TENSEGRITY [noun.] - the characteristic property of a stable three-dimensional structure consisting of members under tension that are contiguous and members under compression that are not.

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Narrative

Tensegrity strives to create an impossible floating structure. To achieve this mark, tensile rods are used to suspend the pavilion mid-air which creates an axial stress governed system. Within this axial force design constraint, a 3D space truss becomes the form. This structure pays homage to famous structural designers of the past, such as Santiago Calatrava and Kenneth Snelson. Similar to these artists, tensile elements are at the forefront of the design. To accommodate the user, we have provided a sitting space nestled in the center of the system. This is intended for visitors first to be puzzled by the seemingly discontinuous load path, then for them to learn and understand this large-scale tensegrity experiment.

Poly Canyon being reopened for student experimentation seemed to be the perfect place for this structure to reside. In this case of the tensegrity system, the compressive elements are redwood 4x4 post and beams while the tensile elements are stainless steel medium strength rods provided by Tri-Pyramid. The joints and columns connecting to the ground are 4x4x0.250 steel hollow structural sections chosen to fit perfectly to the lumber. The gravity system is made of inclined steel rods and lateral system is made up of rod bracing to satisfy stability. Although the project is using rods, the rods have been assumed to have no compressive strength and thus are oriented in an X shape to replace compression struts. Since these rods do have compressive stiffness, a calculation has been provided showing this redundancy. Concrete pad footings anchor the structure to the ground. This structure will take a place on the hill directly below the hay bale arches and horizontal to the Fratessa tower in order to maximize views of the structure while becoming a visible addition to the current experiments.
Executive Summary and Path of Writeup:

This Tensegrity project writeup is broken into three distinct processes/stages/work flows. The first is process which consists of mainly physical modeling of the structure. There were also weekly meetings that contain recaps and design decisions that were recorded in real time each week. These were written hours if not minutes after meetings and thus provide ample insight into the projects beginning process. The second stage of this project was logistics and mockup. Students used the CAED shop to fabricate at smaller scale, the joints of the structure. They also made construction drawings and began their drafts for their permitting. This was the phase in which they collaborated with CAED shop staff in order to figure the amount of time, effort, and equipment necessary for construction of the structure. The next phase in spring was real building of the structure and additionally submitting for permitting. Though this structure has not been built at time of submittal to digital commons, all components have been fabricated and plans made for construction and permit package has been submitted though not yet fully approved. Please see previous narrative about what this project is striving to accomplish.

Tectonics/Concept Statement: Tensegrity strives to create an impossible floating structure. To achieve this mark, cables are used to suspend the pavilion mid-air which creates an axial stress governed system. Within this axial force design constraint, a 3D space truss becomes the form. This structure pays homage to famous structural designers of the past such as Santiago Calatrava and Kenneth Snelson. Similar to these artists, tensile elements are at the forefront of the design. To accommodate the user, we have provided a sitting space nestled in the center of system. This is intended for visitors first to be puzzled by the seemingly discontinuous load path, then for them to learn and understand this large-scale tensegrity experiment.

Program/Purpose: Tensegrity was designed to showcase a total of the ARCE education through a project of architectural and engineering knowledge. Though a simple structure, Tensegrity offers a few different uses for visitors, students, and the SLO community. For visitors, this pavilion will showcase what students can learn and perform in the ARCE program. This will market the project to new students and potential donors of the ARCE program. For students, this pavilion provides an insight into a different structural system that fights the conventional and forces outside of the box thinking. Although it is a small step for students to take to build something different than post and beam, this will hopefully be an inspiration to future design engineers to think different. Additionally, the Tensegrity team hopes that this pavilion will open up the canyon to new student projects. Being one of the few projects built in a while, the team hopes that this will show future students all of the mistakes and pitfalls of one of these projects so that they may avoid them. As a final word to students, this project has had many thinking about retrofitting drainage, water, and electrical to make more interesting projects in Poly Canyon. For the SLO community, this project will offer a bench for hikers to stop and enjoy the view. Though many of the other projects offer shade, this specifically will offer a sitting space, where the other projects currently do not offer this.
Story so far: Tensegrity was assembled as a team of engineers with diverse skill sets and specialties. Although each of us has played to our strengths, all of us together have made Tensegrity what it is today. Will has always been one to have an architectural mind and a passion for model making and hands on learning. He formed the team and took the first step that was followed up and led by others. Kasey has had a mind towards constructability and practicality which is a key aspect to the design of any structure. His experience in the construction industry has made him an invaluable asset to the team. Jose is the analysis captain of EERI and also was one of the ones to be helping with calculation and analysis of this project. His unique way to see engineering in the wild and transfer it to paper was his unique specialty. Ivan has been our revit master. His experience working in the BIM side of industry for a construction company allowed him to be able to model and trade files between eTabs, Revit, and Rhino with ease. Truman with his background in the film industry had an eye for detailing and aesthetics. He has been our main man for photography and film and also has been a person to have careful attention to fabrication/calculation detail. This diverse group of students took their skills and made something that they did not initially understand, into a unique project that was easy to analyze. They then fabricated detail mockups and ordered their materials. Steel and Timber prices skyrocketed in the time that they were building the structure which was a major roadblock to success. Luckily, the team was able to work around this and eventually got the money needed to complete the project. They were able to build all detail components, place all concrete and anchor bolts, and finally complete the canopy portion (though this is not installed yet). The permitting of this project is where this story becomes a tragedy instead of comedy. The team submitted early spring quarter to Cal Poly Facilities for a building permit. This permit was given to different engineers and then rejected. The team realized after this rejection that there were many mistakes that they needed to fix in addition to trying to build each component. More calculations needed to be done and many material specifications were needed for the project in addition to stability studies and models. The lesson learned in this case is to be sure that all information is consistent with itself and that all details have been accounted for instead of just the bare minimum. Often, the bare minimum is confusing to people who have never seen your work. Simply a site where building may occur is not enough to show permitting on structure that is as strange as the one that we were attempting to build. Working on this resubmittal was stressful for the team but certainly an essential building block for each young designer to see and experience.
Though there were more models than these [see meeting recaps], these 5 models were the ones that defined the most crucial steps in our design process.
Model 01:
This model served the purpose of the intro to tensegrity. This word comes from putting the two words tension and integrity together to form a new word. This was coined long ago by better structural artists than us, but nevertheless is a fairly new term. The group needed a base line to start from in terms of their design and this model seemed perfect for this. It had almost every instability you could think of, but in many ways it was simple. It was inspired by Tension Cranes experimentation from winter of 2020 and additionally viral content that has been produced online. The combination of these two inspirations brought about something simple and yet complex. This model was unstable in buckling and in torsion, both modes that the team would fight to combat for the models to come. This model works off of having two hooks that are positioned nearly perfectly on top of one another. The center of mass must align with this interior hook junction and/or the outer cables balance the inherent net moment that comes from having the center of mass not above the “support.” The group decided from this model that the triangular form would be a reoccurring theme but that the instabilities would be fixed by repositioning the cables and platforms to different orientations.
Axial forces should be governing tensegrity arrangements. In many tensegrity is simple because it is simply a truss in 3 dimensions with tension members being the primary stability members. In other words, the load path is governed by tension rather than conventional bending and compression loads. By conventional, it means conventional construction. Tension is most often only called into play when there is uplift or as a cord in a bending member. It is not often the primary driving force of a design with the exception to bridges. This is the model in which this tension space truss was discovered. The basic stability of a platform needing 3 columns and 3 braces was tweaked and modified to find this model. Though unstable, this model tells an amazing story that led the team closer to their final design. As seen in the center of the model, one string comes out of plane to span across both diagonals to form triangular pyramids instead of simply having a uni-planar form. This allows the junction of the hooks that was re-used from the previous model to transfer lateral loads and prevent buckling by automatically balancing the centers of mass by pre-tensioning. As seen on the top, the triangular form was kept from the previous model and balanced by a second triangle. The “railings” were added in order to inspire different architectural features.
Model 03:
The concept of the structure began to develop with further review and modeling. Bridge detailing and experimentation came into play and the team began to find arrangements with cantilevers, as they provided the best shade. They began to think of scale and usability along with form and forces. Bridges naturally have already succeeded in tension governance in the case of suspension bridges and thus would be great inspiration for structure. This elegant form began to emerge of a shade overhanging and looping back to supports. Stability came from the lateral bracing on the edges and the moment frame “basket.” This model led to lots of shade for the people that may come and yet a slender form. This was also the first integration of a piston style version of redundancy. Just as a piston slots perfectly within itself concentrically, the team found that tensegrity is stable in vertical loads by placing forms concentrically and having cable links go from the outside in, as opposed to the hook model which only utilizes one cable for vertical stability. In this way, the center of mass balances itself in the center. Unfortunately, the moment frame basket at the base did not stay true to concept. In the ideal tensegrity model, axial forces would make most of the design. In this case, not only is the cantilever a bending member, but the base is a moment frame. In the next few iterations not shown, this is slowly fixed and delivered into model 04 and 05 as the final design.
Model 04:
This model became one of the final design. This played perfectly by our concept. All axial forces with a piston design. It is stable in each degree of freedom by utilizing vertical and laterally facing cables along with the downward piston gravity cables. With many members facing down from the bottom platform, the problems with this model stem from constructability. Cables coming to a node is significantly different from solid compression members coming to a point. At the middle node, there are 6 members joining there. This will be fixed in the final iteration, model 05. Additionally, the team established scale with this model. They decided that the top shall be 12 feet tall and that they wanted simply a bench space instead of a hammock or netting. This is mostly for the user experience. This added another layer of complexity to the structure. This bench would have to be attached with moment connections which did not stay true to concept or simplicity of form.
Model 05:

Though this design has been tweaked slightly, this is the final design. Pyramids on the outside balance visually with inverted pyramids on the interior to pick up compressive loads. This is essentially a simplified version and double of Model 04. This doubling was done to simply support a bench space that is located in the interior. Instead of needing moment connections, now it could be a compression/stability linkage and additionally not need to be supported by moment connections. Shade slats have also been considered for the top of the structure.
Final Design

The final design of this structure included aspects of each previous design to form a cohesive project. This unfortunately was not modeled in physical sticks and string, but instead was modeled in etabs and in revit/rhino. Provided is an exploded axonometric that shows each part of the final design.
TENSEGRITY

Concept Statement:
Tensegrity strives to create an impossible floating structure. To achieve this mark, cables are used to suspend the pavilion mid-air which creates an axial stress governed system. Within this axial force design constraint, a 3D space truss becomes the form. This structure pays homage to famous structural designers of the past such as Santiago Calatrava and Kenneth Snelson. Similar to these artists, tensile elements are at the forefront of the design. To accommodate the user, we have provided a sitting space nestled in the center of the system. This is intended for visitors first to be puzzled by the seemingly discontinuous load path, then for them to learn...

Tensegrity (noun.) - the characteristic property of a stable three-dimensional structure consisting of members under tension that are contiguous and members under compression that are not.
Site

Historic Poly Canyon has been dormant for the last decade. We hope to revive canyon with a new structural experiment. This site has long been used for structural artistry and experimentation and we hope that Tensegrity contributes yet another piece that has the same effect. This is to fulfill and continue the ARCE legacy by paying homage to great structural artists.
Meeting Recaps

These are recaps of each formal meeting that we met for during the design process. The design of our structure has continued into construction administration and field fixes, but has been well confined to Fall and winter quarters of the school year from 2020-2021. Please skip to page -- if you wish to not seen this process and are instead satisfied with the modeling that was explained and shown previously.
Meeting Recap
meeting at scout coffee on 09.20.20

The Stick Model
Will made a stick model with some applicator sticks and string that worked as a free standing model but did not deal with compressive load effectively. Though strong in torsion, the anticipated threat, it did not hold up in compression likely because of the rigidity of the floor plates. This became apparent when the structure appeared to pivot about an edge beam instead of the center of the triangles like it was supposed to. Here are images of the failure.

Drawings and Ideas
From this base model and sketches, the group then moved about on different plans and ideas. The first of these was to think about a possible architectural use in order to constrain the design and not make the creativity absolutely endless. The ideas thought of were as a shade structure or observation deck of Poly Canyon. This architectural thought mixed with the structural ideas led us to think about the emphasis of the floating structure and how this is going to be our goal as Tensegrity. This should be thought about from the colour of the cable to the colours of the steel so that this floating nature is emphasized all the more. Though the stick model is based off of two triangles, it was also thought of that the group could use two squares instead. Elastic deformation was also brought up with the cables and Jose is planning on researching steel cables this week in order to know exactly what we are working with.

Material and Scale:
It was decided by the group as a whole to use concrete grade beams as the base of the structure with steel as the top floating part of the structure. This would also entail using a wooden deck as the topping of the floating portion of the structure. The scale is going to be either an 18’ equilateral triangle or an 18’ x 18’ bay. This 18’ x18’ is well within the confines of what steel is capable of supporting in flexure, there may need to be an intermediate beam for the purposes of the deck. This is another thing to be thought about this week before next weeks meeting.

Admin Items:
During Will’s meeting with Kevin this week, Kevin told him that the shop will not be available for use until the Winter quarter 2021. It will be within the setting of an additional lab class likely on tuesday or thursday mornings. This means that we are looking to reach out to local shops to see if we can possible “rent” some shop time there. Kasey is heading up this process. The group also decided that this time on Sunday is a great time for them to meet. The next meeting will be on Sunday of next week at 1 p.m. or 13:00. It was also decided that Truman would be treasurer or book keeper for this project so be sure to send him all receipts in some way so that we can be reimbursed when we get funding this Winter.

