Green Roof Feasibility Study
College of Engineering

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**In partnership with the City of
Sioux City**

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Sioux City Rooftop Garden

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UNIVERSITY OF IOWA
DEPARTMENT OF CIVIL & ENVIRONMENTAL ENGINEERING
Project Design & Management (CEE:3084:0001)
Final Design Report - spr2016

Prestige Worldwide

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Executive Summary

We are Prestige Worldwide, a student group at the University of Iowa tasked with determining if the Discovery Parking Garage in downtown Sioux City, IA was capable of handling a green roof on top of the structure. We are appreciative for the opportunity to analyze the structure and explore rain garden designs in an effort to be a cog in the larger green initiative in Sioux City.

This project is part of a larger initiative by the city to create more green space in its downtown area. The discovery parking garage was tabbed as the best option due to its central location, low usage of the parking spots on the top floor, and connectivity to the city's skywalk system. The design procedure included modeling the structure, designing a rain garden based on the floor plan of the garage, and converting that garden to applicable loads in the structural model to see if the structure had enough capacity to handle the designed garden and loads.

Our first garden design included terraces with plants and bushes native to Sioux City as well as areas of turf with benches and picnic tables and walkways. To protect the roof, a system is needed between the growing media for the plants and grasses and the roof. This system includes a waterproofing membrane directly on the roof, a drainage layer, and a filter layer to keep roots and soil from infiltrating the drainage layer.

To see if the structure could handle the design, we compiled the weight of these components and grouped them with live loads due to foot traffic and estimated wind loads and applied them to the structural model. On the model we checked a critical section where the slab, beam, and columns would experience the greatest forces and moments. We obtained the largest bending moment for the beams and computed the strength of the section. We determined that based off the flexural strength of the section and the maximum bending moment in the beam, the beams would not be able to handle the weight of the designed garden.

We explored a variety of options to find a suitable solution to the design objective. Structural modification such as fiber-reinforcement around the beam could have been a feasible option, except the direction of the maximum moment would cause failure in the top of the beam which is inaccessible. Another option was to construct more columns on the level below the roof to give the beam more support and thus more strength to support a garden, but that would take another floor of the parking garage out of service. This option is also very costly based on materials needed in a complete structural modification as well as labor due to the physical constraints making construction difficult. Finally, we checked the strength of the slab on the roof and found that the slab could not handle the load either. Slabs are more difficult to structurally modify. After consulting with structural engineering professor at the University of Iowa, it was deemed virtually not feasible to restructure the slab, deeming a roof garden not feasible for this structure.

Since the parking garage could not handle the garden we designed, we developed a new design that only consisted of turf, walkways, and the thinnest layer of soil based on various industry accepted standards. This design option represented the smallest load that a rooftop garden would require. We reiterated the process based on the new design; calculated the loads, calculated the bending moments and extreme forces in the beams and slab, and checked these values against the strength of the critical sections. We reached a similar solution to the first design, that the beams and slabs cannot handle the weight of the simplest garden.

While the Discovery Garage is not a viable option for a roof garden, the designs we developed are a very appealing option for a building with the capacity to support it. The first

garden design offers interactive areas for community members to share and enjoy. The picnic tables offer a place for community members to have lunch. The location of this garage make it accessible based on its proximity to the hospital, downtown, and skywalk system. There is an area which we left open to give an opportunity for a piece of local art. This has the opportunity to become a local landmark, and giving the community an opportunity to have say in the aesthetic of the space will give them a sense of ownership which will yield a better taken care of space. There is also a multipurpose area which could be used by local restaurants for dining or for public or private events. The native plants will demand little maintenance and were chosen for their ability to withstand cold winters, hot summers, and intense wind conditions that we would expect to see on top of a parking garage in the Midwest. This will lower the city's cost of upkeep and could bring in foot traffic to local businesses for the summer, spring, and fall months. Beyond the economic benefits, a green roof on a suitable building would create cleaner runoff, efficient drainage, and increased green space in urban areas have been shown to increase air quality and cool urban hot spots.

The second alternative offers similar benefits, while lacking some of the flashier design components like terracing and multipurpose areas. This could still act as an interactive space for a future design and would be easily applied if designed for based on the reduced loading and ease of construction. The modifications methods mentioned above would be costly and are not explored in depth in the report below based on their lack of feasibility and cost compared to benefits for the intended purpose of contributing a lot cost garden to the series of green projects being developed in the Sioux City area.

Prestige Worldwide would like to thank you again for the opportunity to contribute to a truly great movement taking place in Sioux City. While a garden may not be feasible for the designated structure, the described designs would both be valid for future green roof projects on suitable structures.

1. Introduction

This report was written in response to the City of Sioux City's request for a structural analysis of the Discovery parking garage and subsequent design for a rooftop garden. In this report we will discuss the background of the project along with design objectives, approaches using applicable manuals, standards, constraints, challenges, and societal impacts. The preliminary development of alternatives will be touched on and afterwards, the selection process for the best alternative and final design details with cost and construction estimates.

2. Problem Statement

In an effort to create a greener environment in an urban area, the City of Sioux City has created a project to turn locations around the city into green spaces. One of these proposed locations is the rooftop of a 753 spot parking garage located in the middle of downtown. Planners favored this structure because it is in a central location downtown and across the street from a large medical facility that has close to no green space of its own. One issue with the location is that the planning committee is not sure if the structure can withstand the extra applied loads from the soil, vegetation, and any other design elements. The design objective for Prestige Worldwide was to analyze the parking garage to determine the maximum load associated with a rooftop garden that the structure can carry. Once the maximum load is found, Prestige Worldwide can design a suitable green space within the maximum threshold.

3. Evaluation and Design Objectives

The specific design objectives include creating a green space that the community will utilize and is structurally sound, functional in the Midwestern climate, and economically viable. With these objectives in mind, the design was focused primarily on engineering a structurally viable garden design to compliment the ongoing green initiative in Sioux City. The aesthetics and functionality, while critical to success and effectiveness of the project, were secondary objectives.

To make a successful garden design applicable, we needed to create an accurate and usable structural model to yield successful analysis. The structural capacity of the parking structure was the governing task. The objectives of the analysis was to accurately model the structure, identify critical sections, and to yield easily communicable results based on the success or failure of the applied loadings from the garden design. The codes used to make this structural analysis possible are discussed below.

4. Design Standards

ASTM is the American Society of the International Association for Testing and Materials. We utilized their standards for living systems when developing the rooftop garden. ASTM is widely accepted in the United States. We also used the German FLL Green Roof Guidelines' Standard, which similarly helped develop our garden to a standard (Breuning & Yanders, 2012). Specifically, ASTM standard E2397 is the Standard Practice

for Determination of Dead Loads and Live Loads associated with Green Roof Systems ("ASTM E2397/E2397M - 15: Standard Practice for Determination of Dead Loads and Live Loads Associated with Vegetative (Green) Roof Systems", 2015). ASTM also utilizes the FLL-guidelines in their standards. The supplier we contacted for our cost estimate and design loadings, Rooflite, used FLL as a design tool for any living roof system, eco roof, granular drainage system, drainage board system, modular green roof system or for selecting green roof plants. The wind loads were calculated using the standards found in ASCE 7.

When modeling the parking garage, we used LRFD load combinations to apply factors to the dead, live, and wind loads. These factors change service loads so they are comparable to ultimate member strength which adds a safety factor. Of the seven load combination equations, combination four was the only one used and is shown in Appendix A. Once the stresses and moments in the beams, columns, and slabs using the model, the strength of the section was checked using American Concrete Institute, ACI, standards and procedures. The standards and procedures developed by ACI show how to determine the strength of beams, columns, slabs, and other concrete sections in flexure, compression, tension, torsion, and axial force. Within the terraced garden design there are retaining walls to create the terracing effect. To create a more aesthetically pleasing appearance, interlocking landscaping blocks from VERSA-LOK will be used. These blocks will be placed on a compressed sand pad at a short depth beneath the surface of the soil. The dimensions of the retaining wall were checked for the factor of safety against overturning and sample calculations can be found in Appendix A.

5. Constraints

This project had few restrictions and guidelines concerning the potential design. There were no budget limitations, but as with any project, limiting the cost as much as possible is favorable. Since the objective was to create green space where there previously was not one, there are little to no negative environmental considerations except for emissions from equipment used during construction. There were also few negative societal impacts that needed to be take into account, especially since the top floor of the parking garage is rarely used in its current state.

One main limitation was the load that the garage can handle. Since the garage is already built, and has sustained weathering and damage the extra load it can support may be limited. This inhibited the breadth of garden design that was available. The lack of structural capacity was a constraint because modifying the structural components of the garage is not feasible both from a structural and cost stance.

Another constraint was the inability to change the footprint of the garage. We had to take the floor plan and slopes as given which limited our design due to lack of space. This physical constraint limited design options and thus creativity to implement some potential purposes the garden could serve to the community of Sioux City.

6. Challenges

Challenges that came about during the design process included the ability to make the design cost effective, constructability based on physical limitations, complimenting the

engineering demands with aesthetics that would create an appealing space for a diverse community, and finding suitable design standards. The challenges by no means limit the feasibility of our design, but instead caused loopholes to jump through to deliver Sioux City a satisfying product.

