
<td>4.002037</td>
<td>0</td>
<td>1.982482093</td>
<td>0</td>
<td>2.304841124</td>
</tr>
<tr>
<td>70.64</td>
<td>237.06</td>
<td>1.2329</td>
<td>4.137474</td>
<td>0</td>
<td>1.910629801</td>
<td>0</td>
<td>2.9488564</td>
</tr>
<tr>
<td>67.98</td>
<td>243.26</td>
<td>1.186474</td>
<td>4.245684</td>
<td>0</td>
<td>1.819726665</td>
<td>0</td>
<td>3.611821915</td>
</tr>
<tr>
<td>65.19</td>
<td>248.33</td>
<td>1.137779</td>
<td>4.334172</td>
<td>0</td>
<td>1.707018204</td>
<td>0</td>
<td>4.296066729</td>
</tr>
<tr>
<td>62.31</td>
<td>252.57</td>
<td>1.087514</td>
<td>4.408174</td>
<td>0</td>
<td>1.571970879</td>
<td>0</td>
<td>5.006936503</td>
</tr>
<tr>
<td>59.36</td>
<td>256.21</td>
<td>1.036027</td>
<td>4.471704</td>
<td>0</td>
<td>1.41194448</td>
<td>0</td>
<td>5.752683356</td>
</tr>
<tr>
<td>56.37</td>
<td>259.41</td>
<td>0.983841</td>
<td>4.527555</td>
<td>0</td>
<td>1.22243608</td>
<td>0</td>
<td>6.538251725</td>
</tr>
<tr>
<td>53.35</td>
<td>262.26</td>
<td>0.931132</td>
<td>4.577297</td>
<td>0</td>
<td>1.00205209</td>
<td>0</td>
<td>7.372430351</td>
</tr>
<tr>
<td>50.31</td>
<td>264.87</td>
<td>0.878074</td>
<td>4.62285</td>
<td>0</td>
<td>0.742103203</td>
<td>0</td>
<td>8.265980159</td>
</tr>
<tr>
<td>47.26</td>
<td>267.27</td>
<td>0.824842</td>
<td>4.664738</td>
<td>0</td>
<td>0.440152815</td>
<td>0</td>
<td>9.230193582</td>
</tr>
<tr>
<td>44.2</td>
<td>269.53</td>
<td>0.771435</td>
<td>4.704182</td>
<td>0</td>
<td>0.084380168</td>
<td>0</td>
<td>10.28289298</td>
</tr>
<tr>
<td>41.14</td>
<td>271.66</td>
<td>0.718028</td>
<td>4.741357</td>
<td>0.331573295</td>
<td>0</td>
<td>0</td>
<td>11.44228343</td>
</tr>
<tr>
<td>38.09</td>
<td>273.71</td>
<td>0.664795</td>
<td>4.777137</td>
<td>0.825495447</td>
<td>0</td>
<td>0</td>
<td>12.73133721</td>
</tr>
<tr>
<td>35.04</td>
<td>275.69</td>
<td>0.611563</td>
<td>4.811694</td>
<td>1.413813619</td>
<td>0</td>
<td>0</td>
<td>14.19003635</td>
</tr>
<tr>
<td>32</td>
<td>277.62</td>
<td>0.558505</td>
<td>4.845379</td>
<td>2.122040055</td>
<td>0</td>
<td>0</td>
<td>15.86204447</td>
</tr>
<tr>
<td>28.98</td>
<td>279.52</td>
<td>0.505796</td>
<td>4.87854</td>
<td>2.986159492</td>
<td>0</td>
<td>0</td>
<td>17.80670116</td>
</tr>
<tr>
<td>25.97</td>
<td>281.4</td>
<td>0.453262</td>
<td>4.911352</td>
<td>4.057914511</td>
<td>0</td>
<td>0</td>
<td>20.1253011</td>
</tr>
<tr>
<td>22.99</td>
<td>283.27</td>
<td>0.401251</td>
<td>4.94399</td>
<td>5.410191978</td>
<td>0</td>
<td>0</td>
<td>22.94065324</td>
</tr>
<tr>
<td>20.03</td>
<td>285.14</td>
<td>0.349589</td>
<td>4.976628</td>
<td>7.164076254</td>
<td>0</td>
<td>0</td>
<td>26.47802987</td>
</tr>
<tr>
<td>17.1</td>
<td>287.02</td>
<td>0.298451</td>
<td>5.00944</td>
<td>9.51445924</td>
<td>0</td>
<td>0</td>
<td>31.08189549</td>
</tr>
<tr>
<td>14.2</td>
<td>288.92</td>
<td>0.247837</td>
<td>5.042601</td>
<td>12.8140438</td>
<td>0</td>
<td>0</td>
<td>37.38451212</td>
</tr>
<tr>
<td>11.33</td>
<td>290.86</td>
<td>0.197746</td>
<td>5.07646</td>
<td>17.7717933</td>
<td>0</td>
<td>0</td>
<td>46.63778845</td>
</tr>
<tr>
<td>8.52</td>
<td>292.83</td>
<td>0.148702</td>
<td>5.110843</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5.76</td>
<td>294.85</td>
<td>0.100531</td>
<td>5.146099</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3.1</td>
<td>296.93</td>
<td>0.054105</td>
<td>5.182402</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.63</td>
<td>299.06</td>
<td>0.010996</td>
<td>5.219577</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Cumulative Light Exposure Plots