To do:
-- Think about detailing of the structure and how you want it to go together(questions mark idea or trusses, deck design, etc.)
-- Reach out to shops to see if we can get shop time to build
-- Jose is researching steel cables but feel free to also do research on this
-- Models to try some different cable configurations(Truman/Will mostly but please join if you have time)
    ----> our goal is to finalize our form by next week.
-- Sketches of any other ideas you have for next week’s 1 p.m. meeting.
Drawing and Image Compilation

Tensegrity Structure
- 'Floating' Platform
- Steel cables in tension

THIS WEEK: Look up steel cables
- Allowable average loads
- Thicknesses
- Flanges connections

Cables in tension
- Typically face of cable in tension

It's like these leading steps that would allow us to use their step.
Drawing and Image Compilation

Tensegrity

- Only vertical supports
- No moment resistance
- Turning/Rotational plane
- Elastic deformation
- No collapse
- All tension
- Center of mass/pitch
Meeting Recap
meeting at scout coffee on 09.27.20

The Stick Models:
Will and Truman both made models of some new elements and ideas to think about. Will's model was mostly about fixing vertical stability within the model. Surprisingly, buckling was the biggest issue which was more or less resolved in these newer models(see model pictures below).

Drawings and Ideas
Architectural Use - determined that platform at top will not be inhabited by human beings and the primary use will be as a pavilion style shade and view point. This decision allows the team to design for minimal live loads(20 psf construction load).
Structural Ideas - team decided that everything that they do needs to have a reason. Whether this is an aesthetic or structural reason, every piece of the puzzle needs thought and reason for the decision. This pretty much eliminates the idea for curved members as these are not efficient structurally.

New Design - Kasey thought of a new version of Tensegrity where a single column protrudes down from the roof deck down to below a ring and then is anchored by multiple cables. In elevation this looks almost as a piston or damper device of some sort(see sketches below). This ups our redundancy in the vertical direction by giving multiple cables connecting the top to the bottom which is a big issue from the previous design. This will also center our pivot point at the center of mass of the roof deck which will give the design a greater ease of stability. The previous issue was the pivot point(the point at which one would sum their moments) was subject to move from the center of the roof deck. This caused a moment imbalance which in turn causes the tension columns to buckle and total structural collapse to occur. This new design of the Tensegrity system will aid in eliminating this issue. This new design also would help with the constructability of the structure as it means multiple members do not have to intersect at a single point. A large and not so new part of the design was also a criteria listed below.

Material and Scale:
It was decided by the group as a whole to use concrete grade beams as the base of the structure with steel as the top floating part of the structure. This decision was confirmed this week again. However, the members making up the hoop part of the structure are likely to be steel along with the members connecting them to the base. This will in many ways look like a truncated pyramid.

Scale - the group decided today to aim to fit the structure within a 12’ x 12’ x 12’ cube at the very least in order to aid in construction of the structure. This scale was determined at Scout Coffee on Foothill Boulevard by estimating the ceiling height of the wooden soffit outside of the main entrance. It was determined to be 10’ clear between the concrete and this soffit. This was the minimum amount that the group wanted to have between the ceiling of the roof deck and the ground of poly canyon. Thus the structure needed to be about 10 - 12’ tall to achieve this(still subject to change). This height is also based on the height of the proposed chevron cable bracing on the exterior faces(3 of 4 faces). The goal is to allow humans to be able to pass freely underneath the structure and that the space is fairly unobstructed. The horizontal bay dimension was determined by looking at the sidewalk squares determined to be 4’ in length. 3 - 4 of these squares seemed to be the best dimension to use. This may be upped to 14’ depending on the feasibility or where the design leads

Admin Items:
During Will’s meeting with Kevin this week, Kevin told him that the shop will not be available for use until the Winter quarter 2021. It will be within the setting of an additional lab class likely on tuesday or thursday mornings(please leave this space open when planning classes for winter quarter). The process for this project being an official senior project is as follows. The students develop the ideas and design for fall quarter 2020 (design development DD). This design is then approved by Kevin Dong SE and soon after submitted to Facilities to be approved by an outside party(likely an SE Cal Poly grad). After this submittal, the students begin to ask companies for funding and begin to fabricate details and prototypes of the project using the lab time allocated. This will also be when official CD and Shop DWG are developed. The class for this lab time will likely be a 453, 415 or 460 section that Kevin will open for us next quarter. The next meeting will be on Sunday of next week at 1 p.m. or 13:00. It was decided that the group will aim to meet at the Poly Canyon trailhead at 1 p.m. in order to do a site visit to get the lay of the land. Kevin will be invited to this meeting in order to have an expert opinion on Site choice.
**Design Criteria**

-- Walking freely beneath the floating element. --> 10' Ceiling Height
-- Conc. grade beams and steel members for everything else.
-- Shaded area
-- HSS tube steel for steel compression members
-- Steel cables for tensile members

**To do:**

-- Ivan --> in charge of the detailing specifically but this should also be a thought for all of us. Look at Jose’s link http://www.tripyramid.com/tension-elements and take a look at how this is put together to start to look at preliminary details. If each of us draw one detail each that concerns us that would be optimal but that will take some effort.

-- by next weekend we want the form fully established so for detailing and member sizing this is ball parking it. However, the action item is to have 5 different models that we can critique and find the best qualities and really determine what we want. To this end, experiment with different scales and find what will work best for what we are doing.

-- Make stick or Revit Model or Rhino model
-- Draw your model or use Revit or Rhino dimensioning to show some basic dimensions that we can discuss next week.

**Models**
The objective of this model was to identify what the effects of a rigid base had on the design and also to analyze what would happen in the primary tensile members where moved to the outside of the model. By placing the main cables on the edge not only is the middle freed up but the vertical supports can be integrated into cross braces. The main issue with this model is racking but adding cables where the dotted lines are shown would counteract this while still keeping the floating illusion.
Drawings and Sketches

09-27-2020  Tensegrity  Kasey Taits  

To-Do

• Contact steel shops to see if we can use some equipment.
• Make an axon drawing of what the model will look like.
This week: Axonometric drawing
Look at foundations

Asymmetry?
Meeting Recap

meeting at scout coffee on 10.04.20

The Stick Models:
Will, Truman and Ivan all made models for this week’s meeting. The models this week took a turn to instead of just being purely conceptual, they were proof of concept. They showed in real time and life how the structure could fit together. This is not often something mentioned but this meeting was especially encouraging for the group to see the ideas actually coming together. Ivan was able to skillfully make some revit models of some design options for us. They ended up looking really nice and made it clear that the team wanted the structure to be serviceable or walkable. A scale figure in Ivan’s model illustrated this point. Truman hand modeled the piston idea from last week. It was a literal representation of Kasey’s sketches. It showed that the structure needed to open up around the cable connection points in order to have a clear floating attribute. It also showed that under self weight, the structure in this configuration is free standing without braces which is proof of the concept working for dead loads only. Truman also proceeded to apply a “ground motion.” This showed that his model held up to the ground motion and acted as a kind of damper. Will’s model applied architectural space in the form of an appendage to the structure. It’s focal point shifted to the canopy element. The concentric triangles formed the same piston arrangement but also the bridge detailing for the top formed a kind of lateral bracing for the top of the structure. Overall, the group pushed on this model and it was solid from all angles which was another proof of concept. The lateral cable bracing prevented torsion and the “moment connections” of the compression base acted as a ductile moment frame in order to provide stability. This will hopefully be implemented in order to open the space for viewing. A slab was also proposed for the architectural space below the structure along with looking into concrete for the truncated pyramid base.

Design Decisions
Scale and Dimensions - The group came to a major decision that they wanted to bulk of the project (the structure minus the shade and inhabitable appendages) to fit within a 12’ cube. -> [final decision]
The group also wants a human being to be able to walk under the compression portion of the structure and be able to see above the hanging tension portion (see revit models).

Architectural Use - The group decided as whole that they wanted a shade appendage plus a lofted net below to not only visually balance the space but also to provide a place to enjoy the structure. This means live load will have to be accounted for. However, this needs to be discussed in order to finalize this decision to limit the liability for this decision.

Structural Ideas - Moment frame base in order to open up the space to better see the tension in action. Extending the top of the structure will not only shade but also provide adequate space for the lateral cable bracing. Structure is self supporting.

Final Decision - the group decided to modify Will’s model to fit the new architectural and spatial restraints mentioned above. Cantilever lengths to be determined by final models. The top triangle shape will be proportioned in order to deliver shade and also brace the top platform. This could be a 2:1 ratio subject to change. The triangle will be extended to meet the shade demands -> [final decision]

Other Important Decisions - the group also decided to use a kind of fabric (possibly with glow in the dark paint or fabric) and a loft netting for the inhabitable space below that matches the shape of the top portion. This is a finalish decision.

Admin Items:
Will met with Kevin on zoom during this week again. They discussed the use of cables as a lateral system. Because the cables will pose a very low risk on a pavillion style structure, cables may be used as the lateral system. It is possible that elastic may be used in weeks to come to construct final models in order to ensure tension. Final design development will be next weekend during the site visit but design is in the final stages at the moment. Next week will see the last of the design decisions and then the calculations will be in full swing.

To do:
-> Preliminary pricing of steel and possible fabrics or nettings - Truman, Kasey, and Will
-> Revit Modeling - Ivan
-> Look into precast concrete construction - Truman
-> Start Calculations (dead take off and live) - Jose and Will
-> Hand modeling final design - Will and Ivan
Meeting Recap [Models]

meeting at scout coffee on 10.04.20
Meeting Recap
Hike To Poly Canyon, Site Visit 10.11.20

The Stick Model
New model proposed to make the design simpler and lighter. To stay truer to the concept while not sacrificing stability. This model was discussed at length during the Thursday impromptu meeting. It was decided that the members connecting the so-called “basket” moment frame at the bottom needed to be removed. [big decision] This was because a moment was largely contrary to concept. The concept of this project thus far has been axial forces through triangulation of cables. A moment frame acting in bending runs contrary to this. The point in space that is then supported by the cables in the center of the main structure was reduced in size to become lighter, more feathery and floaty for lack of a better term. Architects could use the word ethereal, though I think this would likely mislead the audience. Anyways, these design switches are not perfect yet and will be further adjusted to become more elegant. This model in a way took the top off of the basket to better showcase the system we are primarily using for this project.

Site Decisions
Site Location and Reasoning - This site is just off of the main road that goes to the shell house and green house projects already out in the canyon. This is well traveled and accessible. This particular site was also known to already be built on as there are chopped foundations close to it. This means that there is some confidence in how the soil will act for us there. In all, this will be close to some of the other projects that have been built which in general is good because we will be able to glean knowledge from others who have built here in the past.

Site Decisions
Exact Location: 35° 18' 56" N, 120° 39' 13" W or simply Poly Canyon for wind and seismics stuff.
To do:
- Wind Loads at the site
- Seismic Loads at the site
- Dead and live load takeoff (this one is really rough, let's just get into the ballpark here)
- Verify 6x4 or 6x6 member size from dead and live loads (not sure on this one, give it your best shot, not a big deal if this is not finished)
- Cable Detailing (I really just want to know what our constraints are in this respect and overall how these systems work. The more information the better)
- Steel Takeoff (only compression members, let's get an upper bound on material cost)
WRA -- Model making (I am making another model that is going to be more stable and simple) Ivan I will send this to you once I am done so it can be computerized.
- Welding and our compression connection detailing (foundation, member to member, etc)
Meeting Recap
Meeting at Scout Coffee, 11.01.20

The Final Model
This model was approved by KD (advisor for this project) to be stable and buildable given proper detailing consideration. The process for making this model was to stabilize one triangle in the simplest way possible while staying true to concept. Middle “pyramid” structures were thought to look more floating if they were further from the exterior pyramids. Exterior compressive members were thus minimized as much as possible in order to contribute to the tensegrity being the main focus. After stabilizing one of these inverted pyramids, a second pyramid was brought close to it to simply support a sitting platform at the focal point. These two pyramids were then linked together at the intersection point to eliminate the unbalanced rotation from the pivot point at the tip of the inverted pyramids. This linkage also eliminates the need for more cables on the interior freeing up more space for audience to feel less cramped on the sitting platform.

Design Decisions and Next Steps:
Decision was made to scheme this structure out of steel. Standard conservative live load = 20psf for “roof.” Bench live load determined to be 80 psf. Dead load is tbd. Compression + bending is going to be used to size the members at the “roof.” Method of joints will be used to find cable forces based on a 1 kip load and then be scaled according to the real loads applied. Assuming IBC min foundations for now. This is a push for 50 - 75% submittal. Details next. “TI” and finishes and painting will be the last phase.

Site Decisions
Exact Location: 35'-18" N, 120'-39" W or simply poly canyon for wind and seisms stuff.
Meeting Recap
Meeting on Zoom, 01.07.21

**The Final Model**
This set of drawings represents the design at 100% schematic design phase. This means that the sketches and model are ready for final decisions and design of all members. This also means the team may start working on detailing and finer adjustments such as finishes and paint colours to name a few. Below are these drawings and decisions to date.

**Design Decisions and Next Steps:**
The largest decision on this project was to change our material from steel to timber construction. The team went back and forth for a time and then decided that wood with steel connections would not only serve the aesthetic purposes that the team desired but would also lower cost considerably and give them experience using combined materials. The changes made were to make all members on the “floating” part of the structure be made from wood and the bench, the shades, and the members touching the ground would remain steel. Foundations were to remain concrete.