While there were no budgetary constraints, cost effectiveness was always a part of the design so as to make the design more appealing to the municipality of Sioux City and not take momentum away from the community-wide green initiative by using a majority of the city funds. Material cost and constructability put a bind on cost effectiveness, as the closest supplier for the garden system and soil we had contact with was located in Chicago, Illinois. To limit costs future maintenance costs, we used native plant species found on the Sioux City website ("Recommended Rain Garden Native Plants", 2014) that are known to be hearty and drought-resistant. To limit costs we also chose not to modify the existing structural components of the garage. This would potentially allow for a larger, more diverse garden, but for the extreme cost and difficulty in construction, we decided not to pursue this alternative.

Constructability is a challenge because of the physical constraints of the location of the garage. For spreading and handling of soil, a front loader will not be able to travel to the top floor because of the clearance in the garage. This would introduce the challenge of getting a crane downtown to deliver the soil and plant materials. Since the roadways are narrow, urban roadways, there would need to be detours developed for the duration of its use. If no heavy machinery would be able to be used for moving soil, the soil and plants would have to be placed by hand by a landscaping crew which would take more time and thus a far greater expense.

Aesthetics also became a problem due to the orientation of the beams on the seventh level. The beams had limited structural capacity, so the heavier areas of our design needed to be located on beams that had more capacity. This altered what could have been a more functional or aesthetically pleasing garden. A design objective was to make the space appealing to a wide range of community members because of its location next to businesses downtown, the hospital, and connection to the skywalk system. Engineering a safe yet functional space became a challenge, but certainly did not stop us from implementing the strategies discussed in the meetings with the University of Iowa Urban Planning group and Sioux City representatives.

It was also difficult to find suitable and accepted design standards when it came to designing the rooftop garden. Up until about a decade ago, rooftop gardens were not very common in the United States. They have been building rooftop gardens for decades, but finding explicit standards was difficult.

7. Societal Impacts

Some negative societal impacts this project might include the inconvenience of construction on the community and users of the garage. Since this project is located in an urban area, there will be a lot of traffic throughout the day to the local areas of commerce. Construction on the roof of this garage could shut down traffic lanes for deliveries, causing inconveniences as well as potential noise to the local community. Traffic flow in the garage could also be disrupted. Another negative impact will be the decreased revenue caused by

refunctioning a floor of the parking garage. This will take away parking spots and subsequently potential public revenues.

Positive societal impacts are more plentiful and revolve around increased green space for the community. This will serve as a public area and could become a piece of a larger green space initiative that revitalizes and invigorates the spirit of public spaces for this community. Green spaces like these can become monuments and create more closely knit communities. Other positive impacts on the local community include the potential to subcontract work with local businesses to construct the garden. This will bring in local dollars and jobs for a short period of time, and maintenance will create jobs and work in the long term. Having a space to eat lunch for people in the community could also increase the foot traffic through nearby restaurants. Environmentally, green roofs have been proven to create clean runoff, control drainage, and cool hot spots that occur in urban areas.

8. Development of Alternative Solutions

The City of Sioux City, Iowa commissioned Prestige Worldwide to perform a structural analysis on the Discovery Parking Garage to determine the garage's ability to support a rooftop green space. The rooftop green space is a part of a larger plan to make downtown Sioux City more inviting and green.

The Discovery parking garage is located in the heart of downtown Sioux City on Jones Street as show in Figure 3. The Discovery garage is connected to the Sioux City Hotel complex, as well as a system of skywalks that runs throughout downtown Sioux City. A site visit was conducted to visually inspect the parking structure to familiarize ourselves with the structure in relation to the given plans. Prestige Worldwide was provided a conditions report that was conducted in 2014. The conditions report stated that there are no major structural issues. The visual inspection yielded similar results supporting the conditions report. After the site visit, the analysis began. First, Prestige Worldwide determined the maximum loading the parking structure could safely support. This was done by constructing a model on Autodesk Robot as show in Figures 1 and 2. Next the rooftop garden was designed including soil type, thickness and aesthetic design. With the garden designed the loads were calculated and applied to the model. This acted as a double check ensuring the structure can safely withstand the additional loads applied by the rooftop garden. The model analyzed three critical components of the parking structure which included an exterior column, a corner column and an interior beam. These components were analyzed for shear, flexural and axial strength which was in turn checked against the capacities of those components. Prestige Worldwide used the accepted design standards laid out in the ACI 362.1 R97 Guide for the Design of Durable Parking Structures and PCI Parking Structures: Recommended Practice for Design and Construction to analyze the parking structure.

While developing the structural model, a preliminary garden design was drafted. This is shown below in option one. It includes terrace features and a designated area for small community events and potentially local art. When applying the loads for the preliminary design, it was determined that the structure did not have the capacity for the extra features. We then developed a second, more minimalistic alternative that could still function as a green space but not include more alluring features. This alternative is given below as option 2. Both alternatives will be discussed in depth as well as the decision

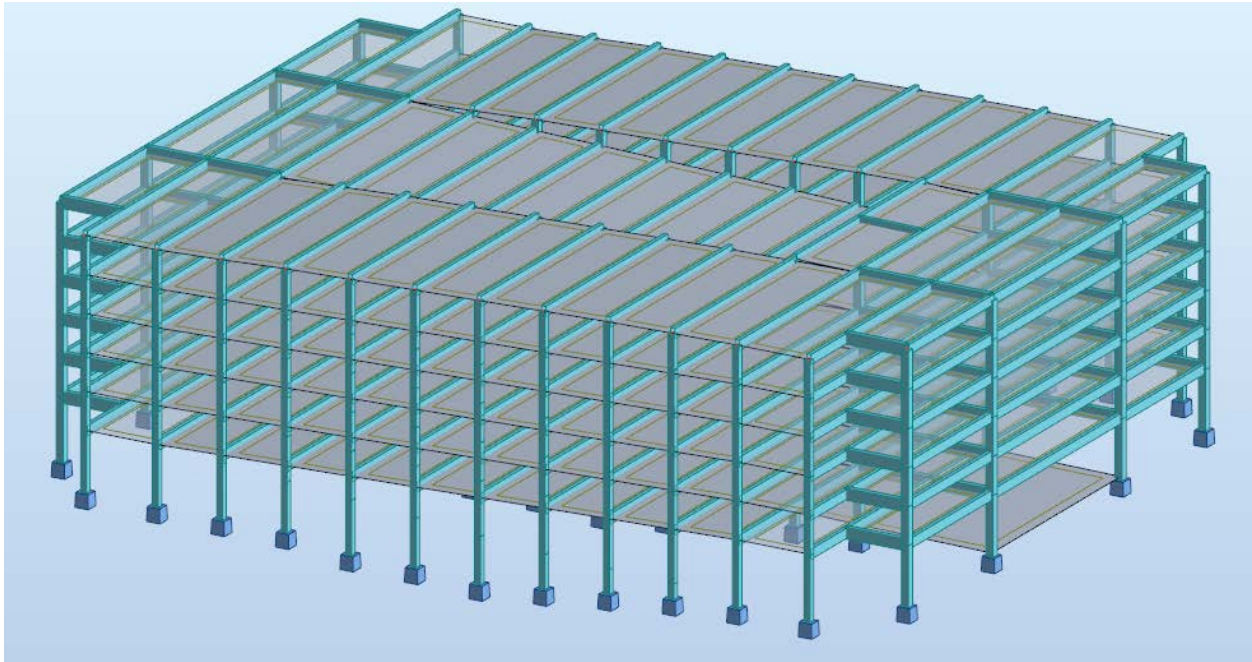making process PWW went through to make conclusions and recommendations.

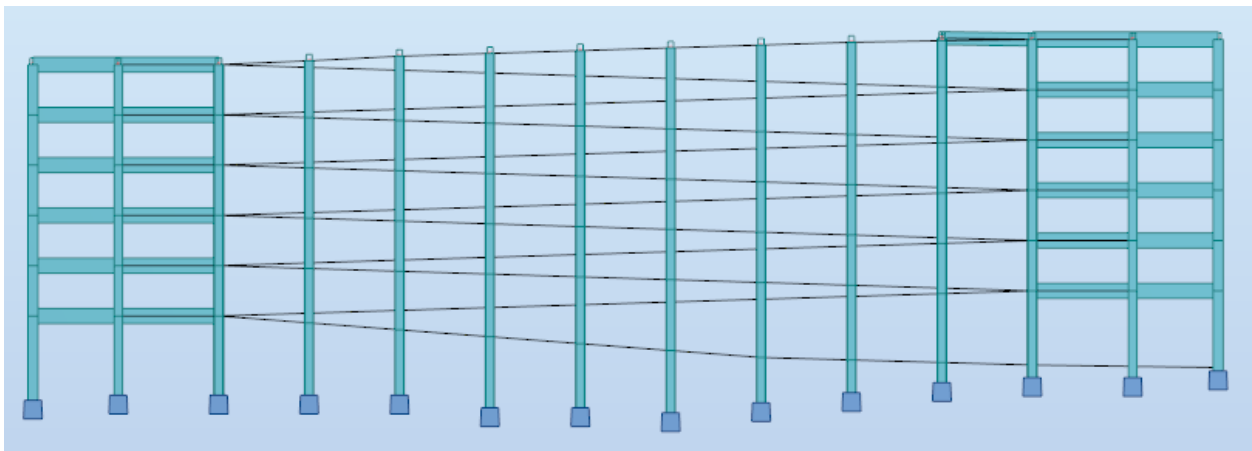Figure 1: Discovery parking garage Robot model: isometric view

Figure 2: Discovery parking garage Robot model: south elevation view

Figure 3: The Discovery parking garage in downtown Sioux City, Iowa

Option 1: Full Garden Design

Our first option includes walkways from each entrance to the roof (three stairwells and one combined stairwell and elevator entrance) wrapping around in a circular fashion. The annotated plan view is shown below in Figure 4. This design offers an additional area for people to park on the ramp from the sixth floor to the roof and have easy access to the garden. There are areas for picnics on the west end, northeast, and southeast corners of the rooftop. There is terracing wrapping around the north and south traffic barriers between the ramps. Each terrace will require a 2 foot tall retaining wall structure. The terraces will be constructed of inter-locking landscaping blocks that conform to the aesthetics and hold back the load created by soil behind it. On the east end of the garage there is a communal multipurpose area. This could be used for local restaurants to hold events, or could be rented by the public for similar events. It could also serve as extra seating for lunch goers and community members looking to enjoy the view. There is also an opportunity for a small piece of local art just west of the multipurpose area.