Fig. 1: SLO Summer Solstice: North Face

*This displays only the morning half of northern light exposure. The evening half is a mirror image of it. Optimal width of growth zone: 6.0 ft.

Fig. 2: SLO Summer Solstice: South Face

Optimal width of growth zone: 2.59 ft.
Fig. 3: SLO Summer Solstice: East Face

Optimal width of growth zone: 17.61 ft.

Fig. 4: SLO Summer Solstice: West Face

Optimal width of growth zone: 19.63 ft.

Fig. 5: SLO Spring Equinox: South Face

Optimal width of growth zone: 17.83 ft.
Fig. 6: SLO Spring Equinox: East Face

Optimal growth zone width: 17.81 ft.

Fig. 7: SLO Spring Equinox: West Face

Optimal growth zone width: 17.67 ft.

Fig. 8: SLO Season 2 Beginning (2/4): South Face

Optimal growth zone width: 31.19 ft.
Fig. 9: SLO Season 2 Beginning (2/4): East Face

Optimal growth zone width: 14.43 ft.

Fig. 10: SLO Season 2 Beginning (2/4): West Face

Optimal growth zone width: 14.29 ft.

Fig. 11: SLO Winter Solstice: South Face

Optimal growth zone width: 61.43 ft.
Fig. 12: SLO Winter Solstice: East Face

Optimal growth zone width: 12.06 ft.

Fig. 13: SLO Winter Solstice: West Face

Optimal growth zone width: 12.09 ft.
References


http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html

http://aa.usno.navy.mil/data/docs/AltAz.php

http://keisan.casio.com/exec/system/1224682277

Works Cited


Although this information is a product of the U.S. Geological Survey, we provide no warranty, expressed or implied, as to the accuracy of the data contained therein. This tool is not a substitute for technical subject-matter knowledge.

\[ \varphi = 90 - (\text{LAT.} + 23) \]
\[ \theta = \varphi \times (\% \text{ exposure desired}) \]

Tiered bldg. vs. straight vertical
find max width of growth region, angle is center of bldg arc

artificial light grow zone

natural light grow zone

go until no longer efficient

mainenance, stairwells, etc.
\[ \Theta = \Theta_{\text{max}} \sin \beta \]
\[ d_i = \frac{h}{\tan(\Theta_{\text{max}} \sin \beta)} \]
\[ d(t) = \frac{h}{\tan(\Theta_{\text{max}} \sin \beta)} \]
\[ L = \int_{\text{sunrise}}^{\text{sunset}} d(t) \]

\[ x^2 + y^2 = r^2 \]
\[ y = \sqrt{r^2 - x^2} \approx \frac{r^2}{2} \quad \text{as } x \to 0 \]

\[ \Delta \Theta = \text{constant} \]
\[ \Theta = \text{1st order} \]
\[ \Theta = \frac{t}{\text{hours/deg}} \]

\[ d(t) = \frac{h}{\tan \left( \frac{t}{\text{hours/deg}} \right)} \]

\[ L = \int_{\text{sunrise}}^{\text{noon}} \frac{h}{\tan \left( \frac{t}{\text{hours/deg}} \right)} \]
3-4 hr direct sun/day

6-10/hr ft.