Given that the team wants to make as many elements in the shop as possible, this lends itself to the thought of prefabrication. All of the connections can be prefabricated in shop. The corner connections will be cut at the correct angle and then additionally welded with the steel sun shades to provide a jig for the structure to be assembled upon. The interior members will be set up in a similar manner. The HSS members will then be slotted onto the timber members and then the intermediate framing members will be framed into them. See the sketch, I understand this may be quite confusing to hear in words. The sun shades will be made by welding a steel angle equilateral triangle to 1x steel members in order to drop easily into the the outer triangles of the top platform. These will then be nailed or bolted to the 6x members.

The bench at the base will be completely prefabricated out of HSS steel members and the ends detailed to receive the posts from the two tetrahedrons. These are all the details that we have figured out at the time.

**To do:**
- Ivan --> Revit updates, posts
- Will --> Site Plan, Rendering, Top platform
- Jose --> Cable information and design
- Kasey --> Pillars
- Truman --> Connections (cont.)
Meeting notes, drawings and sketches archive:

\[2 \times 2\]
1) "Decking" Shave Connection

2) Typical Corner Conn.

Nail or Fastener
6x

2x1 Angle

6x

1x STL

6x STL
TENSEGRITY

Designed: [Name]
Date: [Date]

Metal Joint w/ Metal Members (Cont'd)

This design works very similar to the first one. However, there is the addition of a coupler that places the pieces of the joint and the member to be fused.

The screws in the member approach can be accomplished by welding the coupler to either the joint or member creating a P-ten or I-beam system. This box system is also suitable for wood.
**OBJECTIVES**
- Create interesting & functional connections
- Connections that can be assembled in field or shop
  * Will be able to withstand long term weather
  * Cost effective
  * Efficient load transfer

**MATERIALS**
- Metal joint w/ metal members - bolted
- Metal joint w/ timber members - bolted
- Welded metal members

**METAL JOINT w/ METAL MEMBERS**

*IDEA:* A joint will be shop fabricated that will allow members to be bolted into the joint allowing for ease of construction in the field.

**MEMBERS ARE SLID INTO HSS JOINT AND THEN BOLTED INTO PLACE. # OF BOLTS WILL DEPEND ON SHEAR AND SECTION THICKNESS.**

**THIS DESIGN WOULD ALSO WORK FOR WOOD MEMBERS**
The Design Review

Kevin, our advisor agreed to have an informal review of the design and construction plans with us. A physical model, a revit model of all of the connections, analysis results, connection models, and a 10 percent draft of the presentation was presented in this meeting. Overall, the presentation and design progress was accepted positively. Connections are still in the works. They need to be practiced and executed still and additionally Kevin did not seem confident in them. The bench connection is pretty solid. There is lots of plasma cutting and moving targets to keep track of. Thankfully for the overall project there were no stability issues but unfortunately the bench design was incomplete. The bench was rhombus shaped as seen in other plans and ultimately was something that had no resistance to torsion. Strange how none of us picked up on it until now. Anyways, the group decided to fix this problem by making the bench purely a beam with a wooden platform on top to provide some seating but not to the degree they had planned before. This eliminates the torsion moment and makes this structure stable again. Another architectural change discussed was removing members of the pyramids protruding from the upper platform. There really only has to be one member in that location. However, Kevin made the call that the architectural move made of the pyramids speaking geometrically to the outer pyramids was an elegant and thoughtful move and it should be considered before the group decides to remove the pyramids. Overall, the calculations that have been completed have been well received. The bending calculations proved to be somewhat arbitrary. With only a 4 foot moment arm and a load of approximately 0.5 kip at the danger zone (namely the tip of the cantilever), this produced a load of 1.35 k*ft. While sizeable, this load can easily be carried by the 4x4 lumber with all of the factors considered. This was a worriesome element for the team so working this through with Kevin certainly helped their confidence. The connection design was also somewhat of a dark tunnel. Kevin explained that we could treat the material similarly to a two span truss in that we can take two pieces of the steel and place them in risa to see how much load each one will take respectively. It will distribute based on relative stiffness. The final thoughts in this review were all about our connections and how many cables were coming and going. The team discussed these connections and arrived at some of the conclusions drawn below. The hooks are to be bolted and welded together in order to have a more secure connection and provide a more constructable option.

Images of progress

Design Decisions and Next Steps:

the group agreed that the biggest priority this week was to get the “bones presentation” done. By this, the group is talking about their presentation that they would give to companies to persuade them to give us money or bones as they are more popularly called. The other priorities would be the base plate design, the cable connections (100 percent design) and some of the calculations that need to be done to prove that this works for facilities engineers.

To do:

__ Ivan --> Revit updates (fix bench to be 2x12 that we decided upon) and 100% CD set
__ Will --> Slides in indesign and calculations
__ Jose --> Slides and calculations
__ Kasey --> Slides and calculations
__ Truman --> Connections (cont.) and calculations
Meeting Recap  
Meeting on Zoom, 02.02.21

Advice and Thoughts From Our Advisor
Kevin liked our progress that we had made on the connections and such and also was a fan of the recording idea that we had for the presentation. However he had a few critiques that boiled down to some important items.

1. The connections have to be really clear and since we are inventing them, they really have a lot of freedom to make them nearly a pure axial(pins) connection. Kevin also mentioned that we need to think about cables hitting the posts and bending or deforming. In other words we need a clear path to the other end of the cable.

2. On the note of the drawings, Kevin said to make a compilation of sorts of all of the drawings and focus on the axonometric or perspective view of the structure. We do not necessarily want critique from the companies on the quality of the construction documents but we would rather have instead them see that we worked hard and put thought and effort into making them.

3. Another few notes on the connections is water as an issue on all joints. It does not rain all that much in slo but it rains enough that it would not be a bad idea to put weep holes or some kind of drainage sloping on the connections.

4. Another note on the connections. We need to grind the welds smooth for the end plate connections we have so that all of the members will fit together nicely at the nodes where there are so many coming together.

5. Foundations - Kevin explained that in short we need to do more of our own statics. I think this is one of the main things that we need to do before we show facilities what we have done is that we need to have the statics to back up what the eTabs model is telling us and what our fancy spreadsheets are also saying. He gave the example of summing moments about one of the connection points. Another thing to note is that Kevin advises against the design of a footing without a base plate. He said that a lot of times embedment leads to corrosion and water damage due to shrinkage and unequal strains. Additionally, the reinforcement of the footing is something that will be obtained at a later date. Truman, Ivan, and Jose will all be learning how to reinforce a footing to the most basic degree in ARCE 452 and thus we will figure this out later. Not necessary for the facilities submittal or the presentation. We will simply note that it is a reinforced concrete footing. Final thing is that the anchorage of the base plate will resolve the sliding and tensile forces. In other words we can design the footing as an entire mat instead of designing for individual loads like in 422. This means all the loads are resolved to axial loads (nearly no sliding yay!). This likely means that strap beam is not necessary.

In short - we need to do more statics this week to present to facilities. Just simple back of the napkin as kevin says to show them our thoughts and why/how we know it will work.

To do:
- Ivan --> Revit Drawing package
- Will --> Misc + report compilation + statics on beam and column
- Jose --> Foundation design --> base PL + statics
- Kasey --> Cost estimate + statics for other members
- Truman --> Connections (cont.)
Meeting Recap
Meeting on Zoom, 04.05.21

Where we are:
This last Saturday, Truman and Will made the hike out to the canyon. A few ideas here: we could save time by biking if everyone brought their bike and had one for Kasey. Truman jokingly said that his tandem bike could work if Kasey did not have a bike. Just a thought haha. Anyways, they laid out some string to show a rough footprint of the angles. It was a conservative estimate with 10’ sides and the correct arrangement. Nothing fancy. As you can see, one of the stakes did not really work and so they used a screwdriver and duct tape for one corner. Another discovery was that the existing Fratessa tower is top of slab at 10.5 feet. To make our structure higher than that at 12 feet seems to not be attainable. This structure additionally provided some great detailing examples for our cable design (see below). It seems to have a multi part connection to the actual cable application point and then a long threaded rod that connects to a cable by looping. This is definitely something we need to mock up and I think Truman is working on it.

Design Decision: Scaling to 10’ instead should be a much better alternative while keeping member sizes the same.

Big Takeaways - We are on a serious time crunch. The footing design and all the items we talked about need to be in high gear and hopefully finished this week. The money is also a big problem. Email as many as you can. Shop is now restricted to welding on T, TH, F. Friday will mostly be used to wrap up the week and plan for the next week.

Tasks:
- Ivan --> Revit Drawing package + an added site plan + shop dwgs
- Will --> Email companies + plan meetings + jig designs
- Jose --> Foundation design + Emails
- Kasey --> scheduling + construction sequencing + grading?
- Truman --> Connections (cont.) + scheduling + shop dwgs
preliminary analysis model for our own reference and sanity check.

Structural Design by Will Adam, Ivan Cruz, Joe-Kasey Tatis, and Jose Hernandez

Modeling

P/A - Axial stress is not as simple as it seems in this case. In order to remove doubts and to make calculation less arduous, the group made predictions based on their knowledge of statics and then made the etabs model to prove to others and themselves that their conservative predictions were true. In order to make the model, the group exported a 3D DXF from revit (yes it can be done!) and imported this to etabs. After this, all materials were turned to massless and a point mass applied to the middle of the platforms. The platforms were assigned semi-rigid diaphragms in order to have force flow through the members at the top of the structure in lateral motion. This allowed for modal analysis to occur on the structure but also to have members act together to mimic the steel triangles that will be inserted where the grey areas are in the images above and below. The members that were supposed to be cables were assigned compression limits of 0 kips in order to force them into compression. This has to be done within a nonlinear load case however because etabs is written to do tensile analysis within braced frame failure which is a nonlinear process. The moment was also released from these members as cables cannot carry moment (or very little). Pyramid pillars were modeled as HSS 4x4 members, the beams were modeled as timber 4x4 members and the cables were modeled as steel rods that could only take tension. Etabs seems to be outputting the correct expectations with translation, translation, rotation and with the yellow above being tension, it is also making the cables pure tension elements. The model above is under pure gravity load of 1.2D + 1.6 L. Go to next page for predictions and conclusions.

Plan View (undeformed)  Plan View Mode 1  Plan View Mode 2  Plan View Mode 3
Predictions

Prediction 1 - Point loading at extreme corner of structure will yield the opposite cable to be in tension and the members closest to it to be in compression. Cables at point of application will buckle and the cables furthest will resist moment axially. Moment will be temporarily transferred by the top beam members before being picked up by the cables on the other end.

Prediction 2 - Gravity loading will yield cables connected to the base of the pyramids to be in tension and the other members around it to be in compression.

Prediction 3 - Loading the structure laterally will cause the cables oriented in the direction of loading to either buckle or take tension of the load. The connecting beams on the top of the structure will be in compression to transfer the axial load.

Loading

Prediction 1 - 0.5 kip load at point

Prediction 2 - \( D = 10 \text{psf} \)
\( L = 80 \text{psf} \)
then using load combination 2 ASCE 7
\( 1.2D + 1.6L \)
Live load derived from 4 - 250 pound people at once on any given surface. This is 1 kip spread across our square footage.

Prediction 3 - 1 kip load at point noted

Maximum Forces

For the model in general and for each material: [LRFD]

Wood:
- Compression - 2k
- Tension - 1k
- Bending - 1.65kft

Steel:
- Compression - 9k
- Tension - 7k
- Bending - 5kft

Cables:
- Tension - 4.1k
Design Submittal
Skip to page -- for construction process photos
Tensegrity (noun) - the characteristic property of a stable three-dimensional structure consisting of members under tension that are contiguous and members under compression that are not.

Strucutural Designers: Ivan Cruz, Kasey Tatis, Jose Hernandez, William Adam, Truman Waller

Faculty Advisor: Kevin Dong
**Project Description/Data:**

**Project:** Tensegrity  
**Location:** Poly Canyon, San Luis Obispo, CA 93405 --> CAED Experimental Structures Lab  
**Use:** Pavilion  
**Architect:** Tensegrity Senior Project Team  
**Jurisdiction:** SLO County/ Cal Poly Facilities  
**Building Code:** 2018 International Building Code (IBC)  
2019 California Building Code (CBC)  
**Design Ref:**  
Wood: 2018 NDS  
Concrete: ACI 318-19  
Loads: ASCE 7-16  
**Rough Footprint:** 8’ x 16’ x 10’ tall

**Structural Systems:**

**Vertical:**  
4x4x0.250 Hollow Structural Section[HSS]  
4x4 Redwood Con Heart, No.2 or better  
**Lateral:**  
0.250"Ø Medium Strength Stainless Steel Rod provided by Tri-Pyramid  
**Foundations:** Shallow Pad footings 48” x 48” x 2’ deep  
**Soil Classification:** Site Class 4  
**Soil Bearing:** 2000 psf (for Dead + Live)  
**Passive Pressure:** 150 psf per ft of depth  
Increase for downward allowable loads when considering Seismic( * 1.333)  
**Other Soils Data:** Low expansive soils  
60-70 miles to closest fault  
Coefficient of friction for sliding $\mu = 0.25$, $Ff = \mu W$, where $W =$ sustained load
Design Criteria:

Building Use:
Occupancy (per IBC section 304,310)
Pavilion
Occupancy U

Design Loads: (see dead and live load takeoffs)

Dead Load:
Canopy: 20.5psf --> (can use 18.5 psf for beams and neglect column dead load)

Live Load: [Manufactured for worst case scenario]
L = 500# (2 250# people hanging or sitting on a point)
Live loads applied at each canopy corner to represent 2 250# people climbing on the free end.
[these loads govern design since all rods are same spec and largest loads are in the gravity downward rods and rods that resist overturning based on people loads.]