The reason we made many of the design decisions we did was to make the area as functional and interactive as possible. By giving the public opportunities to hold events, make memories, and influence the way it looks, they will be more attached to the space and it has a greater chance to have a lasting impact on the community. The parking spaces leading up to the garden make it easy to access, which would encourage the community to utilize the space for more activities. The separated dining areas will encourage multiple groups of lunch goers or picnickers to be encouraged to share the space while still having their own space. The design decision to add terracing came from a suggestion at a conference with the University of Iowa Urban Planning group. This offered an area to include native perennial plants that could add variety of colors and

style to the aesthetics. The multipurpose area was chosen to encourage local businesses to interact with the new garden. Having this area will offer a supplemental opportunity for summer, spring, and early fall programs to bring in more business. There was also a small area west of the multipurpose area that could be utilized by a small piece of local art. This could be a keystone piece and could greatly increase public input to the success of the garden.

The design decisions were made in an effort to create opportunity for the community to interact, while also taking pride in a new green area. We want to offer as much space to be functional, aesthetics to be appealing, and opportunity to encourage a sustained sense of ownership.
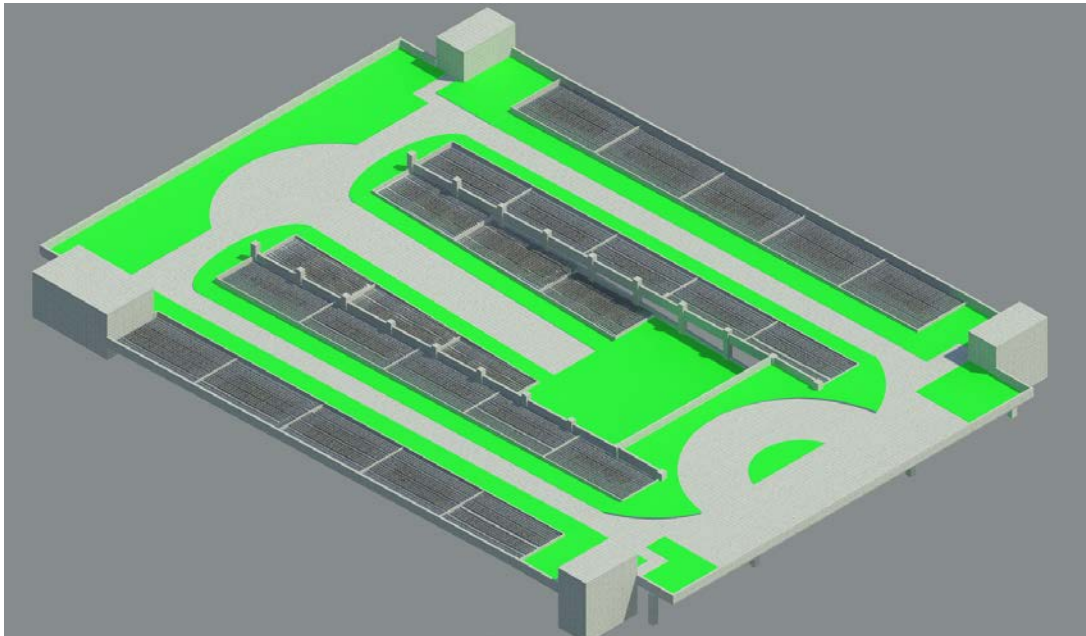

Figure 4: View of Proposed Garden Design, Option 1

Option 2: Minimal Garden Design

This design option has the same walkway style and layout as well as the same grasses as the first design option. The difference in this option is that there will be no terracing or multipurpose area, instead there will be turf in place. This is to reduce the loads on the garage in areas where the loads were previously extreme and potentially unsafe based on the structural model we are analyzing.

This alternative still offers multiple spaces for lunch and picnics and even more green space. This design is simpler, but achieves the design objectives of creating a functional space for the community while being cost effective and incorporating native, low maintenance plant species into the aesthetics. This will offer opportunities for the community to include different types of local art into the design. Some options include murals on the large concrete facades of the stairwells or exterior traffic barriers. This will also create a sense of ownership for the community and can deter graffiti in some cases.
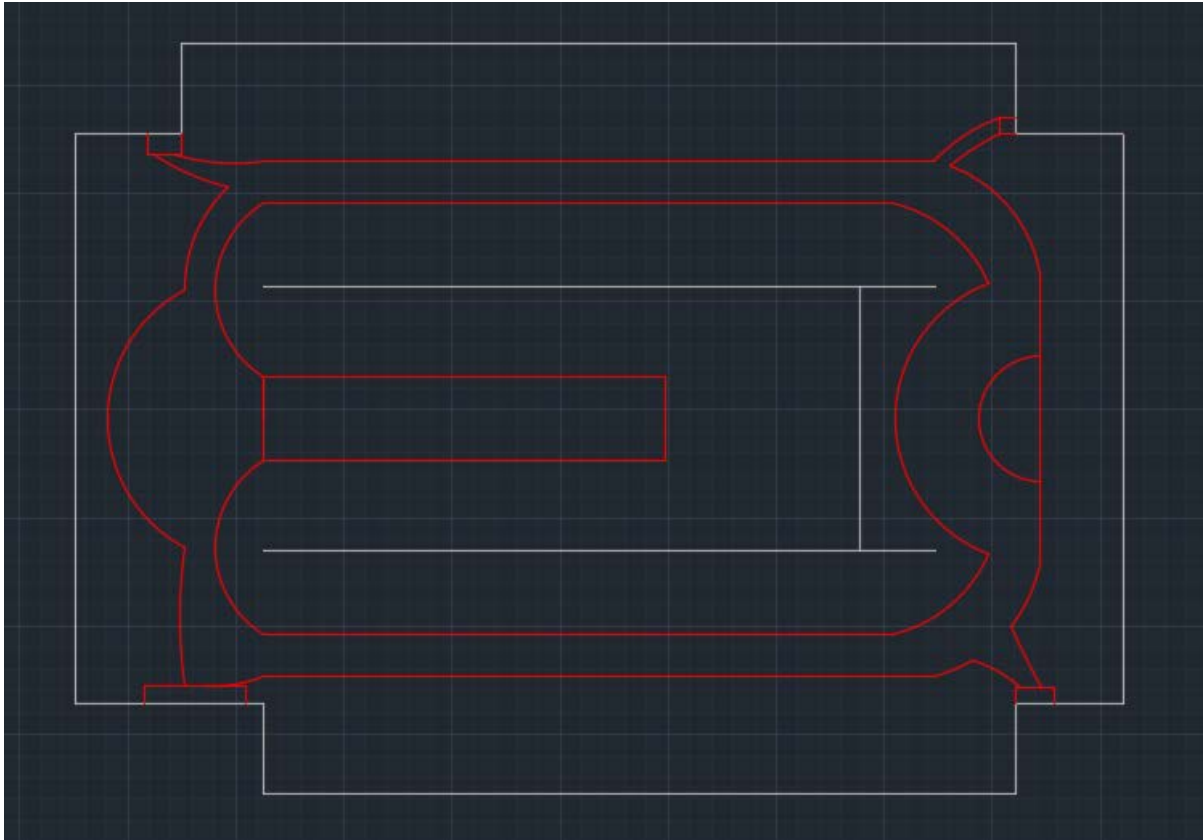
Figure 5: Plan View of Proposed Garden Design, Option 2

9. Selection Process

The selection process was governed by the feasibility and structural strength of the garage. Option 1 was ideal because of the interactive features it offered, but ran into problems with the structural model. Option 2 offered a minimalistic, yet functional, version to give a design that can be proven structurally viable based on our modeling and analyses.

Option 1 and option 2 both offered a variety of native wild life to the Sioux City area that will require little to no maintenance. This makes both alternatives appealing economically and functionality-wise so that the plants will be essentially self-sustaining in an environment exposed to extreme heat in the summers, extreme cold in the winters, and harsh winds throughout. This resilience was critical in our design to show that the green initiative won't put a large demand on the city in sustained funding.

The ultimate deciding factor was the structural strength of the critical component, or the weakest component of the garage. After completing the designs of both garden options the loads were calculated and applied to the Robot model. The results of this model were then compared to the strength capacity of the slab. The applied loads from both Option 1 and Option 2 were unfortunately too great for either the slab or beams in flexure. While the question was to see if a garden could be built on the structure as it is, we still explored the option to structural modify the garage to try to reach a solution. This option proved too costly and hardly viable based on physical constraints and scope of the project. The cost of the strategies greatly outweighed the benefits. Based on these findings, we decided that the Discovery garage is not suitable for a roof garden, but the designs that we

created would still be great choices for a new garage built to have enough capacity for a garden. The design details shown below describe execution option 1 for a new garage.