12" spacing in soil

typ 260° design region (Vancouver) 35-75° ideal temp.

80' max ht., 5 floors

90,000 SF
Summer Solstice, SLO (6/21)
\[ A_1 = 90^\circ @ 9:36 \text{ AM} \Rightarrow \Theta = 43.65^\circ \] \[ A_2 = 270^\circ @ 4:33 \text{ PM} \Rightarrow \Theta = 43.57^\circ \] \[ \Rightarrow 67.5^\circ \text{ \& 54 hr \Rightarrow 4.15'} \]

Winter Solstice, SLO (12/21)
\[ \Theta > 10^\circ @ 9:10 \text{ AM} \Rightarrow 25.79^\circ @ 4 \text{ hr} \Rightarrow 20.7' \]
\[ \Theta > 10^\circ @ 11:51 \text{ PM} \]

Source: esrl.noaa.gov/gmd/grad/solcalc/azel.html

- \[ 1 \text{ hr} \Rightarrow 49.72^\circ \Rightarrow 8.47' \]
- \[ 2 \text{ hr} \Rightarrow 59.77^\circ \Rightarrow 6.80' \]
- \[ 3 \text{ hr} \Rightarrow 61.75^\circ \Rightarrow 5.37' \]
- \[ 4 \text{ hr} \Rightarrow 71.65^\circ \Rightarrow 3.12' \]

- \[ 1 \text{ hr} \Rightarrow 14.59^\circ \Rightarrow 38.4' \]
- \[ 2 \text{ hr} \Rightarrow 18.88^\circ \Rightarrow 29.34' \]
- \[ 3 \text{ hr} \Rightarrow 21.75^\circ \Rightarrow 24.05' \]
- \[ 4 \text{ hr} \Rightarrow 28.92^\circ \Rightarrow 18.56' \]

- \[ 1 \text{ hr} \Rightarrow 15.94^\circ \Rightarrow 35' \]
- \[ 2 \text{ hr} \Rightarrow 21.89^\circ \Rightarrow 24.88' \]
- \[ 3 \text{ hr} \Rightarrow 27.11^\circ \Rightarrow 19.04' \]
- \[ 4 \text{ hr} \Rightarrow 33.31^\circ \Rightarrow 15.22' \]
- \[ 5 \text{ hr} \Rightarrow 38.62^\circ \Rightarrow 12.52' \]
- \[ 6 \text{ hr} \Rightarrow 43.92^\circ \Rightarrow 10.53' \]

Spring EQ:
\[ A_1 = 90^\circ @ 7.19 \text{ AM}, \Theta > 10^\circ @ 7:56 \text{ AM} \]
\[ A_2 = 270^\circ @ 7.05 \text{ PM}, \Theta > 10^\circ @ 6:23 \text{ PM} \]
Summer Solstice, SLO (6/21)
1h \rightarrow 25.38'
2h \rightarrow 15.11'
3h \rightarrow 9.77'
4h \rightarrow 6.36'
5h \rightarrow 3.79'
6h \rightarrow 2.24'
7h \rightarrow -
8h \rightarrow -
9h \rightarrow -
\theta > 10^\circ \text{ @ 6h, peak @ 105 PM}

Spring Equinox, SLO (3/21)
\theta > 10^\circ \text{ @ 7:57 AM, peak @ 110 PM}
1h \rightarrow 24.69'
2h \rightarrow 19.15'
3h \rightarrow 10.51'
4h \rightarrow 7.99'
5h \rightarrow 6.97'

Winter Solstice, SLO (12/21)
1h \rightarrow 29.41'
2h \rightarrow 20.79'
3h \rightarrow 17.33'
4h \rightarrow 16.54'
5h \rightarrow -
\theta > 10^\circ \text{ @ 9:10 AM, peak @ 1:01 PM}

keisan.casio.com/exec/system/12241682277
aa.wso.navy.mil/data/dx1/AltAz.php
STRUCTURAL DESIGN QUESTIONS

- Lateral truss Diaphragm
  - Between every beam or 1 brace/bay?
  - Lateral shear connections for beams?

- Beam Framing
  - Change direction or some bays?
  - Frame steel beam/girder into conc. wall?
  - Need conc. col's embedded into walls?

- Lateral System
  - Braced Frames vs. Conc. Shearwalls
  - Placement and redundancy