Wind Loads: [see wind load takeoff]
Based on ASCE Section 27.3 with Risk Category I and a basic wind speed of 86mph
\[ p = qGCp - qi(CGpi) \rightarrow \text{See Wind Load Takeoff} \ p = 16 \text{ psf} \]

Use ASCE 7-16 minimum roof suction pressure \( p = 8 \text{ psf} \)
for net suction load case

Seismic Load: [see seismic load takeoff]
Based on ASCE Section 12.8 and Chapter 11
Seismic Design Category (11.6) : D
Design Base Shear (from Appendix A)
\( V = CsW \)

Where;
\( Cs = SDS/(R/Ie) \)
SDS = 0.888
\( Ie = 1 \rightarrow \text{not important by ASCE 7-16} \)
\( R = 3 \) for category H table 12.2-1 ASCE 7-16 (conservative value)
Category H is for non-seismically detailed lateral force resisting systems
System is Medium Strength Stainless Steel Rods X-braced provided by Tri-Pyramid.

\( W = \text{Seismic weight from Dead load only} \)
\( Cs = 0.296 \)

\( V = 303.4 \text{ lbs} \)
Material Specifications:

**Timber:**
For beams and columns, 4x4 Redwood, Con Heart No.2  
Fb = 725psi  
Fc// = 700psi  
Fv = 425psi

**Steel:**
Structural Tubing[HSS]  
ASTM A500, Fy = 50ksi

Steel Plate  
ASTM A36, Fy = 36ksi

Steel Rod  
Medium Strength Rod 1/4” Ø Provided by Tri-Pyramid  
Ty = 5.4kips Bs= 6.8kips

High Strength Bolts (HSB) 1/2”Ø

Welding Electrodes: E70

Anchor Bolts  
3/4” Ø Threaded rod[RFB] w/ Simpson Strong Tie SET-XP epoxy

**Reinforced Concrete**
For foundation: normal-weight concrete (NWC) with a minimum 28-day compressive strength of 4000psi

**Steel Reinforcement**
ASTM A615, Grade 60, smooth bars, typical
**Governing Load Maps:**

- **2 people load: max local bending effects**
- **Live + dead - max rod forces (lower rods)**
- **Governing conventional wind load**
- **Governing lateral load**
- **Suction load case**
Dead Load Takeoff --> square footage of canopy = 50 sq ft.

<table>
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<th>Item</th>
<th>Unit Weight</th>
<th>Calculation</th>
<th>[Canopy]</th>
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<tr>
<td>Steel connections</td>
<td>12 plf</td>
<td>amt * unit wt/sqft</td>
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<td>Redwood beams</td>
<td>3</td>
<td>7 sticks * 10ft long</td>
<td>4.2 psf</td>
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<tr>
<td>Steel Panels(angle)</td>
<td>2</td>
<td>150 linear ft approx</td>
<td>6.0 psf</td>
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<td>3</td>
<td>6 sticks * 8 ft long</td>
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<tr>
<td>Misc</td>
<td>n/a</td>
<td>roughly 0.04 * Total</td>
<td>1.0 psf</td>
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</table>

Total Column Dead Load *

*Rod/Pillar Loads are gathered from center columns and thus will be derived from column dead load.

Total Building Weight = 50sqft * 20.5psf = 1025lbs --> seismic wt.
Factored Weight with ASCE LRFD LC 2 = 3630 lbs for rod design

Live Load Takeoff
Assuming 1 person weighing 250 lbs will sit or stand on all the panels at once
250 * 6 = 1500 lbs

1500lbs/panel sqft = 1500 / 50 sq ft = 30psf --> governing area load

Live otherwise = 20 psf --> non-governing construction load

The governing case in our analysis models proved to be
2 people hanging or sitting on a single point or corner of the structure

Live Point Load = 2 * 250lb = 500lb

** live load reduction not applicable**

Seismic Takeoff
Seismic Resisting System --> Cable X bracing Assuming R = 2.0

Sds = 0.888
Ie = 1.0
R = 3.0 (conservative value for category H table 12.2-1 ASCE 7-16)

Ta(approximate period) = 0.112 sec --> short period SDs plateau Plateau is a conservative estimate since we do not have site specific ground information and we have assumed site class default D.

Cs = Sds/(R/Ie) = 0.296
V = Cs(seismic weight)

Design Seismic Base Shear = 1025 lbs * 0.296 = 303.4lbs
--> to be applied at story level h=10'-0"
ATC Hazards by Location

Search Information

Coordinates: 35.3155555, -120.6536111
Elevation: 564 ft
Timestamp: 2021-01-18T23:16:32.615Z
Hazard Type: Seismic
Reference Document: ASCE7-16
Risk Category: II
Site Class: D-default

Basic Parameters

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* See Section 11.4.8

Additional Information

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</table>

https://hazards.atcouncil.org/#/seismic?lat=35.3155555&lng=-120.653611111&address=
**Wind Takeoff**

Wind takeoff executed by simplified directional procedure

ASCE 7-16 ch 26 and 27 -- 27.2

We shall assume that our structure is regular. Despite its irregular configuration, the shape and directions of lateral force resisting systems are fairly regular, even though a structure like this may not show in ASCE.

**Risk Category: I** --> this is a pavilion style canopy structure that shall only be visited and not inhabited.

**Basic Wind Spd** (from ATC hazard tool): 86mph

Wind directionality factor Kd: 0.85 --> Table 26.6-1 Main wind force resisting system

**Exposure Category: B** --> has trees and some structures around and < 30ft tall

Topographic factor Kzt: 1.0 --> not at the top of a hill, ridge, or enscape

Ground Elevation Factor: Ke: 1.0 --> San Luis Obispo is nearly sea level and permitted to be taken as 1.0

Gust-effect factor: 0.85 --> other analysis techniques not permitted

Enclosure Classification: Open Buildings - GCpi = 0 --> since fully open, internal pressure is negligible.

Velocity pressure coefficient: Kz = 0.57

**Velocity Pressure qz:** 0.00256 Kz Kzt Kd Ke V^2 = 9.2 psf

**External Pressure Coefficient:**  
- Cp = 0.8 [windward]  
- Cp = -0.7 [leeward]

\[
p = qGCp - qi(CGpi)
\]

\[
p = (9.2\text{psf}) \times 0.85 \times 0.8 - (9.2\text{psf}) \times 0 \quad [\text{windward}]
\]

\[
p = (9.2\text{psf}) \times 0.85 \times -0.7 - (9.2\text{psf}) \times 0 \quad [\text{leeward}]
\]

**Total p = 11.7 psf -- round to 12 psf**  
Per ASCE 7-16 must be 16 psf for wall which is what we are assuming  
For roof suction, wind loading shall be taken as minimum 8 psf

Long side of the structure would govern the design if wind were to govern this design  
15'-10.5" long and assuming 2'-0" of area to push against (tubes and members are only 4 inches thick so this is extremely conservative). This area is also placed at the very top of the structure as opposed to throughout to be even more conservative.

**For base shear val:** [unfact]  
Force = 15.875' \times 2' \times 16 psf = 508\text{lbs}  
[see wind area image to the right, yellow region is 2'-0" deep]

**For top max suction:** [unfact]  
Force = 50sf \times 8\text{psf} = 400\text{lbs}  
[see red outlined region]
Hazard loads are interpolated from data provided in ASCE 7 and rounded up to the nearest whole integer. Per ASCE 7, islands and coastal areas outside the last contour should use the last wind speed contour of the coastal area – in some cases, this website will extrapolate past the last wind speed contour and therefore, provide a wind speed that is slightly higher. NOTE: For queries near wind-borne debris region boundaries, the resulting determination is sensitive to rounding which may affect whether or not it is considered to be within a wind-borne debris region.

Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions.

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https://hazards.atcouncil.org/#/wind?lat=35.3155555&lng=-120.653611111&address=
Commentary on Design Loads and Criteria:

Assumptions
When designing something as strange as a tensegrity structure, students used computer programs but also some assumptions in order to simplify the problem. The member sizes based on past projects and geometric configuration were determined to be the 4x size. This size was chosen in order to be slender enough to convey elegance and intentionality, but also strong and stiff enough to resist the minimal loading on the structure. The team had built shade style structures of similar scale with 4x4 redwood and decided that this was a good starting point. These members were conservatively assumed to be 4x4 lumber with end detailing of HSS 4x members. The goal of this would be to fit a 3.5in. x 3.5in. wood member perfectly into an HSS 4x4x0.250.

The group also assumed the worst case design human to be 250 lb. Factoring two of these people per triangle canopy yielded the live load that would be applied for design. Standard loads for design are as follow:

- Dead = 20.5 psf (per conservative weight calculation), 18.5 psf(for beams)
- Live = 30 psf (people load) or 250 lb(one person load)

In order to design the wood members, the group assumed allowable stress design (ASD), and when designing steel members and medium strength rods, the group used LRFD design. Important to note that all members are well below their yield stress.

Load Distribution and general capacities of steel and anchorage:
The HSS members attached to the foundation base plates at the highest assumed load would only result in maximum of 5.5 k*ft of moment and 5.5 kips of compression. This is with LRFD factored weight as shown in the next pages. HSS 4x4x0.250 has 17.6 k*ft of bending capacity and 113 kips of compression capacity. This means the members are only 30 percent stressed in bending and compression at maximum. For the weld used to connect these pieces, the stress levels are similar. See the welds part of the connections and rods for the weld capacity.

Finally, the foundation was assumed to be designed by the IBC soil presumptions with a welded base plate connection. The HSS connection is anchored by Simpson 12” x 3/4”Ø RFB threaded rod connections with Simpson SET-XP epoxy filled holes. The design values for this specification of bolts are also much higher than necessary. Using the Simpson anchor designer tool with epoxy coated 3/4” x 8inch embedment (a conservative assumption of embedment of a 12 inch long bolt), the tension capacity was 8500 pounds or 8.5 kips. With a factored load of 2.16 kips, the bolts in tension were still only 32.5 percent stressed.

Rods and Connectors:
To distribute load to tensile rod members, the group assumed that in pure dead loading, the three rods at the base of each of the inverted pyramids would each take 1/6 of the total load (this would be 1/3 of each half of the canopy). This is because in theory all of the rods once pre-tensioned shall have equal stiffness and thus equal tension. If this were not the case, equilibrium would not be reached. These rods were assumed from large allowable loads given by rod manufacturer to be able to take loads much greater than any of the other members and thus were of little to no concern. The yield strength of a Tri Pyramid rod assembly is at yield 5.4 kips and at breaking strength to be 6.8 kips. These design values show that even one cable oriented correctly could support the entire factored weight of the structure and thus with 6 primary gravity rods the structure shall not fail.

The connections of the structure are geometrically complicated but surprisingly simple. Their goal is to deliver the tension load to the compression members of the structure. The 4x4 lumber is sized to fit perfectly within the cavity of the HSS tube. The rods are manufactured by Tri-pyramid and have axial capacities of 5.4 kips in yielding and 6.8 kips in breaking strength. As said before, each rod will at most have 635 pounds which is about 8.5 times less than the strength of the rod that is presented by Tri-pyramid. This strength is also less than the rod’s actual capacity. These rods are connected to the rest of the structure by an adjustable jaw connector. See detail. These connections shall have a pin connection through an A36 plate that shall be welded to HSS tube. These plates will have at least the 0.6 in2 of steel acting in tension. This is 21.6 kips of capacity which is 3-4 times the yield of the rods themselves. To finish this overdesign, we can also include the weld strength of a 3/16 weld which is 4.17 k/in for a fillet weld. Flare bevel welds are stronger per inch than fillet welds and thus can be assumed strong enough by inspection. All connections shall be welded all the way around and all seams shall be stiched with a 3/16” weld or greater which results in the capacity of the weld connections far exceeding loads delivered to them.
Lateral Loads:
With the seismic ground coefficient (Cs) being equal to Sds / R, with an R [ductility coefficient] of 3 per ASCE 7-16 CH 12, this would yield approximately a 300 pound load given that the structure is 1025 pounds. Cs is 0.296. When distributed to the members and applied at the corners, this load finds itself to be below 100 lbs in each rod. Seismic loading when distributed to 4 different rods would result in loads that are under 100 pounds per rod. By inspection, this would not govern design of rods or other members. Wind loading is similar to seismic loading in its magnitude. Wind loading with a conservative area of contact and on the long side of the structure still only results in 381 lbs. Similar to seismic loading, when distributed to 4 different rods, this results in less load than gravity loads from people hanging or standing on the structure. Design was governed by non-code based approaches of statics.

Loads were generated as mentioned before by assuming a 500 pound person (likely a 2 person load) stood or hung on a corner of the canopy. This was factored for the rods and used ASD load combinations for the wood members. These loads from this person point load governed the design of all the members because the laterally facing rods not only resist strictly lateral loads but also keep the structure in equilibrium.

Please see drawings for all final framing decisions. Please see calculations for these non-code based loads.

Stability and Rod placement/purposes:
Stability is a large player in the design of a Tensegrity structure. We used conventional stability and worked off of the basic pyramid stability model (6 members total, 3 columns and 3 struts to stabilize a flat surface). Each compressive member in the basic stability model has been replaced with two tension members. We do not rely on displacement to fix the torsional or lateral instability that occurs without lateral or vertical tensile members. Instead, we have placed x braces and vertically oriented rods to capture these instabilities. The top is treated as a platform that the rods are attempting to stabilize. The steel connections, since they are significantly more rigid than wood and they have small stresses compared to capacity, are treated as rigid fixed connections for the cantilever timber beams. See following images of how this works. First is a description of each rod’s purpose, and then a series of images that show different stability tests. The first of these is how we have tested this on a physical model. Most sculptural designs do not consider conventional stability and rely instead on displacement of tensile members to correct the structures lateral loads. This is NOT how we designed our tensegrity structure.