While option 1 offered a variety of extra components, it could not be built based on our structural evaluation of the garage. Option 2 offers a functional, simplistic, and open space that offers a lot of similar areas for the community that option 1 did, only at a lower cost and assurance of success. There will be areas for lunch, overlooking the city, and green spaces that will attract potential consumers to the nearby businesses.

10. Design Details

The preferred garden design is option 1 which consists of a walkway circling the entire top level bordered by plants and terraces on the sloped lengths. A drawing of the design can be seen above in figure 4. This offers more features and if a garage could be built to have enough capacity to support this garden, it would be preferred over option 2.

Each terrace contains native grasses and plants such as prairie smoke, black-eyed Susan, and little bluestem. Native, hearty plants were chosen because they are the most resilient and require less maintenance ("Recommended Rain Garden Native Plants", 2014).While the chosen plant species function in the space for aesthetic purposes, there are many engineering and cost benefits of the design. Prairie smoke was chosen for its use as a good border. It will only grow to 1 foot tall and can separate the walkways from turf areas without being blown away by harsh winds on top of the garage. This will save maintenance costs in the long term and benefit the space by bringing color and creating separate spaces. Black eyed Susan is a larger, more vibrant plant that can create some excitement for garden goers. It is biennial, so while it won't create useful space year round, it will be a more special occasion when they bloom and bring a bright feel to the space aside from the deeper colors of the prairie smoke and little blue stem. Little bluestem is our most functional choice, as it is a native grass that lasts all winter. This will encourage people to use the garden later into the fall and earlier into the spring. Mulch will be spread around the plants to hinder weed growth to further reduce maintenance. It will also slow moisture evaporation, break down into the underlying soil gradually and thereby improve the soil's texture, and helps moderate soil temperatures. This will increase the quality of the soil, the success of plant growth and yield, and will pay for itself over time. The functions of much of the planting strategies is to lower costs, and by designing the plants in the arrangement that we did, create a more effective garden in relation to the ultimate design objectives while limiting cost in the long term.

Each terrace will require a 2 foot tall retaining wall. The terraces will be constructed of inter-locking landscaping blocks that conform to the aesthetics of the garden and stone walkways. The ramp leading to the lower level will also have multiple terraced sections as seen in the plan drawing. At the lower elevation landing there is turf with picnic tables and benches for people to sit, relax, eat lunch, or enjoy the atmosphere. At the higher elevation landing there is a multipurpose area which is a very functional space. It will have stone floor, same aesthetic as the walkways and landscaping bricks, and will have areas to eat and serve to function as a venue for local restaurants or small public or private events.

The rooftop garden system consists of multiple layers to protect the current structure, provide adequate drainage, and be conducive to growing hearty plants. The general components can be seen in Figure 6. The layer separating the concrete deck and the

garden is the waterproofing layer made of a thick PVC membrane. This layer protects the structure from water infiltration which will eventually wear the concrete and reduce its structural capacity. This could lead to failure, so the waterproofing membrane is a critical step. Overall a roof garden will mitigate the current ponding problems on the roof and should lengthen the life span of the garage, but only if the waterproofing effectively separates the garden from the deck. Next is the drainage layer. This layer allows water to percolate through the soil and then be transported to the garage's existing drainage system. The drainage layer, based on the systems Rooflite Supply offer, includes pervious soils and aggregates that will effectively let water percolate to the drains and they also offer 1 ½" channel drains. Channel drains are a triangular path that will act as a guide for water to travel through so it doesn't sit in the soil during heavy storm events. Above the drainage layer is the separation fabric which lets water through but separates the growing media from the drainage layer so as to contain root growth. It is made of one or two layers of non-woven geotextile and includes a root inhibitor like copper or a mild herbicide. These base layers will also run underneath the walk way stones and which will act as a permeable paver system. This continuation of the drainage layer will ensure full drainage throughout the whole roof. Finally, above the filter layer is the growing media. This area is different than regular soil because of its rich mineral content to encourage healthy plant growth and sustained life in tough conditions. For turf areas this layer will be about 6 inches and for the perennials and taller grasses it will be about 16 inches (Wark, 2003). The permeability of the drainage layer is at least 100 in/min and that of the growing medium is 2.83 in/min, so the drainage layer has more than enough capacity for the water that will be filtering through the soil.
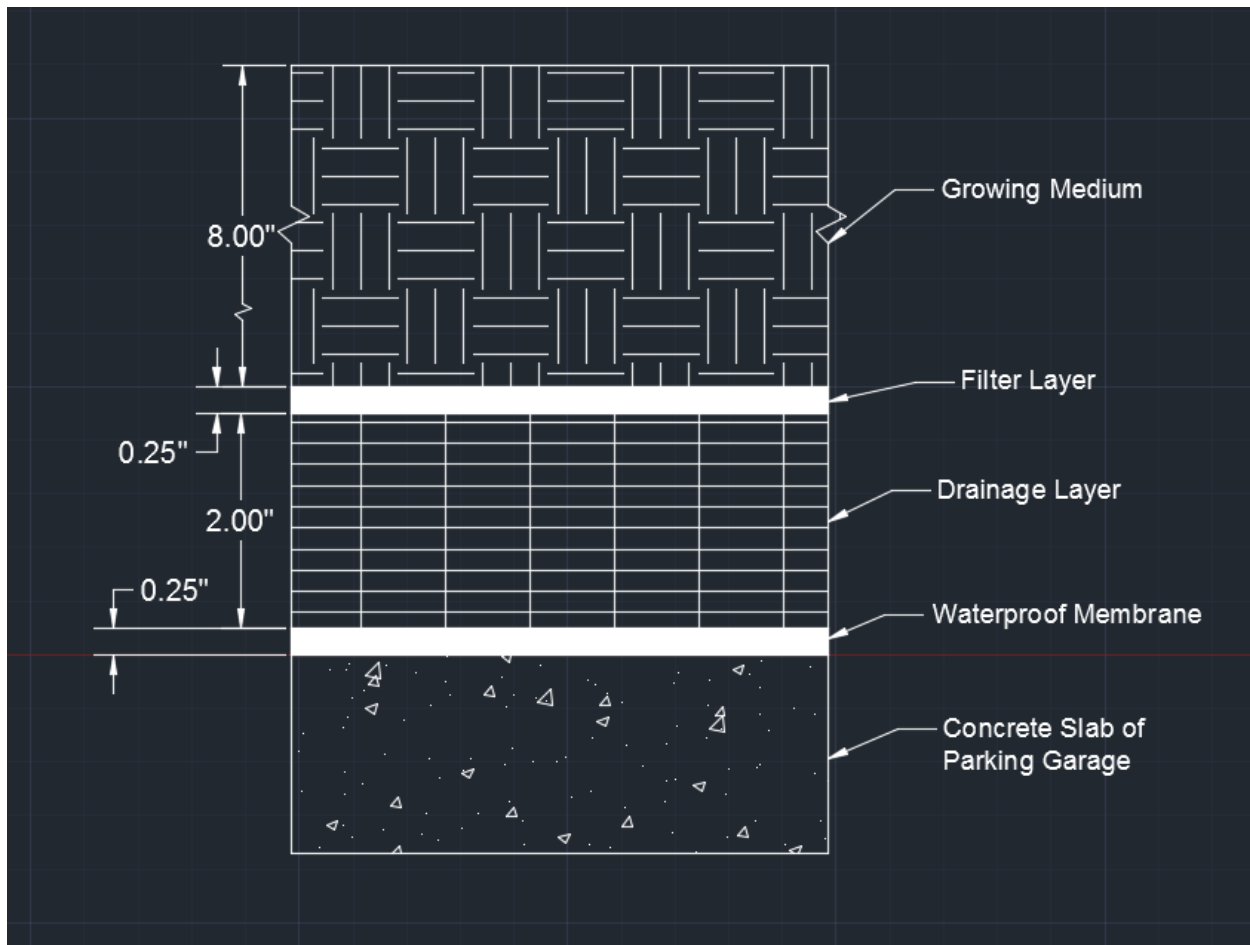
Figure 6: General components garden cross section

11. Cost and Construction Estimates

For the design option 1, the total construction cost was estimated at $451,500. To reference the details of the estimate, see Appendix C. While this design is the most costly, it is also the most involved when it comes to construction due to its various components. Since neither design option could be feasible built on the chosen structure, this cost estimate represents the cost of building design option 1 on a new garage structure with sufficient capacity.

The supplier we referenced in cost and load estimation offers two variations of soil delivery and application to rooftop. They described a "bulk" material delivery where a crane could raise the blocks to the top of the structure and a "loose" material delivery which included pneumatic placement of soil into designated areas. The loose delivery method was more feasible as it would be a challenge to fit a crane downtown due to physical constraints, and could cause problems for traffic for the duration of the loading. The rates given in Appendix B include the cost of equipment, labor for spraying, and cost of materials. The rest of the materials given are based on areas from the AutoCAD model given above in Figure 4, and rates based on the most logical references and suppliers based in nearby Northwestern Iowa or Eastern Nebraska. Labor was estimated assuming that the construction team would include four laborers and one supervisor at any given time. There

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are physical restrictions when it comes to getting heavy equipment on the roof of the garage, so we assumed that the components will be created by hand based on small deliveries via work trucks. While this will increase the labor costs due to longer hours, it will save on rental costs of heavy machinery, costs of creating and signing a detour for downtown traffic, and the potential of permanently damaging the roof by overloading it. The pay rates for labor were derived from work experience in a similar market. The total cost of labor was calculated as the total team hours per task multiplied by the rate of the five person team working one hour.