Lower Rod Arrangement
These rods primarily hold the structure in place from the downward loads. These are analogous to compression gravity columns in a conventional building.
**Short Upper Rods**

These upward facing rods balance the structure when it is pushed in a non-uniform way, i.e., point loads on the top of the structure. These point loads are from people deciding to climb up on top of the structure. As one side comes down, the rod on the other side is put into tension and equilibrium is reached.

**X-Braces:**

This structure has some redundancies due to wanting symmetry and being over designed. For the basic stability model, 3 struts are used to resist lateral movement of the structure. For each of these 3 struts, we have replaced them with 2 tensile rods thus making a stable structure.
Stability Diagrams:

Note: The HSS steel connections are assumed to be rigid since the bending stresses on them are so low and they are so much more rigid compared to the wood members. This structure's cantilevers are fixed by these connections. Where the bending moments are noted on diagrams, this is where these rigid steel fixities occur.

Overturning about short axis:
Overturning about short axis:

Overturning about long axis:
In Plane diaphragm loading (at center of rigidity = no torsion)
Torsion
Scope/Structural Notes:
SCOPE/STRUCTURAL NOTES:

Shop Drawings and Submittal:
This submittal includes a set of shop drawings providing detail connections and a set of construction documents showing a site plan and plans for construction. Tri-Pyramid has provided detailing for rod end connections.

Scope Introduction:
Tensegrity is a pavilion-style structure that shall be built in poly canyon’s accessible space. The structure will be in close proximity to the Fratessa and hay bale towers that were previous long-lasting projects of the ARCE department. These projects are available for access by trail/road, thus our project will be accessible for the public both students and the San Luis Obispo Community. Cal Poly facilities can view these past projects via the site plan and/or Cal Poly website.

Specific Project Scope:
Our specific scope is designing and constructing this structure. Our design development and construction document phases have lasted from Fall of 2020 until Winter of 2021 and the project is in its final phases of Permitting and Construction/Construction Administration. A permit is now required by Cal Poly Facilities to start work and be on schedule to complete this project by May 28th, 2021.

Material Specifications:[see calculations if necessary]

WOOD - Wood 4x4 members to be used on canopy structure as compression and bending members. These shall be anchored by steel bolts and steel Hollow Structural Sections (HSS). Wood members shall be Redwood Con Heart and NDS No.2 or better per RIS grading rules agency. Design Values shall be used per NDS 2018.

STEEL - Hollow Structural Section(HSS) 4x4x0.250 shall be used as compression, bending, and rigid connections in this structure. HSS members shall be ASTM A500 steel 50ksi or greater yield strength. Tensile rods shall be used to connect exterior pillars to the main interior structure. Tensile rods shall be anchored per specifications from the manufacturer(Tri-Pyramid). Tensile members shall be medium strength rods with 5.4 kips yield strength in tension with 6.8 breaking strength. Plate steel members and components shall be ASTM A36 steel with 36 ksi yield strength. Anchor bolts shall be Simpson RFB 3/4”Ø to be used with epoxy filled holes. Welds shall be fillet or flare bevel welds(depending on connection and location, see dwgs) per AISC table J2.4 and shall be minimum 3/16” width. Bolts designed and checked with Simpson Anchor Designer software(see appendix for screenshots of simpson anchor designer software) which is in accordance with ACI 318.

CONCRETE - Foundations shall use 4000 psi concrete with 2018 IBC and ACI 318 code minimums for rebar for temperature and shrinkage. Footings are sized based on soil assumptions of the 2018 IBC code. Base plates and anchor bolts shall be used to construct and connect main structural items to foundation.

Fabrication Scope:
The Tensegrity Senior Project team shall fabricate or place all elements listed above in material scope.

Inspection, Oversight, and Supervision:
Kevin Dong, a licensed structural engineer and the team’s advisor, shall inspect all drawings prior to submittal to Cal Poly Facilities and additionally shall supervise fabrication of structurally critical members. All work done on structural components shall be done in the CAED support shop upon approval and permit by Cal Poly Facilities. Dave Kempken and Tim Dieu shall be in the CAED support shop during all work hours to provide necessary safety supervision.
Work in CAED Support Shop:

Necessary PPE - Necessary personal protection equipment (PPE) shall be worn at all times by students performing work on the project. This includes safety glasses and coveralls for welding and welding gloves. Shade 10 shall be required when performing all welds. Shade 5 required for all plasma cutting. PPE includes a face covering for covid safety and testing compliance per Cal Poly and CDC guidelines. Student testing is available at San Luis Obispo County and/or Cal Poly Performing Arts Center (PAC) for no charge to students.

In the event of injury - In the event of an injury, the campus health center is within 5 min of the injury, while Tenet health center and emergency is within 10-30 min of all injuries.

Wood - Wood 4x4 members shall be cut in the CAED support shop using shop saws and electronic sanders, planers.

Metal - This will include cutting steel members using fluid cold saws and autofeed bandsaws. Welding of steel members for connections is required and shall be completed by students under shop supervision as listed above. CNC Plasma cutting of steel shall also be done in the support shop for detail connections. Additionally, plasma/waterjet cutting for signage and commemorative donor plaques will be done in the CAED support shop and ITP support shop.

Finishes - Powder coating and painting will also occur in the CAED support shop along with plasma cutting. This includes the oil sealing of all wood members prior to transport to the canyon to avoid spilling paint and oil into the canyon soil.

Field Fabrication:

Necessary PPE - Vis, hardhat, and safety glasses shall be required at all times when work is being performed on the project. Additionally, face coverings per CDC guidelines and testing per CDC guidelines shall be provided to prevent the spread of COVID-19 (until regulations lifted). Student testing is available on Cal Poly Campus or at SLO county.

In the event of Injury - In the event of an injury, the campus health center is within 15 min of the injury, while Tenet health center and emergency is within 15-30 min of all injuries.

Transportation - Poly Canyon Road allows ample access to the site and will be the main route of transportation of materials and people to the site. Rental equipment, personal vehicles, and CAED vehicles shall be the only vehicles permitted to access Poly Canyon Road.

Foundations - The team shall also excavate and pour the necessary foundations required for building. These shall have pins connections to the pyramid pillars which will be fabricated per shop drawings. These will additionally be attached to base plates. The rebar required and anchor bolts will be properly capped and covered during the duration of the necessary cure time to prevent public injury.

Field Welds - In the event that field welds are necessary either for precise fit up or extenuating time lines, all brush within spark radius shall be cleared. Soaked Plywood or sheet metal shall be provided to deflect sparks downwards towards bare, cleared earth. Flux core welding with similar specs to shop welders shall be used to achieve same strength welds. Gloves, shield, and coveralls shall be worn by those who are welding on the project.

Material Changes during CA and CD phases:
In the event that Schedule, Plans, materials, or locations changes, Cal Poly Facilities shall be notified for approval. For all items not listed here, please see the drawing package or the plans and elevations.
Drawings
Site Plan:
1. SITE ELEVATION VARIES. ENSURE TOP OF FOOTINGS ARE AT SAME HEIGHT
2. TAKE TOP OF FOOTING TO BE (+/- 0") RELATIVE TO TOP OF SOIL
3. SEE 8/3.2, 3/S3.3 FOR PYRAMID DETAILS
4. SEE 1/3.3 FOR FOUNDATION DETAILS
5. SEE S2.5 FOR ELEVATION OF STRUCTURE
6. SEE S3.1 FOR ROOD SCHEDULE

SHEET NOTES:

- GUIDELINES FOR TRIANGULAR SHAPES AT BASE

Foundation Plan

TENSEGRITY

Scale: 1" = 1'-0"

Drawn By:
Checked By:
Print Date: 6/10/2021 10:29:25 AM
1. TOP OF BENCH ELEVATION AT (+2'-6") RELATIVE TO TOP OF FOOTING
2. SEE S3.1 FOR ROD SCHEDULE AND DETAILS
3. LEGEND OF ANY SYMBOLS USED:
   - R1 INDICATES ROD SEE ROD LENGTHS PER SCHEDULE ON S3.1
   - ROD GOING UPWARDS
   - ROD GOING DOWNWARDS

 SHEET NOTES:

 S2.2

 BENCH LEVEL

 SCALE: 1" = 1'-0"

 DRAWN BY: 

 CHECKED BY: 

 PROJECT NUMBER: 

 PROJECT STATUS: 

 PRINT DATE: 6/10/2021 10:29:25 AM
SHEET NOTES:
1. PLAN ELEVATION AT (+7'-0") RELATIVE TO TOP OF FOOTING
2. SEE S3.1 FOR ROD SCHEDULE AND DETAILS
3. LEGEND OF SYMBOLS USED:
   - C1 INDICATES COLUMN, SEE COLUMN INFO ON SCHEDULE ON S3.1
   - R1 INDICATES ROD, SEE ROD LENGTHS PER SCHEDULE ON S3.1
   - ROD GOING UPWARDS
   - ROD GOING DOWNWARDS

Sheet Notes:
- C1 INDICATES COLUMN
- R1 INDICATES ROD
- ROD GOING UPWARDS
- ROD GOING DOWNWARDS

Scale: 1" = 1'-0"
SHEET NOTES:

1. PLAN ELEVATION AT 10' - 0" RELATIVE TO TOP OF FOOTING
2. SEE S3.1 FOR ROD SCHEDULE AND DETAILS
3. LEGEND OF ANY SYMBOLS USED:
   - C1 INDICATES COLUMN, SEE COLUMN INFO PER SCHEDULE ON 1/S3.1
   - R1 INDICATES ROD, SEE ROD LENGTHS PER SCHEDULE ON 2/S3.1
   - ROD GOING UPWARDS
   - ROD GOING DOWNWARDS

1. PLAN ELEVATION AT 10' - 0" RELATIVE TO TOP OF FOOTING
2. SEE S3.1 FOR ROD SCHEDULE AND DETAILS
3. LEGEND OF ANY SYMBOLS USED:
   - C1 INDICATES COLUMN, SEE COLUMN INFO PER SCHEDULE ON 1/S3.1
   - R1 INDICATES ROD, SEE ROD LENGTHS PER SCHEDULE ON 2/S3.1
   - ROD GOING UPWARDS
   - ROD GOING DOWNWARDS

4x4 RW CONTINUOUS BEAM

Scale: 1" = 1'-0"
SHEET NOTES:

1. SOIL BEARING q = 200psf PER IBC 2018 TABLE 1806.2 CLASS 4
2. ALL ANCHOR BOLTS TO BE THREADED PER SIMPSON RFB ANCHOR BOLT SPECIFICATION, STEEL SPECIFICATION ASTM F1554, GRADE 36
3. USE SIMPSON STRONGTIE SET-XP EPOXY FOR ALL ANCHOR BOLTS

FOOTING DETAILS

1. SCALE: AS INDICATED
2. SCALE: NONE

FOOTING ELEVATION
1 1/2" = 1'-0"

FOOTING PLAN VIEW
1 1/2" = 1'-0"

TENSEGRITY IC
TJW
Construction photos
Surveying:
Using the drawings created by Ivan Cruz, the team laid grid lines with string and stakes just as construction practice.

Kasey hammering a stake
Concrete Forms:
These wooden forms helped to level and place the concrete in the desired location:
Concrete Placement and String Leveling:
String was used with a string level to level all forms and then concrete was placed with 9cuft concrete mixer and ready mix bags. See next page for finished concrete.
Steel Fabrication:
Mig Welding and Plasma Cutting was used to fabricate all joints and connections. Steel purchase is large image above. It was 4X4X0.250 HSS and 1/4" plate.
Steel Fabrication:
Mig Welding and Plasma Cutting was used to fabricate all joints and connections. Steel purchase is large image above. It was 4X4X0.250 HSS and 1/4" plate.
Welding and Plasma:
Wood:
Notice dado cut for seam in HSS
Conclusions and Reflections
Conclusions and Reflections:

Team Reflection:
Throughout the quarter our team has been working hard on making this idea come to life. This project has taught each of us what it takes to fully bring a structure to life and this opportunity to be on a design-build project has given us firsthand experience in being the architect, structural engineers, as well as the construction manager. Having gone through each phase of the process it has given us a much better understanding of how these separate, often times conflicting, roles operate and gave us much more appreciation for the jobs and decisions that must be made by each one. The structure itself posed various challenges and obstacles that would show up throughout the year; however, with the knowledge that our team has gained throughout our college career through the ARCE program and internship opportunities we were able to overcome them. The tensegrity design proved to be a very complex structure to convey load flow and provide adequate calculations that were simple and easy to follow, so upon reflecting on this senior project if there was a place that we now understand needs to be extremely solid and thorough it would be the calculations and drawings. We underestimated how clear we were in the submittal packages, but now moving forward we will learn from our mistakes made previously and aim to not repeat them again. In all, we believe we did the best we could with the circumstances given and hope to learn from the mistakes that were made.