In terms of construction phasing, the project should be fairly linear and able to be completed handily with five workers at a time. Waterproofing of the roof of the garden will need to take place first. This is independent of other processes and governs all other progress. The soil cannot be placed without the membrane being in place, neither can the components be built. Once the waterproof membrane is in place, the soil can be sprayed into place using pneumatic placing. This should be a relatively quick process, as the supplier delivers the soil and sprays it based on the specifications given. After the soil is settled, the components can begin being placed. The terracing should be built first, so that the soil has time to settle and be fully compacted before the walkways and grasses are laid into place. The terracing blocks can be delivered to the roof via maintenance truck and set in place by the laborers one block at a time. This will be tedious, but overall more feasible than prefabricating the terraces or ordering machinery. Once the terraces are in place, the sequence of events is not limited. The stone walkways could be laid before or after the laying of plants, grasses, seeding, and mulch. The last step to construction would be placing the amenities including picnic tables, benches, and whatever is to be laid in the multipurpose area.

Option 2 will include similar cost estimate strategies, but the phasing will be even simpler by taking out the various components offered in option 1. This will lower labor costs and drastically lower the material costs. With these lower costs and loads, different construction strategies may be employed such as larger teams working at the same time, or possibly small machinery to make the processes more efficient.

12. Conclusions

Based on our in depth structural model and analysis of the Discovery Parking Garage and design loads for a developed and minimalistic garden, we recommend that a roof garden not be built on top of this structure. Both alternatives were explored, analyzed, and were proven to fail based on the current condition of the structure. While the designs are not feasible on this structure, they are fully functioning designs to be employed on a future garage that has the structural capacity to carry the calculated loads. The design objectives and requests were met in the structural analysis and garden design realms in the delivered calculations, figures, and narratives. We hope the insight provided can be useful in Sioux City decision making and can offer constructive conclusions that can forward the current green initiative and urban planning in the community as a whole.

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Appendix A – Structural Design Model and Calculations

LRFD Load Combination 4

$$1.2 \times Dead\ Load + 1.6 \times Wind\ Load + 1.0 \times Live\ Load$$

For loads along the critical beam analyzed in alternative 1:

- The dead load consists of the load from the terraced soil and roof garden system, the turf soil and roof garden system, the retaining wall and the slab weight which are all multiplied by the tributary area between beams.

$$Dead = \left(\left(117\,\frac{lb}{sf} + 9.667\,\frac{lb}{sf} + 0.03\,\frac{lb}{sf}\right) \times 9ft\right)$$
$$+ \left(\left(52\,\frac{lb}{sf} + 9.667\,\frac{lb}{sf} + 0.03\,\frac{lb}{sf}\right) \times 10ft\right) + 153\,\frac{lb}{ft}$$
$$+ \left(115\,\frac{lb}{cf} \times 0.66667\,ft \times 19\,ft\right) = 3.367\,\frac{kip}{ft}$$

- The live load accounts for the human traffic on the garden and is mutliplied by the tributary area between beams.

$$Live = 50\,\frac{lb}{sf} \times 19\,ft = 0.950\,\frac{kip}{ft}$$

- The wind load is a standard value, but is converted to a point load which acts at the end of the beam. It is converted to a point load by mulitplying by the tributary area between beams and also the tributary area between floors.

$$Wind = 40\,\frac{lb}{sf} \times 19\,ft \times 5ft = 3.8\,kip$$

- Because the wind load is a point load, it cannot be added directly to the dead and live loads, but it is still multiplied by the load factor.

$$Wind = 1.6 \times 3.8\,kip = 6.08\,kip$$

$$Dead\ and\ Live = 1.2 \times 3.367\,\frac{kip}{ft} + 1.0 \times 0.95\,\frac{kip}{ft} = 5\,\frac{kip}{ft}$$

Retaining Wall Sample Calculations (Retaining Wall between Terraces)

Active Pressure of Backfill

$$P_a = 0.5 \times \gamma_{bf} \times H'^2$$
$$P_a = 0.5 \times 78 \frac{lb}{cf} \times (1.5833 \, ft)^2 = 97.77 \frac{lb}{ft}$$

Weight per Unit Length of Each Component

$$w = \gamma \times area$$
$$\bar{x} = x \, distance \, to \, centroid \, of \, area$$

(There is a w and $\bar{x}$ for the soil behind the retaining wall, the stem of the retaining wall, and the base)

$$w1 = 78 \frac{lb}{cf} \times 0.25ft \times 1.33333 \, ft = 26 \frac{lb}{ft}$$
$$\overline{x_1} = 0.25 \, ft + 1 \, ft + \frac{0.25}{2} ft = 1.375 \, ft$$

Moment Driving Overturning

$$M_D = P_a \times \frac{H'}{3}$$
$$M_D = 97.77 \frac{lb}{ft} \times \frac{1.5833}{3} ft = 51.6 \frac{lb - ft}{ft}$$

Moment Resisting Overturning

$$M_R = w_1 \times \overline{x_1} + w_2 \times \overline{x_2} + w_3 \times \overline{x_3}$$
$$M_R = \left(26 \frac{lb}{ft} \times 1.325ft\right) + \left(153.33 \frac{lb}{ft} \times 0.75 \, ft\right) + \left(43.13 \frac{lb}{ft} \times 0.75 \, ft\right) = 183.09 \frac{lb - ft}{ft}$$

Factor of Safety Against Overturning

$$FS_O = \frac{M_R}{M_D}$$
$$FS_O = \frac{183.09 \frac{lb-ft}{ft}}{51.6 \frac{lb-ft}{ft}} = 3.55 > 3 \quad \text{(Design is sufficient)}$$

Column Strength Calculations

To calculate the strength capacity of a column a five point interaction diagram was constructed. First the critical column was identified through a Robot analysis of a frame. The critical column was identified as the exterior column A-2.
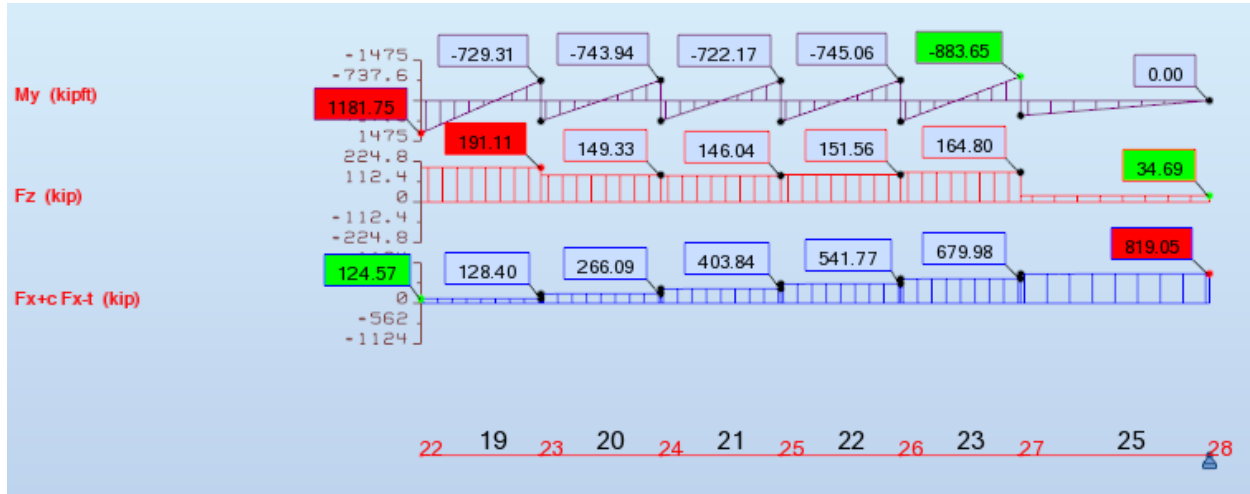

Figure 7: Robot Analysis of Column A-2

Column A-2 Strength Calculations:

Figure 8: Column A-2 Reinforcement Cross Section

Material Properties
$Unit\ Weight\ of\ Light\ Weight\ Concrete\ (wc), wc = 115\ pcf$
$28\ day\ Compression\ Strength\ of\ Concrete\ (fcp), fcp = 4000\ psi$
$Yield\ Stress\ of\ the\ Reinforcing\ Steel\ (fy), fy = 60,000\ psi$
$Young's\ Modulus\ of\ Steel\ (Es), Es = 29,000,000\ psi$
$Young's\ Modulus\ of\ Steel\ (Ec), Ec = 33 * wc^{1.5} * \sqrt{fcp}\ psi$
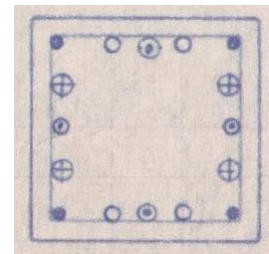$Reduction\ Factor\ (\phi), \phi = .9$

Column Dimensions
$Column\ Width\ (b), b = 20\ in$
$Column\ depth\ (h), h = 20\ in$
$Column\ Cross\ Sectional\ Area\ (Ac1), Ac1 = b * h\ in^2$

Reinforcement Data
$Diameter\ of\ bar\ group\ A, B, C\ (Dia1), Dia1 = 1.693\ in$
$Diameter\ of\ the\ Ties\ (dt), dt = .5\ in$
$Clear\ Cover\ (cc), cc = 1.5\ in$
$Cover\ (c0), c0 = cc + dt + .5 * Dia1\ in$

Distances and Area's
$Distance\ from\ the\ bottom\ to\ the\ Elastic\ Neutral\ Axis\ (ybar), ybar = 10\ in$
$Distance\ from\ the\ bottom\ to\ the\ centroid\ of\ the\ first\ row\ of\ rebar\ (ys1), ys1 = c0\ in$

$$\text{"" second row of rebar } (ys2), ys2 = \frac{ybar + c0}{2} \text{ in}$$

$$\text{"" third row of rebar } (ys3), ys3 = ybar \text{ in}$$

$$\text{"" fourth row of rebar } (ys4), ys4 = \frac{(h - c0) + ybar}{2} \text{ in}$$

$$\text{"" fifth row of rebar } (ys5), ys5 = h - c0 \text{ in}$$

$Area\ of\ Steel\ in\ the\ first\ and\ fifth\ rows\ (As1), As1 = As5 = 11.25\ in^2$

$Area\ of\ Steel\ in\ the\ second, third\ and\ fourth\ rows\ (As2), As2 = As3 = As4 = 4.5\ in^2$

$Total\ Area\ of\ Steel\ Reinforcement\ in\ the\ Column\ (Ast), Ast = (2*As1) + (3*As2)\ in^2$

Calculation of the Interaction Diagram Point A, Axial Loading Only

$Rectangular\ Column\ Eccentricity\ Reduction\ Factor\ (eccFact), eccFact = .8$

$Used\ to\ Define\ the\ Equivalent\ Rectangular\ Stress\ Block\ (\beta), \beta = .85$

$Depth\ of\ the\ Elastic\ Neutral\ Axis\ from\ the\ compression\ face\ (c), c = 10\ in$

$Equivalent\ Rectangular\ Stress\ Block\ Depth\ (a), a = \beta*c\ in$

$Force\ of\ Concrete\ (Fc1), Fc1 = -.85*fcp*Ac1\ kip$

$Design\ Flexural\ Strength\ at\ Point\ A\ (\phi Mna), \phi Mna = 0\ kip - ft$

$Design\ Axial\ Strength\ at\ Point\ A\ (\phi Pna), \phi Pna$

$$= \frac{eccFact * \phi * (Fc1 + (Ast * (-fy + .85 * fcp)))}{1000}\ kips$$

Calculation of Point B, setting the strain in the bottom most row of rebar to 0

$Ultimate\ strain\ of\ concrete\ (ecu), ecu = .03\ in/in$

$Compressive\ strain\ at\ the\ top\ (eh), eh = -ecu\ in/in$

$Strain\ in\ the\ bottom\ most\ row\ of\ rebar\ (et), et = es1 = 0\ in/in$

$$Tensile\ Strain\ at\ the\ bottom\ (e0), e0 = \frac{et*h - eh*ys1}{h - ys1}\ in/in$$

$Used\ to\ Define\ the\ Equivalent\ Rectangular\ Stress\ Block\ (\beta), \beta = .85$

$$Depth\ of\ the\ Elastic\ Neutral\ Axis\ from\ the\ compression\ face\ (c), c = \frac{eh*h}{eh - e0}\ in$$

$Equivalent\ Rectangular\ Stress\ Block\ Depth\ (a), a = \beta*c\ in$

$Force\ of\ Concrete\ (Fc1), Fc1 = -.85*fcp*Ac1\ kip$

$$Strain\ in\ the\ second\ row\ of\ rebar\ (es2), es2 = e0*\frac{h - ys2}{h} + eh*\frac{ys2}{h}\ in/in$$

$$Strain\ in\ the\ forth\ row\ of\ rebar\ (es4), es4 = e0*\frac{h - ys4}{h} + eh*\frac{ys4}{h}\ in/in$$

$$Strain\ in\ the\ fifth\ row\ of\ rebar\ (es5), es5 = e0*\frac{h - ys5}{h} + eh*\frac{ys5}{h}\ in/in$$

$rebarStress = sign(\epsilon s, i)\ (Min[Abs(Es\ \epsilon s, i), fy] - If[\epsilon s, i < 0, 0.85\ fcp, 0])\ kip/in^2$

$Force\ of\ the\ first\ row\ of\ rebar\ (Fs1), Fs1 = As1*rebarStress[es1, Es, fy, fcp]\ kip$

$Force\ of\ the\ second\ row\ of\ rebar\ (Fs2), Fs2 = As2*rebarStress[es2, Es, fy, fcp]\ kip$

$Force\ of\ the\ forth\ row\ of\ rebar\ (Fs4), Fs4 = As4*rebarStress[es4, Es, fy, fcp]\ kip$

$Force\ of\ the\ fifth\ row\ of\ rebar\ (Fs5), Fs5 = As5*rebarStress[es5, Es, fy, fcp]\ kip$

$$Moment\ caused\ by\ the\ concrete\ (momFc), momFc = Fc1 * \left(ybar - \left(h - \frac{a}{2}\right)\right)\ kip - ft$$

$Moment\ caused\ by\ the\ first\ row\ of\ rebar\ (momFs1), momFs1$
$$= Fs1 * (ybar - ys1)\ kip - ft$$
$Moment\ caused\ by\ the\ second\ row\ of\ rebar\ (momFs2), momFs2$
$$= Fs2 * (ybar - ys2)\ kip - ft$$
$Moment\ caused\ by\ the\ forth\ row\ of\ rebar\ (momFs4), momFs4$
$$= Fs4 * (ybar - ys4)\ kip - ft$$
$Moment\ caused\ by\ the\ fifth\ row\ of\ rebar\ (momFs5), momFs5$
$$= Fs5 * (ybar - ys5)\ kip - ft$$

$$\phi Pnb = \frac{\phi * (Fc1 + Fs1 + Fs2 + Fs4 + Fs5)}{1000}\ kip$$

$$\phi Mnb = \frac{\phi * (momFc + momFs1 + momFs2 + momFs4 + momFs5)}{12 * 1000}\ kip - ft$$

Calculation of Point C, setting the strain in the bottom most row of rebar to fy/Es

$Ultimate\ strain\ of\ concrete\ (ecu), ecu = .03\ in/in$
$Compressive\ strain\ at\ the\ top\ (eh), eh = -ecu\ in/in$

$Strain\ in\ the\ bottom\ most\ row\ of\ rebar\ (et), et = es1 = \dfrac{fy}{Es}\ in/in$

$Tensile\ Strain\ at\ the\ bottom\ (e0), e0 = \dfrac{et * h - eh * ys1}{h - ys1}\ in/in$

$Used\ to\ Define\ the\ Equivalent\ Rectangular\ Stress\ Block\ (\beta), \beta = .85$

$Depth\ of\ the\ Elastic\ Neutral\ Axis\ from\ the\ compression\ face\ (c), c = \dfrac{eh * h}{eh - e0}\ in$

$Equivalent\ Rectangular\ Stress\ Block\ Depth\ (a), a = \beta * c\ in$
$Force\ of\ Concrete\ (Fc1), Fc1 = -.85 * fcp * Ac1\ kip$

$Strain\ in\ the\ second\ row\ of\ rebar\ (es2), es2 = e0 * \dfrac{h - ys2}{h} + eh * \dfrac{ys2}{h}\ in/in$

$Strain\ in\ the\ forth\ row\ of\ rebar\ (es4), es4 = e0 * \frac{h - ys4}{h} + eh * \frac{ys4}{h}\ in/in$

$Strain\ in\ the\ fifth\ row\ of\ rebar\ (es5), es5 = e0 * \dfrac{h - ys5}{h} + eh * \dfrac{ys5}{h}\ in/in$

$fs, i = sign(\epsilon s, i)\ (Min[Abs(Es\ \epsilon s, i), fy] - If[\epsilon s, i < 0, 0.85\ fcp, 0])\ kip/in^2$
$Force\ of\ the\ first\ row\ of\ rebar\ (Fs1), Fs1 = As1 * rebarStress[es1, Es, fy, fcp]\ kip$
$Force\ of\ the\ second\ row\ of\ rebar\ (Fs2), Fs2 = As2 * rebarStress[es2, Es, fy, fcp]\ kip$
$Force\ of\ the\ forth\ row\ of\ rebar\ (Fs4), Fs4 = As4 * rebarStress[es4, Es, fy, fcp]\ kip$
$Force\ of\ the\ fifth\ row\ of\ rebar\ (Fs5), Fs5 = As5 * rebarStress[es5, Es, fy, fcp]\ kip$

$$Moment\ caused\ by\ the\ concrete\ (momFc), momFc = Fc1 * \left(ybar - \left(h - \frac{a}{2}\right)\right)\ kip - ft$$

$Moment\ caused\ by\ the\ first\ row\ of\ rebar\ (momFs1), momFs1$
$$= Fs1 * (ybar - ys1)\ kip - ft$$
$Moment\ caused\ by\ the\ second\ row\ of\ rebar\ (momFs2), momFs2$
$$= Fs2 * (ybar - ys2)\ kip - ft$$