Team Conclusion:
In conclusion, this senior project has allowed this team to learn not just how to be a better engineer by taking learned concepts and applying them to a real-life structure, it has more importantly challenged us with making a project constructable and an appreciation for all the trades that goes into construction. This tensegrity structure will be a wonderful addition to the Poly Canyon list because of its uniqueness since there is nothing else out there that incorporates this concept as much as our senior project will and we are so incredibly proud to be able to bring a new idea and resting point to existence for students and others to see.
WRA: This project has been a journey. From its conception in summer of 2020, to its design, logistics and construction, it has been a ride that has allowed me to learn such important life and structural engineering lessons. From the design phase, I learned that your first idea is often not your best and that the input of your team mates is so important for the quality of design. The piston concept design that become our final design was crafted from multiple ideas coming together to form that physical model and even more design input to reach our final construction documents. At the later phases, I also became much more acquainted with constructability and how things actually fit together. This was also as a result of listening to shop technicians and my team mates who knew a lot more about this than I did. In general, an important conclusion I drew is that working with your fabricators and/or fabrication experts is most important for figuring out your final design. The day you are fighting your fabricators and shop technicians is the day that your project starts to fall behind schedule and not look the way you really want it to look. These are skills I shall take with me out into industry to make my future endeavors in engineering and design more prosperous. I want to thank our advisor Kevin Dong, for trusting us with the responsibility of building in the Canyon and the CAED shop staff for their dedication to the project and finally my team for accompanying me on this crazy journey with all of its sidesteps, struggles and challenges. It is something I will never forget.
JKT: This past year working on the Tensegrity project has allowed me to showcase my knowledge, communication, leadership and problem solving skills. Though I grew up working construction jobs with my father doing hands on work, I have never been a part of a team that has taken an idea and followed through with it as far as my team has this year. I was fortunate enough to have gained firsthand experience in developing an idea into a fully formed structure by being a part of the design, calculation, permitting, and construction phase during each quarter throughout this past school year. The knowledge I have been able to obtain from this senior project is something that cannot be taught by a professor during a college course, instead it is only acquired through real life situations that engineers, architects, and construction managers face every day. In a sense this project was a bit easier to coordinate and bring to life since each members of the team were acting as the engineers, architects, and construction managers, so decisions were made with relative ease due to our similar mindedness; however, being able to take on all these roles could not have been done without the knowledge gained by my Cal Poly education and summer construction internships. I would like to thank everyone that was apart of this project both directly and indirectly, we truly could not have gained this invaluable experience without each and every one of those individuals.
IC: Working on the Tensegrity project has allowed me to hone my skills in design and understand the complications of preparation and construction. Throughout each phase of the project, we worked steadily to achieve our projection completion date. Along the way, we ran into issues that allowed us to test our problem-solving skills to stay in line with our completion date. This knowledge of the flow and design of a project gave us valuable insight into the proper coordination for real-world projects. After running into such complications, our team took on the roles of architects, engineers, and construction managers, to work together more efficiently in forming this project. Another valuable lesson I have learned throughout this project has been the importance of organization and the presentation of documentation. With the irregular 3D structure we were generating, the organization of members and the expression became a big challenge in our documentation process. Our team worked in various programs like Revit, AutoCAD, Rhino, and others to effectively portray our project to our intended audiences. This documentation affected our ability to gain fundraising from sponsors and retrieve our permit for construction. After various trials, we were able to convey our idea to sponsors and reviewers adequately. Overall, this project has been very beneficial for me, and it was a pleasure working with my team.
JH: When Will first approached me with the idea of designing and building out in Poly Canyon, I knew that it was going to be a lot of work, but I had no idea how much work it was really going to be. The design portion of the project was very iterative and I found it interesting to see the evolution of our design as we essentially went through trial and error to find lateral and torsional stability in our model. It was also great to see our CAD and computer analysis skills applied to the documentation and modeling of our model in REVIT and ETABS. I enjoyed working on the construction portion the most. I definitely learned about the value of clear communication from the engineer to whoever is working in the field or in the shops. For this project, our whole team were engineers and also working hands on on the project. So, I can only imagine how much more valuable communication is when the two roles are occupied by different people with different backgrounds. Another reason why I really enjoyed working hands-on on the project was that it gave me a reason to get out of the labs and apply what I have learned in my classes to physically see what I was calculating on paper. This will certainly give me some form of empathy with workers when I start working in the industry. I will consider the complications that come when bigger members are used such as the literal moving of said member and finding a way to install it. I forget where I heard this quote from but it is essentially, “nothing that is worth doing is easy,” and this perfectly describes how I feel about this whole project. This was a lot of work but I have learned so much about team communication and leadership as well a great feeling of accomplishment.
Since August, the five of us have been working to design and build a tensile pavilion out in poly canyon. The goal was to create an experimental structure to showcase everything that we had learned over the past four years. Little did we know that we would learn far more through the process than we had ever anticipated. The initial design phase was more difficult than we had anticipated. We had a concept that we wanted to showcase but there were infinite ways to show this concept. We eventually settled on the design we have now after many models and stability checks. Then it was off to the structural design, which again posed more complications than initially predicted. The structure’s shape was geometrically complex and forced us to think about how loads move in three directions and through irregular shapes. There weren’t many times in our education where we worked with buildings that weren’t rectilinear. Nonetheless we were able to translate what we had seen before to fit our situation allowing us to complete the design. Then it came to the physical construction. Most of the time we are designing imaginary buildings that will never get built or have already been built. Now here we were tasked with building something we designed. We worked hand in hand with the shop technicians to ensure that we were working safely and efficiently. There were many times where we had designed a member to be welded together at irregular angles and then when it came to welding the pieces, we had to reevaluate how to go about that. The physical production of the structure taught me a lot about how to efficiently design for someone else to build. The plans can be precise as to how things come together and where they come together, but the built world doesn’t work down to exact measurements. We learned the importance of tolerances in design. The showcase of our educational development ended up being another lesson in architectural engineering.
Appendix:
# Appendix:

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RFBs are pre-cut threaded rod, supplied with nut and washer. For use with Simpson Strong-Tie® adhesives. May be ordered in bulk without the nut and washer. Use with Simpson Strong-Tie adhesives to anchor into existing concrete and masonry. Each end of the threaded rod is stamped with rod length in inches and our “No-Equal” symbol for easy identification after installation.

**MATERIAL:** ASTM F1554 Grade 36  
**COATING:** Zinc-plated, hot-dip galvanized

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<td>RFB#4x10HDG</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>3/8&quot; x 5&quot;</td>
<td>RFB#5x5</td>
<td>RFB#5x5HDG</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>3/8&quot; x 8&quot;</td>
<td>RFB#5x8</td>
<td>RFB#5x8HDG</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>3/8&quot; x 10&quot;</td>
<td>RFB#5x10</td>
<td>RFB#5x10HDG</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>1/4&quot; x 12&quot;</td>
<td>—</td>
<td>RFB#12xHDG</td>
<td>—</td>
<td>10</td>
</tr>
<tr>
<td>5/16&quot; x 16&quot;</td>
<td>RFB#5x16</td>
<td>RFB#5x16HDG</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>3/8&quot; x 10 1/4&quot;</td>
<td>RFB#6x10.5</td>
<td>RFB#6x10.5HDG</td>
<td>25</td>
<td>—</td>
</tr>
</tbody>
</table>

1. Bulk quantities do not include the nut and washer and must be ordered with a "-B" suffix (example: RFB#4x5-B). Hot-dip galvanized RFBs not available in bulk.
2. Retail packs must be ordered with a "-R" suffix (example: RFB#5x12HDG-R).
SET-XP® Cure Schedule

<table>
<thead>
<tr>
<th>Base Material Temperature</th>
<th>Gel Time (minutes)</th>
<th>Cure Time (hrs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>°F</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>75</td>
</tr>
<tr>
<td>60</td>
<td>16</td>
<td>60</td>
</tr>
<tr>
<td>70</td>
<td>21</td>
<td>45</td>
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<tr>
<td>90</td>
<td>32</td>
<td>35</td>
</tr>
<tr>
<td>110</td>
<td>43</td>
<td>20</td>
</tr>
</tbody>
</table>

For water-saturated concrete, the cure times must be doubled.

SET-XP Typical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Class C Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property</td>
<td>(&gt;60°F)</td>
</tr>
<tr>
<td>Consistency</td>
<td>non-sag</td>
</tr>
<tr>
<td>Bond Strength, Slant Shear</td>
<td>2.900 psi</td>
</tr>
<tr>
<td>Compressive Yield Strength, 7-Day Cure</td>
<td>14,100 psi</td>
</tr>
<tr>
<td>Compressive Modulus, 7-Day Cure</td>
<td>612,000 psi</td>
</tr>
<tr>
<td>Heat Deflection Temperature, 7-Day Cure</td>
<td>136°F (58°C)</td>
</tr>
<tr>
<td>Glass Transition Temperature, 7-Day Cure</td>
<td>126°F (52°C)</td>
</tr>
<tr>
<td>Decomposition Temperature, 24-Hour Cure</td>
<td>500°F (260°C)</td>
</tr>
<tr>
<td>Water Absorption, 24-Hours, 7-Day Cure</td>
<td>0.10%</td>
</tr>
<tr>
<td>Shore D Hardness, 24-Hour Cure</td>
<td>84</td>
</tr>
<tr>
<td>Linear Coefficient of Shrinkage, 7-Day Cure</td>
<td>0.002 in./in.</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>2.4 x 10^-4 in./in.°F</td>
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</table>

SET-XP Installation Information and Additional Data for Threaded Rod and Rebar

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>Units</th>
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<tr>
<td>Drill Bit Diameter</td>
<td>d_{hole}</td>
<td>in.</td>
</tr>
<tr>
<td>Maximum Tightening Torque</td>
<td>T_{inst}</td>
<td>ft.-lb.</td>
</tr>
<tr>
<td>Minimum Permitted Embedment Depth Range</td>
<td>h_{ref}</td>
<td>in.</td>
</tr>
<tr>
<td>Maximum Permitted Embedment Depth Range</td>
<td>h_{max}</td>
<td>in.</td>
</tr>
<tr>
<td>Minimum Concrete Thickness</td>
<td>h_{concr}</td>
<td>in.</td>
</tr>
<tr>
<td>Critical Edge Distance</td>
<td>c_{AC}</td>
<td>in.</td>
</tr>
<tr>
<td>Minimum Edge Distance</td>
<td>c_{min}</td>
<td>in.</td>
</tr>
<tr>
<td>Minimum Anchor Spacing</td>
<td>s_{min}</td>
<td>in.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nominal Anchor Diameter (in.) / Rebar Size</th>
<th>3 / #3</th>
<th>4 / #4</th>
<th>5 / #5</th>
<th>6 / #6</th>
<th>7 / #7</th>
<th>8 / #8</th>
<th>9 / #9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation Information</td>
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<tr>
<td>Drill Bit Diameter</td>
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<td>in.</td>
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<tr>
<td>Maximum Tightening Torque</td>
<td>T_{inst}</td>
<td>ft.-lb.</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Minimum Permitted Embedment Depth Range</td>
<td>h_{ref}</td>
<td>in.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Permitted Embedment Depth Range</td>
<td>h_{max}</td>
<td>in.</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Minimum Concrete Thickness</td>
<td>h_{concr}</td>
<td>in.</td>
<td></td>
<td></td>
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<tr>
<td>Critical Edge Distance</td>
<td>c_{AC}</td>
<td>in.</td>
<td></td>
<td></td>
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<tr>
<td>Minimum Edge Distance</td>
<td>c_{min}</td>
<td>in.</td>
<td></td>
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<tr>
<td>Minimum Anchor Spacing</td>
<td>s_{min}</td>
<td>in.</td>
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<td></td>
</tr>
</tbody>
</table>

1. The information presented in this table is to be used in conjunction with the design criteria of ACI 318-14 and ACI 318-11.
2. c_{AC} = h_{ref} / \left( \frac{f'c}{1500} \right)^{0.5} \times \left( 1.1 - 0.7 \left( \frac{h}{h_{concr}} \right) \right)

\[ h_{ref} = h_{concr} \left( \frac{f'c}{1500} \right)^{0.5} \times \left( 1.1 - 0.7 \left( \frac{h}{h_{concr}} \right) \right) \]

\[ h_{ref} = h_{concr} \left( \frac{f'c}{1500} \right)^{0.5} \times \left( 1.1 - 0.7 \left( \frac{h}{h_{concr}} \right) \right) \]

\[ h = \text{the member thickness (inches)} \]

\[ h_{concr} = \text{the embedment depth (inches)} \]

* See p. 12 for an explanation of the load table icons.
### Table 2-4

**Applicable ASTM Specifications for Various Structural Shapes**

<table>
<thead>
<tr>
<th>Steel Type</th>
<th>ASTM Designation</th>
<th>$F_y$ Yield Stress $^a$ (ksi)</th>
<th>$F_u$ Tensile Stress $^a$ (ksi)</th>
<th>Applicable Shape Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>A36</td>
<td>36</td>
<td>50-80 $^a$</td>
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<tr>
<td></td>
<td>A53 Gr. B</td>
<td>35</td>
<td>60</td>
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<tr>
<td></td>
<td>A500</td>
<td></td>
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<tr>
<td></td>
<td>Gr. B</td>
<td>42</td>
<td>58</td>
<td></td>
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<tr>
<td></td>
<td>Gr. C</td>
<td>46</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gr. A</td>
<td>36</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gr. B</td>
<td>50</td>
<td>70</td>
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</tr>
<tr>
<td></td>
<td>Gr. 50</td>
<td>50</td>
<td>65-100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gr. 55</td>
<td>55</td>
<td>70-100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A529 $^c$</td>
<td>36</td>
<td>58-80 $^b$</td>
<td></td>
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<tr>
<td></td>
<td>A709</td>
<td>36</td>
<td>36-52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A1043 $^{ca}$</td>
<td>50</td>
<td>50-65</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A1065 $^{b}$</td>
<td>Gr. A</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gr. 42</td>
<td>42</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gr. 50</td>
<td>50</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gr. 55</td>
<td>55</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gr. 60 $^d$</td>
<td>60</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gr. 65 $^d$</td>
<td>65</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A618 $^f$</td>
<td>Gr. II</td>
<td>50 $^h$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gr. III</td>
<td>50</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A709</td>
<td>50</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A913</td>
<td>50</td>
<td>50 $^h$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A992</td>
<td>50</td>
<td>65 $^h$</td>
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<tr>
<td></td>
<td>A1065 $^{b}$</td>
<td>Gr. 50 $^j$</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