$Moment\ caused\ by\ the\ forth\ row\ of\ rebar\ (momFs4),momFs4$
$$= Fs4*(ybar - ys4)\ kip - ft$$
$Moment\ caused\ by\ the\ fifth\ row\ of\ rebar\ (momFs5),momFs5$
$$= Fs5*(ybar - ys5)\ kip - ft$$
$$\phi Pnc = \frac{\phi*(Fc1 + Fs1 + Fs2 + Fs4 + Fs5)}{1000}\ kip$$
$$\phi Mnc = \frac{\phi*(momFc + momFs1 + momFs2 + momFs4 + momFs5)}{12*1000}\ kip - ft$$

Calculation of Point D, setting the strain in the bottom most row of rebar to .005

$Ultimate\ strain\ of\ concrete\ (ecu),ecu = .03\ in/in$
$Compressive\ strain\ at\ the\ top\ (eh),eh = -ecu\ in/in$
$Strain\ in\ the\ bottom\ most\ row\ of\ rebar\ (et),et = es1 = .005\ in/in$
$Tensile\ Strain\ at\ the\ bottom\ (e0),e0 = \dfrac{et*h - eh*ys1}{h - ys1}\ in/in$
$Used\ to\ Define\ the\ Equivalent\ Rectangular\ Stress\ Block\ (\beta),\beta = .85$
$Depth\ of\ the\ Elastic\ Neutral\ Axis\ from\ the\ compression\ face\ (c),c = \dfrac{eh*h}{eh - e0}\ in$
$Equivalent\ Rectangular\ Stress\ Block\ Depth\ (a),a = \beta*c\ in$
$Force\ of\ Concrete\ (Fc1),Fc1 = -.85*fcp*Ac1\ kip$
$Strain\ in\ the\ second\ row\ of\ rebar\ (es2),es2 = e0*\dfrac{h - ys2}{h} + eh*\dfrac{ys2}{h}\ in/in$
$Strain\ in\ the\ forth\ row\ of\ rebar\ (es4),es4 = e0*\frac{h - ys4}{h} + eh*\frac{ys4}{h}\ in/in$
$Strain\ in\ the\ fifth\ row\ of\ rebar\ (es5),es5 = e0*\dfrac{h - ys5}{h} + eh*\dfrac{ys5}{h}\ in/in$
$fs,i = sign(\epsilon s,i)\ (Min[Abs(Es\ \epsilon s,i),fy] - If[\epsilon s,i < 0,0.85\ fcp,0])\ kip/in^2$
$Force\ of\ the\ first\ row\ of\ rebar\ (Fs1),Fs1 = As1*rebarStress[es1,Es,fy,fcp]\ kip$
$Force\ of\ the\ second\ row\ of\ rebar\ (Fs2),Fs2 = As2*rebarStress[es2,Es,fy,fcp]\ kip$
$Force\ of\ the\ forth\ row\ of\ rebar\ (Fs4),Fs4 = As4*rebarStress[es4,Es,fy,fcp]\ kip$
$Force\ of\ the\ fifth\ row\ of\ rebar\ (Fs5),Fs5 = As5*rebarStress[es5,Es,fy,fcp]\ kip$

$Moment\ caused\ by\ the\ concrete\ (momFc),momFc = Fc1*\left(ybar - \left(h - \dfrac{a}{2}\right)\right)\ kip - ft$

$Moment\ caused\ by\ the\ first\ row\ of\ rebar\ (momFs1),momFs1$
$$= Fs1*(ybar - ys1)\ kip - ft$$
$Moment\ caused\ by\ the\ second\ row\ of\ rebar\ (momFs2),momFs2$
$$= Fs2*(ybar - ys2)\ kip - ft$$
$Moment\ caused\ by\ the\ forth\ row\ of\ rebar\ (momFs4),momFs4$
$$= Fs4*(ybar - ys4)\ kip - ft$$
$Moment\ caused\ by\ the\ fifth\ row\ of\ rebar\ (momFs5),momFs5$
$$= Fs5*(ybar - ys5)\ kip - ft$$
$$\phi Pnd = \frac{\phi*(Fc1 + Fs1 + Fs2 + Fs4 + Fs5)}{1000}\ kip$$

$$\phi Mnd = \frac{\phi * (momFc + momFs1 + momFs2 + momFs4 + momFs5)}{12 * 1000} \ kip - ft$$

Calculation of Point E, setting the strain in the bottom most row of rebar to .02

Ultimate strain of concrete $(ecu), ecu = .03 \ in/in$
Compressive strain at the top $(eh), eh = -ecu \ in/in$
Strain in the bottom most row of rebar $(et), et = es1 = .02 \ in/in$
Tensile Strain at the bottom $(e0), e0 = \dfrac{et * h - eh * ys1}{h - ys1} \ in/in$
Used to Define the Equivalent Rectangular Stress Block $(\beta), \beta = .85$
Depth of the Elastic Neutral Axis from the compression face $(c), c = \dfrac{eh * h}{eh - e0} \ in$
Equivalent Rectangular Stress Block Depth $(a), a = \beta * c \ in$
Force of Concrete $(Fc1), Fc1 = -.85 * fcp * Ac1 \ kip$
Strain in the second row of rebar $(es2), es2 = e0 * \dfrac{h - ys2}{h} + eh * \dfrac{ys2}{h} \ in/in$
Strain in the forth row of rebar $(es4), es4 = e0 * \frac{h - ys4}{h} + eh * \frac{ys4}{h} \ in/in$
Strain in the fifth row of rebar $(es5), es5 = e0 * \dfrac{h - ys5}{h} + eh * \dfrac{ys5}{h} \ in/in$
$fs, i = sign(\epsilon s, i) \ (Min[Abs(Es \ \epsilon s, i), fy] - If[\epsilon s, i < 0, 0.85 \ fcp, 0]) \ kip/in^2$
Force of the first row of rebar $(Fs1), Fs1 = As1 * rebarStress[es1, Es, fy, fcp] \ kip$
Force of the second row of rebar $(Fs2), Fs2 = As2 * rebarStress[es2, Es, fy, fcp] \ kip$
Force of the forth row of rebar $(Fs4), Fs4 = As4 * rebarStress[es4, Es, fy, fcp] \ kip$
Force of the fifth row of rebar $(Fs5), Fs5 = As5 * rebarStress[es5, Es, fy, fcp] \ kip$
Moment caused by the concrete $(momFc), momFc = Fc1 * \left(ybar - \left(h - \dfrac{a}{2} \right) \right) \ kip - ft$
Moment caused by the first row of rebar $(momFs1), momFs1$
$\quad\quad = Fs1 * (ybar - ys1) \ kip - ft$
Moment caused by the second row of rebar $(momFs2), momFs2$
$\quad\quad = Fs2 * (ybar - ys2) \ kip - ft$
Moment caused by the forth row of rebar $(momFs4), momFs4$
$\quad\quad = Fs4 * (ybar - ys4) \ kip - ft$
Moment caused by the fifth row of rebar $(momFs5), momFs5$
$\quad\quad = Fs5 * (ybar - ys5) \ kip - ft$
$$\phi Pne = \frac{\phi * (Fc1 + Fs1 + Fs2 + Fs4 + Fs5)}{1000} \ kip$$
$$\phi Mne = \frac{\phi * (momFc + momFs1 + momFs2 + momFs4 + momFs5)}{12 * 1000} \ kip - ft$$

Interaction Diagram and Summary of Points Calculated

$$\begin{pmatrix} 0 & 1766.75 \\ 423.887 & 1250.7 \\ 739.467 & 354.23 \\ 653.944 & -52.3522 \\ 221.697 & -878.879 \end{pmatrix}$$

Figure 9: Summary of the Point Calculated A-E

{1181.75, 819.05}
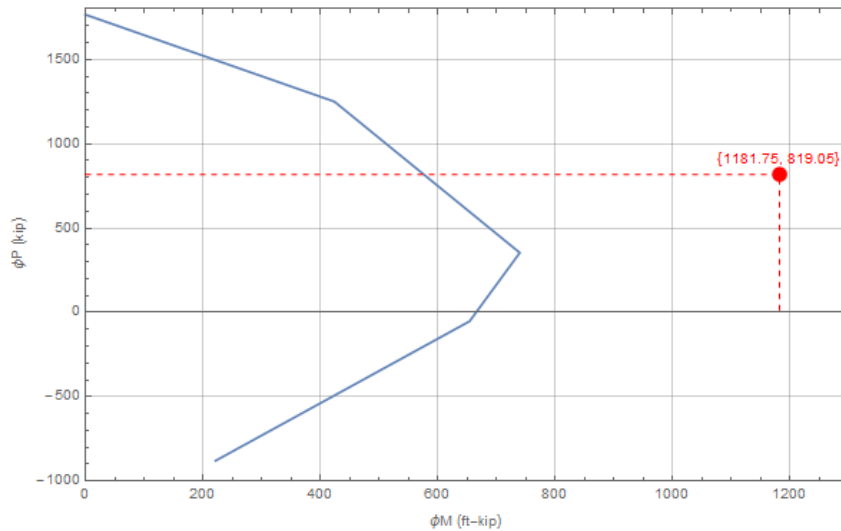
Figure 10: Interaction Diagram of Column A-2

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Beam Strength Calculations

Beam in Negative Moment Region Line 2 Sample Calculation

Dimensions of the beam

$$b = 15\ in, h = 36\ in, cover\ (co) = 2\ in, cover\ of\ outtermost\ row\ (cob) = 1.5\ in$$

Number of #10 rebar and dimensions

$$number\ of\ rebars\ (n) = 7, area\ of\ each\ \#10\ rebar = 1.27\ in^2$$
$$total\ area\ of\ rebar\ (As) = 8.89\ in^2$$