- $F_y$: Yield Stress
- $F_u$: Tensile Stress

*Footnotes on facing page.*

- Preferred material specification.
- Other applicable material specification, the availability of which should be confirmed prior to specification.
- Material specification does not apply.
### Table 2-5

**Applicable ASTM Specifications for Plates and Bars**

<table>
<thead>
<tr>
<th>Steel Type</th>
<th>ASTM Designation</th>
<th>$F_y$ (ksi)</th>
<th>$F_u$ (ksi)</th>
<th>Plates and Bars, in.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>over 0.75 incl.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>over 1.25 incl.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>over 1.5 incl.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>over 2.0 incl.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>over 2.5 incl.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>over 4 to 5 incl.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>over 5 to 6 incl.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>over 6 to 8 incl.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>over 8</td>
</tr>
</tbody>
</table>

| Carbon     | A36              | 32          | 58–80       | Gr. C: 30 55–75     |
|            |                  | 36          | 58–80       |                      |
|            | A283 Gr. C       | 30          | 55–75       |                      |
|            | Gr. D            | 33          | 60–80       |                      |
|            | A529 Gr. 50      | 50          | 65–100      |                      |
|            | Gr. 55           | 55          | 70–100      |                      |
|            | A709 Gr. 36      | 36          | 58–80       |                      |
| High-Strength Low-Alloy | A572 | Gr. 42 | 42 | 60 |
|            | Gr. 50           | 50          | 65          |                      |
|            | Gr. 55           | 55          | 70          |                      |
|            | Gr. 60           | 60          | 75          |                      |
|            | Gr. 65           | 65          | 80          |                      |
|            | A709 Gr. 50      | 50          | 65          |                      |
|            | Gr. 36           | 36–52       | 58          |                      |
|            | A1043 Gr. 50     | 50–65       | 65          |                      |
|            | Gr. 50           | 50          | 65          |                      |
|            | Gr. 60           | 60          | 75          |                      |
|            | A1066 Gr. 65     | 65          | 80          |                      |
|            | Gr. 70           | 70          | 85          |                      |
|            | Gr. 80           | 80          | 90          |                      |

#### Footnotes on facing page.
### Table 3-13
Available Flexural Strength, kip-ft
Square HSS

<table>
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<tr>
<th>Shape</th>
<th>$M_n/\Omega_b$</th>
<th>$\phi_b M_n$</th>
<th>Shape</th>
<th>$M_n/\Omega_b$</th>
<th>$\phi_b M_n$</th>
</tr>
</thead>
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<td>LRFD</td>
<td></td>
<td>ASD</td>
<td>LRFD</td>
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<tr>
<td>HSS16×16×</td>
<td>5/8</td>
<td>499</td>
<td>HSS1/2×5/2×</td>
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<td>32.7</td>
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<td>9/16</td>
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<td>247</td>
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<td>1/4</td>
<td>23.3</td>
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<td>193</td>
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<td>3/8</td>
<td>17.3</td>
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<td>HSS14×14×</td>
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<td>377</td>
<td>HSS5×5×</td>
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<td>9.58</td>
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<td>309</td>
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<td>5/16</td>
<td>22.9</td>
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<tr>
<td>HSS12×12×</td>
<td>5/8</td>
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<td>HSS4×4×</td>
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<td>120</td>
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<td>3/8</td>
<td>15.9</td>
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<td>183</td>
<td>HSS4×4×</td>
<td>1/4</td>
<td>18.1</td>
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<td>90.9</td>
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<td>19.2</td>
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<td>19.2</td>
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<td>44.2</td>
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<td>7/8</td>
<td>6.07</td>
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<td>HSS8×8×</td>
<td>5/8</td>
<td>112</td>
<td>HSS3×3×</td>
<td>1/4</td>
<td>5.79</td>
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<td>93.6</td>
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<td>1/4</td>
<td>6.19</td>
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<td>1/8</td>
<td>3.49</td>
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<tr>
<td></td>
<td>1/4</td>
<td>46.7</td>
<td>HSS2×2½×</td>
<td>3/8</td>
<td>4.69</td>
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<tr>
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<td>3/16</td>
<td>30.8</td>
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<td>5/16</td>
<td>4.69</td>
</tr>
<tr>
<td></td>
<td>1/8</td>
<td>17.7</td>
<td></td>
<td>1/4</td>
<td>4.07</td>
</tr>
<tr>
<td>HSS7×7×</td>
<td>5/8</td>
<td>82.6</td>
<td>HSS2×2½×</td>
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<td>4.07</td>
</tr>
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<td>69.6</td>
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<td>2.36</td>
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<td></td>
<td>5/16</td>
<td>47.2</td>
<td>HSS2½×2½×</td>
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<td>1.88</td>
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<td>38.7</td>
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<td>3.19</td>
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<td>3/16</td>
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Note: Values are reduced for width-to-thickness criteria, when appropriate. See Table 1-12A for limiting dimensions for compactness.
### Table 4-4 (continued)

**Available Strength in Axial Compression, kips**

$F_y = 50$ ksi

**Square HSS**

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<th>Shape</th>
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<th>$\gamma_{f_{16}}$</th>
<th>$\gamma_{t_4}$</th>
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<th>$P_n/\Omega_c$</th>
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<td>$I_p = I_p$, in.$^4$</td>
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<td>$r_x = r_y$, in.</td>
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<td>1.52</td>
<td>1.55</td>
<td>1.58</td>
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<tr>
<th>$\Omega_c = 1.67$</th>
<th>$\phi_c = 0.90$</th>
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</thead>
</table>

Note: Heavy line indicates $L_{ef}/L_y$ equal to or greater than 200.
Calculation Index:

Canopy Member Design ................................................................. 22 - 25
Canopy Interior Post Design .......................................................... 26 - 27
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---Wind Suction ........................................................................... 36
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**TENSEGRITY**

**Interior Top Beam**

**Design Criteria**
- Allowable Stress Design (ASD)
- ASCE Load Combination (DL+L)

**Design Loads**
- **P** = 18.6 PSF
- **Live Load** = 500#

**Distributed Load**

\[ w = DL + Fu \]

\[ TW = \frac{1}{3}(\frac{1}{2}V)(\frac{1}{2}T) = \frac{1}{2}(\frac{1}{2})/4 \times 60 \times 60/2.5 \times 0.6 \]

\[ TW = 1,15' \]

\[ w = (18.6 \text{ PSF})(1.15 \text{ LF}) = 21 \text{ PLF} \]

**Statics**

- \[ 2M_{ho} = 0 \times R - (458)(21^{2})(9.16) \]
- \[ -F_{post}(9.16) \]
- \[ E_{f} = 0 - (21 \text{ PSF})(9.16) - 500 \times 1192.36 \]
- \[ R_{bd} = 500 \]

**Shear**

\[ V(x) = 500 - 2.1 x, (0.4 \times 458) \]

\[ V(x) = 516.18 - 2(x - 458), (458 \times 9.16) \]

\[ V_{max} = 696.18 \]

**Moment**

\[ M(x) = 500 \times 21^2, (0.4 \times 458) \]

\[ M(x) = 2510.25 \times 59.18 \times 21(x - 458), (458 \times 9.16) \]

\[ M_{max} = 2510.25 \text{ ft lb} \]
TENSEGRITY

**Interior Top Beam (Cont')**

**Capacity:** 4x4 Redwood No. 2

\[
\begin{align*}
\sigma_b &= 725 \text{ psi} \\
\sigma_v &= 425 \text{ psi} \\
\sigma_b' &= (725 \text{ psi})(C_d)(S_e)(S_e')(S_e^1)(S_e^2)(S_e^3)
\end{align*}
\]

\[
C_d = 2.00, \text{ for intact beams}
\]

\[
C_r = 1.5
\]

\[
\sigma_b' = (725 \text{ psi})(2.00)(1.5) = 2175 \text{ psi}
\]

\[
\sigma_v = 425 \text{ psi}(C_d)(S_e)(S_e)(S_e') = 950 \text{ psi}
\]

\[
M_{allow} = \sigma_b' S_e' = (2175 \text{ psi})(7.15 \text{ in}^2)(1/12) = 1300 \text{ lb-ft/beam}
\]

\[
M_n = 1300 \text{ lb-ft (3 beams)} \times 3900 \text{ lb} > 2510.25 \text{ lb-ft} \quad \text{OK}
\]

\[
F.S. = \frac{3900}{2500} = 1.56
\]

\[
V_{allow} = \sigma_v A = (950 \text{ psi})(12.25 \text{ in}^2) = 11640 \text{ lb} > 596.18 \text{ lb} \quad \text{OK}
\]

\[
F.S. = \frac{11640}{596} = 20
\]

4x4 Redwood Interior Beam will support manufactured load

**USE 4x4 Redwood No. 2**
**TENSEGRITY**

**Exterior Canopy Beam (B1)**

**Design Criteria**
- Allowable Stress Design (ASCE)
- Load Combinations (D+L)

**Design Loads**
- \( D = 18.5 \text{ kips} \)
- \( L = 500 \text{ ft} \)

**Distributed Load**
- \( w = DL \cdot Tw \)
  - \( Tw = \frac{1}{3} (4') (\frac{1}{2}) (2') \tan(10) / 4' \)
  - \( Tw = 0.6 \)
- \( w = 18.5 \text{ kips} (0.6) = 10.7 \text{ kips} \)

**Demand**
- **Shear**
  - \( V(x) = -500 - 11.1x \)
  - \( V_{max} = 550.84 \text{ kips} \)
- **Moment**
  - \( M(x) = -500x - 11.1x^2 / 2 \)
  - \( M_{max} = 2406.42 \text{ ft}\cdot\text{kips} \)

**Capacity**
- **From Interior Beam**
  - \( P_b = 2175 \text{ kips} \)
  - \( V_b = 950 \text{ kips} \)
  - \( M_n = 2175 \text{ kips} \cdot (7.15 \text{ ft}) \cdot (1/2) = 1300 \text{ ft}\cdot\text{kips} \)
  - \( 1200 \text{ kips} \cdot \text{beam} (2 \text{ beams}) = 2400 \text{ ft}\cdot\text{kips} > 2406.42 \text{ ft}\cdot\text{kips} \) \( \text{... OK} \)
  - \( f_s = 2400 / 2400 = 1.1 \)
  - \( V_n = 11640 > 550.84 \text{ kips} \) \( \text{... OK} \)

**Notes**
- 4x4 Reused OK by inspection
- all exterior and interior beams
Typical Wood to HSS Connection

Wood Member

4" x 4" Redwood No. 2

A: 12.25 in²
Fb: 725 psi
Fv: 160 psi
E: 1,100,000 psi

Assume (2) 5/8" Bolts

Z_h = 1,450#
Z_v = 720#
G = 0.37

Capacity

\[ Z' = Z \left[ \frac{c_p (c_g) (c_x) (c_y) (c_z)}{1.0} \right] \]

C_p = 1.5
C_x = 0.5

From Eq.

\[ C_g = \left[ \frac{m (1 - m^2)}{n [(1 + R_e a m^n) (1 - m) - 1 - m^n]} \right] \left[ \frac{1 - R_e a}{1 - m} \right] \]

\[ R_e a = \min \left\{ \frac{F_b}{E_{tot}} , \frac{F_v}{E_{tot}} \right\} \]

\[ R_e a = 0.14 \]

\[ m = U - \frac{132.1}{110.3} \]

\[ U = 1 + 8 \left[ \frac{F_b}{E_{tot}} + \frac{F_v}{E_{tot}} \right] = 1 + 95,600 (0.95) \left[ \frac{1}{110.3 (12.25)} + \frac{1}{2900 (33.1)} \right] = 13.1 \]

\[ \delta = 27,000 (1.5) = 40,500 (0.85) = 34,000 \] Wood to Metal

For loads to shear

\[ U = 13.1 \]

\[ m = 13.1 - \frac{40.11}{33.1 - 1} = 0.4 \]

\[ C_g = 0.94 \]
**TENSEGRITY**

**Pressure**
If cable loading is unknown compression will be fixed into adjacent members.

Max assumed compression from max tension $T = 6304$ lb

\[
C = T \cos(15^\circ) = 6304 \cos(15^\circ) = 6104 \text{ lb}
\]

Calculated: $13,750$ lb from previous page.

A symmetrical tension load would form on the opposite side of the member.

\[
T = 6104 \text{ lb}
\]

**Tension Capacity**

\[
f_t = \frac{C}{A_b}
\]

\[
f_t = \frac{6104}{1.25 \text{ in} \times 1.25 \text{ in}} = 2108 \text{ psi}
\]

**Note:**
The single tension cable only is the most severe lateral load assumed. The most amount of compression comes from this. Rotation is ok by inspection because $y = 125^\circ$ is significant less steep than 100 degrees member members.
**INTERIOR COLUMN**

**DESIGN CRITERIA**
- ASD
- ASCE Load Combination (D+L)

**DESIGN LOADS**
- D = 18,500#
- L = 500# - Point Load

**THERE ARE 2000 SEPARATE COLUMN "TREES" WITH (3) 4x4 MEMBERS FORMING INTO A SINGLE POINT. EACH COLUMN WILL EQUAL SPLIT THE LOAD, MEANING EACH COLUMN TAKES 1/2000 OF THE TOTAL LOAD. THIS LOAD RESOLVES INTO 1/2 OF THE TOTAL LOAD POINTS INTO THE CABLES & 3/2 AT THE BASE.**

**DEMAND**

Moments are resolved to the upper column. There go only shear:

$$ P = \left(18 \frac{psf}{A_{3f}}\right) + 4(500#) $$

$$ P = 3,275 # $$

Each column takes $$\frac{3,275#}{2000} = 1.64#$$

**Axial Capacity**

$$ f_c = 7000psf $$

$$ f_c' = f_c \times (C_c)(C_p)(C_f)(C_e)(C_t)(C_f)' $$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>C_c</td>
<td>1.25</td>
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<tr>
<td>C_p</td>
<td>1.5</td>
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</table>

$$ f_c' = 13,125 psf $$

$$ C_{buil} = 13,125 psf (10%) \times 18,750# > 5,600# \text{ OK on comp} $$

**TENSEGRAITY**

**Topic: Geometric Design**
**TENSEGRITY**

**Seat Connection**

![Diagram of seat connection](image)

**Bolt Capacity**

\[
2'' = 2(96) = 1.82k \quad \text{OK by inspection}
\]

\[
2'' = 2(46) = 0.9k
\]

**Weld Capacity**

\[
\phi R_n \text{ for } \frac{1}{8}'' \text{ weld } = 1.39 \text{k/m}
\]

\[
L_{\text{weld}} = 2(6.4'') = 14'' \quad \Rightarrow \quad \phi R_n = 1.39 \text{k/m}(14) = 20k \quad \text{OK by inspection}
\]

**Seat to Connection Weld**

![Diagram of seat to connection weld](image)

\[
\phi R_y = \frac{M}{S} = \frac{(5)(6'')}{250(4'')(1.14)(14)} = 0.8\text{k/m}
\]

\[
f_{b} = \frac{84\text{k/m}}{t} = 0.4'' \text{ weld okay by inspection}
\]
TENSEGRITY

**ROD**

- **From slope base**
- **P = 1640#**
- **Each rod will take \( \frac{1}{3} \) of the load, in addition to \( \frac{1}{2} \) load from the bench**

**Bench Design Loads**

- **D + L load combination**
  - **D = Weight of beam only = 3PLF**
  - **L = (2) 250# Point loads \( \rightarrow \) to represent Two People Sitting**

**Bench Load**

- **\( R_y = 250# + (3PLF)(2.75') = 265# \)**
- **4x4 Redwood No. 2 OK, Nails by irrigation**

**Steel Rod**

- **\( T = \frac{1640# \times 2 \times 265#}{3} = 635# \) Per Rod**

**Rod Capacity from Tripod**: \( 5.4 \) k \( \geq 635# \) OK
ROD TO PILLAR CONNECTION

*Will only connect rod w/ max tension

\[ T_y = 635 \text{#} \]

STEEL CAPACITY

\[ A_{sc} : T_y = 3650 \]

RIPPLE SECTION

Plane A-A

\[ A_c = 0.125 \text{in}^2 \]

\[ T_y = 3650 (0.125) = 462.5 \text{#} > T_y \]

... OK for pull off

WELD CAPACITY

\[ R_n = 1.39 \frac{\text{ksi}}{\text{in}} (2.0) (2.5) (3.5) \]

\[ R_n = 3.5 \text{ksi} \]

OK for connection, weld capacity far exceeds demand

NOTE: See S3.1 for Tri-Pyramid Rod Information
**TENSEGRITY**

**ROD CONNECTIONS (COMPRESSION)**

The steel rods are all assumed to be exclusively in tension, but they have compressive capacity should they be in extreme loading.

**Steel Rod Capacity**

\[
L = 26.5''
\]

\[
K = 1.0
\]

\[
y = \frac{d}{4} = 0.250 = 0.0625\text{in}
\]

\[
\frac{KL}{y} = \frac{1.0(26.5)}{0.0625} = 409.6
\]

\[
4.71\sqrt[3]{\frac{29000}{36}} = 133.48 = \frac{KL}{y} > 4.71\sqrt[3]{\frac{29000}{36}}
\]

So, for \(0.877\text{ksi} = 0.877\left(\frac{\pi^2(2(2000)k)}{4}ight) = 1.71\text{ksi}\)

\[
\Rightarrow \text{Each rod has a compressive strength of } 1.71\text{ksi}(2.23^2)\pi = 851\text{lbs}
\]

\[
c^2 = 85\text{lb}, \text{ the rods are assumed to all be in tension but the top rods are all able to support additional compression load providing more safety.}
\]
Steel Pyramid

Design Criteria
- LRFD (1.2D + 1.6L)

Design Loads

\[ T_{ud} = 635\text{#/fdo} \]

Only 2 rods carry load, the others provide stability therefore:

Top of Pyramid

\[ T_{ud} = 2(635) = 1270\text{#} \]

\[ T_{ux} = (1270\text{#}) \cos(36.3) (1.6) = 116.40\text{#} \]

\[ T_{u\theta} = (1270\text{#}) \sin(36.3) (1.6) = 1200\text{#} \]

Demands

\[ M_u = (7.583)(1.6)^2 = 12.13k' \]

\[ P_u = 1200\text{#} = 400\text{#/colum} \]

Graphite

From AISC \( \phi N_a = 1.62\text{#/colum} \rightarrow \phi N_a = 3(1.62\text{#/colum}) = 5.3k' \)

\[ \phi P_u = 113k \rightarrow 400\text{#} \rightarrow \text{OK} \]
**TENSEGRITY**

**FOOTING DESIGN (cont'd)**

- Top of footing must be 4' x 4' min. - Geometric center.

Assume $d = 18''$, $h = 21''$, $B = h/2 - 3$.

To prevent nodes from loosening, check the reinforcement.

Check $W_E$:

$$W_E = 14.5 \text{pcf} (4' \times 4' \times \frac{31}{12}) = \frac{406 \text{ lb} + 11.5 \text{ lb}}{161} = 330 \text{ psf} < e$$

OK for bearing.

Check $S_{slip.}:

$$\mu = 0.25 (4.06 \times \frac{4}{18}) = 0.34 k$$

$$1.034 (4) = 4.12 k > 1.6$$

$$F_S = \frac{4.12}{1.6} = 2.56 \text{ ...OK } F_S$$
From Simpson Strong Tie Anchor Bolt Calculator (see page 57) each anchor bolt has a capacity of 16.9 kips which greatly exceeds the 1.34 kip uplift. The bolts in the calculator were calculated at strength level loads.
LOAD COMBINATION (PER IBC 1606.2)

EQ 16-6 0.9D - 1.0W

Compare to 0.9D + L WHERE L is THE LOAD APPLIED FROM SOMEONE.

SINCE 1.0W is SIGNIFICANTLY LESS THAN USE 0.9D + L

\[ \Delta M = W_{FK}(2') + 750\text{#}(2') - 1020\text{#}(17.5\text{"} \div 12) \]

\[ W_{FK} = 145\text{pcf}(4')(4')(\frac{30}{12}/12') = 5800\text{#} \]

\[ M_{OT} = 1020\text{#}(7.5 + \frac{30}{12}) = 10200\text{#ft} \]

\[ M_{RESIST} = 5800\text{#}(2') + 750\text{#}(2') - 13100\text{#ft} = 7.9D - 0.9(M_{RESIST}) = 11790\text{#ft} \]

\[ F_{S} = \frac{M_{RESIST}}{M_{OT}} = \frac{11790\text{#ft}}{10200\text{#ft}} = 1.16 > 1.00 \]

\[ \Rightarrow \text{OK FOR OVERTURNING} \]

\[ \Rightarrow \text{MOST OF THE DOWNWARD LOAD IS SELF WEIGHT} \]

\[ \Rightarrow \text{CONSERVATIVE TO REDUCE ENTIRE VALUE BY 0.9} \]
TENSEGRITY

Pu & Mu
Pre-service Level Loads (1.0D + 1.0C)

\[ \begin{align*}
Pu &= 760 \text{#} \\
Mu &= 10,200 \text{#} \\
W_{FS} &= 5,800 \text{#}
\end{align*} \]

Eccentricity

\[ e = \frac{Mu}{Pu + W_{FS}} = \frac{10,200 \text{#} \text{ft}}{760 \text{#} + 5,800 \text{#}} = 1.56 \]

\[ y = \left( \frac{1}{3} \right) = 0.167 \quad \Rightarrow \quad e > 0.167 \]

\[ \phi_{\text{max}} = \frac{2(760 \text{#} + 5800 \text{#})}{3(\frac{3}{12})(\frac{4}{2} - 1.56)} = 1.9 \text{ KSF} \]

\[ \phi_{\text{allow}} = 2 \text{ KSF} > 1.9 \text{ KSF} \quad \Rightarrow \quad \text{Foot is OKAY in Reoring} \]
WIND SUCTION LOADING

A wind load of 8 psf upward will be applied to analyze potential uplift per ASCE CH 27.

Load Combination

\[0.9D + 1.0W = 0.9(18.5\text{psf}) + 1.0(6)\text{psf}\]

= 8.65 psf  The net force is downward because the self weight of the canopy is greater than possible wind load.

Assume only wind load

Upward load of 8 psf on canopy

\[P = 8\text{psf}(75\text{sf}) = 600\text{# net upward force}\]

\[P\text{ supports the resistance force must be greater than } 150\text{# (600#/4).}\]

Rod capacity in tension is 5.4 k which can exceed = OK by inspection.
LATERAL LOAD ANALYSIS

Since the loads due to wind and seismic came out pretty low, we want to imagine a worst case lateral load on the structure.

Assumptions:
- A 250 lb person swinging from a corner at an initial acceleration of 2g/2s (500 lb force)
- Consider top two layers of rods to be engaged in restraining the lateral load.
- Reasoning: lower gravity cables are connected to bottom portion (bench)

3-D VIEW OF LOADING

TOP VIEW OF LOADING

For analysis, will move load to c.c.m. and apply a moment

\[ \frac{9 \times 12}{2} = 54 \text{ in}^2 \times 195.26^2 = 7.94 \text{ in} = \text{take } B' \]
EXPECTED DEFORMATION OF CANOPY
ASSUME: RODS ONLY TAKE TENSILE FORCES

\[
\begin{align*}
C_x &= C \left(\begin{array}{c}
120.5'' \\
120.5''
\end{array}\right) = 0.854 C \\
C_y &= C \left(\begin{array}{c}
65'' \\
120.5''
\end{array}\right) = 0.456 C \\
E_x &= E \left(\begin{array}{c}
120.5'' \\
120.5''
\end{array}\right) = 0.864 E \\
E_y &= E \left(\begin{array}{c}
65'' \\
120.5''
\end{array}\right) = 0.466 E \\
I_x &= I \left(\begin{array}{c}
1038'' \\
120.5''
\end{array}\right) = 0.854 I \\
I_y &= I \left(\begin{array}{c}
65'' \\
120.5''
\end{array}\right) = 0.456 I
\end{align*}
\]

RELATIVE STIFFNESSES OF RODS
\[
\begin{align*}
K_x &= \frac{EA}{L} = \text{constant} / 120.5'' \\
K_x &= K_x \\
K_y &= \frac{1}{16.25''} \\
K_{L1} &= K_L = K_n \\
K_0 &= \frac{1}{26.45''}
\end{align*}
\]
DISTRIBUTING LOAD BASED ON RELATIVE STIFFNESS

TRANSLATIONAL LOAD ONLY:

\[ J_y = 0.5k (0.5264) = 0.2632 \]
\[ L_y = H_y = 0.5 (0.1210) = 0.0605 \]
\[ C_y = E_y = 0.5 (0.1158) = 0.0579 \]

APPLIED MOMENT ONLY:

\[ C_x = 4\frac{h}{k} (0.2444) = 0.2126 \]
\[ I_x = 4\frac{h}{k} (0.2444) = 0.2126 \]
\[ L_y = \frac{4h}{k} (0.2566) = 0.1278 \]
\[ N_y = \frac{4h}{k} (0.2566) = 0.1278 \]

<table>
<thead>
<tr>
<th>ROD</th>
<th>Y-COMPONENT</th>
<th>Z-COMPONENT</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TRANSLATION</td>
<td>ROTATION</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.0679°</td>
<td></td>
<td>0.2126°</td>
</tr>
<tr>
<td>E</td>
<td>0.0679°</td>
<td></td>
<td>0.2126°</td>
</tr>
<tr>
<td>K</td>
<td>0.1238°</td>
<td></td>
<td>0.256°</td>
</tr>
<tr>
<td>H</td>
<td>0.0605°</td>
<td></td>
<td>0.2126°</td>
</tr>
<tr>
<td>H</td>
<td>0.2632°</td>
<td>0.1278°</td>
<td>0.1278°</td>
</tr>
<tr>
<td>T</td>
<td>0.0605°</td>
<td>0.1278°</td>
<td>0.1278°</td>
</tr>
</tbody>
</table>
**TENSEGRITY**

**Rod 1 experiences largest stress of:**

\[
\frac{F}{\frac{A}{(0.2 \text{ m}^2)}} = \frac{2.65 \text{ kN}}{0.2 \text{ m}^2} < \frac{f_y}{27 \text{ kN} / \text{m}^2}
\]

**NOTES:** This analysis superimposes two different loading conditions.

The interaction of simultaneous translation and rotation would result in a small amplification in force in rods C, D, & L.

However, considering that only 10% of the yield stress was achieved when superimposing the loads, this should not be a concern.

\(\frac{1}{4}'' \phi \) rods are OK

To achieve more accurate results, a computer analysis of stiffness matrix analysis could be used and checked against these values (considering only the top two layers of rods)