Concrete and rebar properties

$$concrete\ strength\ (fcp) = 4{,}000\ psi, maximum\ strain\ of\ concrete\ (ecu) = 0.003$$
$$rebar\ strength\ (fy) = 60{,}000\ psi, Young's\ modulus\ of\ steel\ (Es) = 29{,}000{,}000\ psi$$

Procedure to find the maximum design moment for a reinforced concrete beam

$$depth\ (d) = h - co = 36\ in - 2\ in = 34\ in$$

$$depth\ to\ bottom - most\ row\ of\ rebar\ (dt) = h - cob = 36\ in - 1.5\ in = 34.5\ in$$

$$Force\ in\ the\ steel\ (Fs) = As \times fy = 8.89\ in^2 \times 60{,}000\ psi = 533{,}400\ lb$$

$$Equivalent\ stress\ block\ depth\ (a) = \frac{Fs}{0.85 \times fcp \times b} = \frac{533{,}400\ lb}{0.85 \times 4{,}000\ psi \times 15\ in}$$
$$= 10.4588\ in$$

$$Yield\ strain\ of\ steel\ (ety) = \frac{fy}{Es} = \frac{60{,}000\ psi}{29{,}000{,}000\ psi} = 0.00207$$

$$Parameter\ to\ define\ the\ equivalent\ stress\ block\ (\beta) = 0.85$$

$$Distance\ from\ side\ in\ compression\ to\ neutral\ axis\ (c) = \frac{a}{\beta} = \frac{10.4588\ in}{0.85} = 12.3045\ in$$

$$Strain\ in\ the\ rebar\ (et) = \frac{ecu \times (dt - c)}{c} = \frac{0.003 \times (34.5\ in - 12.3045\ in)}{12.3045\ in} = 0.005411$$

$$Nominal\ flexural\ strength\ (Mn) = \frac{Fs \times (d - \frac{a}{2})}{1000 \times 12} = \frac{533{,}400\ lb \times (34\ in - \frac{12.3045\ in}{2})}{1000 \times 12}$$
$$= 1278.85\ kip - ft$$

$$Strength\ reduction\ factor\ (\varphi) = 0.9$$

$$Design\ Flexural\ Strength\ (Mr) = \varphi \times Mn = 0.9 \times 1278.85\ kip - ft = 1150.97\ kip - ft$$
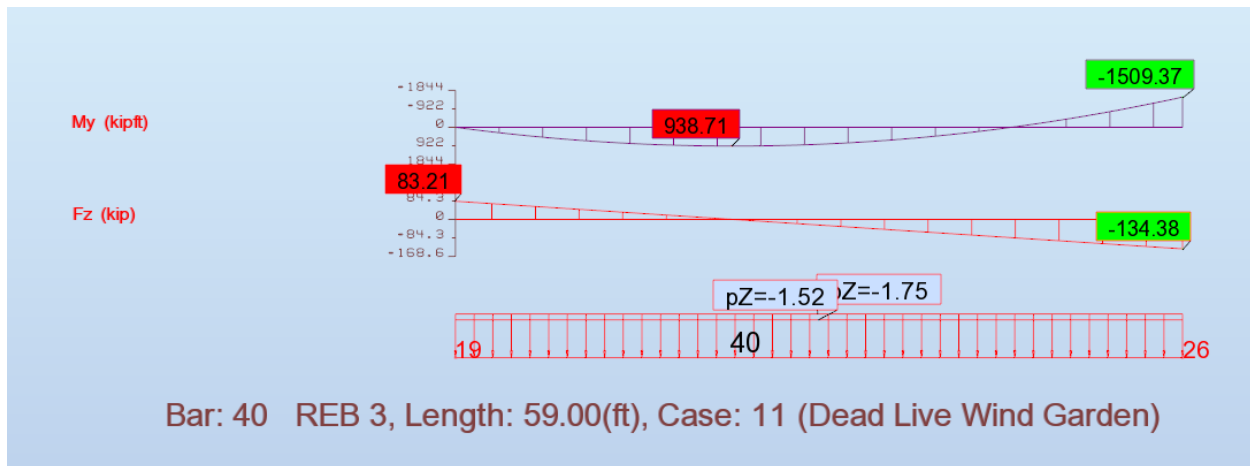

Figure 11: Robot Analysis of Critical Beam EB5 located on the 2nd floor

Slab Strength Calculations

To calculate the strength capacity of the slab, first the slab was catorized between one and two way action. Next, a one foot width of slab in the direction of one-way load transfer was taken and then applied with a uniformally distributed factored load. The maximnm applied shear, positive and negative moment were found using ACI coefficents. This value was then compared

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to the slab strength, which was calculated using the ACI equivalent rectangular stress block for concrete compression at ultimate method listed in ACI 318-14 Sections 22.2.2.3 and 22.2.2.4.

Slab Strength Calculations

Material Properties

$Unit\ Weight\ of\ Light\ Weight\ Concrete\ (wc), wc = 115\ pcf$
$28\ day\ Compression\ Strength\ of\ Concrete\ (fcp), fcp = 4000\ psi$
$Yield\ Stress\ of\ the\ Reinforcing\ Steel\ (fy), fy = 60{,}000\ psi$
$Young's\ Modulus\ of\ Steel\ (Es), Es = 29{,}000{,}000\ psi$
$Young's\ Modulus\ of\ Steel\ (Ec), Ec = 33 * wc^{1.5} * \sqrt{fcp}\ psi$

Dimensions of the Slab and Beams

$Base\ of\ the\ beam\ (bb), bb = 14\ in$
$Height\ of\ the\ beam\ (hb), hb = 36\ in$
$Thickness\ of\ the\ Slab\ (ts), ts = 8\ in$
$Average\ Spacing\ of\ the\ beams\ (beamSpacing), beamSpacing = 18\ ft$
$Beam\ Span, (L1), L1 = 59\ ft$
$Checking\ for\ 1\ way\ action{:}\dfrac{L1}{20} \geq 2, True\ therefore\ it\ is\ a\ one\ way\ slab$
$Clear\ Spans{:}\ 18\ ft\ span\ (Ln18) = 18 - \dfrac{bb}{12}$
$\qquad\qquad = 16.833\ ft\ (also\ done\ for\ the\ 17\ and\ 20\ foot\ spans)$

Reinforcement Data

$Diameter\ of\ bar\ group\ B, C\ (bar4Dia), bar4Dia = .5\ in$
$Diameter\ of\ the\ Ties\ (dt), dt = .5\ in$
$Clear\ Cover\ (cc), cc = 1.5\ in$
$Cover\ (c0), c0 = cc + .5 * bar4Dia\ in$
$depth\ of\ rebar\ (d), d = hb - c0\ in$

Calculate the Flexural Strength of the Slab

$depth\ (d) = ts - co = 8\ in - 1.5\ in = 6.25\ in$

$depth\ to\ bottom - most\ row\ of\ rebar\ (dt) = ts - cob = 8\ in - 1.5\ in = 6.25 in$
$Area\ of\ Steel\ reinforcement\ (As) = As = \dfrac{unitSlabWidth * bar4Area}{barSpacing}$
$\qquad\qquad = 0.133\ in^2/12\ in\ width\ of\ slab$

$Force\ in\ the\ steel\ (Fs) = As \times fy = 0.133\ in^2 \times 60{,}000\ psi = 8000\ lb$

$$\text{Equivalent stress block depth } (a) = \frac{Fs}{0.85 \times fcp \times b} = \frac{8000 \, lb}{0.85 \times 4,000 \, psi \times 12 \, in}$$
$$= 0.1961in$$

$$\text{Yield strain of steel } (ety) = \frac{fy}{Es} = \frac{60,000 \, psi}{29,000,000 \, psi} = 0.00207$$

$$\text{Parameter to define the equivalent stress block } (\beta) = 0.85$$

$$\text{Distance from side in compression to neutral axis } (c) = \frac{a}{\beta} = \frac{0.1961 \, in}{0.85} = 0.2307 \, in$$

$$\text{Strain in the rebar } (et) = \frac{ecu \times (dt - c)}{c} = \frac{0.003 \times (6.25 \, in - 0.2307 \, in)}{0.2307 \, in} = 0.0815 \, in/in$$

$$\text{Nominal flexural strength } (Mn) = \frac{Fs \times (d - \frac{a}{2})}{1000 \times 12} = \frac{8000 \, lb \times (6.25 \, in - \frac{0.1961in}{2})}{1000 \times 12}$$
$$= 4.1013 \, kip - ft$$

$$\text{Strength reduction factor } (\phi) = 0.9$$

$$\text{Positive Design Flexural Strength } (MrPos) = \phi \times Mn = 0.9 \times 4.1013 \, kip - ft$$
$$= 3.6912 \, kip - ft$$
$$\text{Negative Design Flexural Strength } (MrNeg) = \phi * Mn = 0.9 \times 4.1013 \, kip - ft$$
$$= 3.6912 \, kip - ft$$

<u>Calculate the Shear Strength of the Slab</u>

$$\lambda = 1$$
$$\text{Shear Resistance of the Concrete slab}, Vc = \frac{2 * \lambda * \sqrt{fcp} * 12 * d}{1000} = 9.49 \, kip$$
$$\text{Shear Reinforcement requirement check,}$$
$$Vu < .5 * Vc, True, Therefore \, no \, shear \, reinforcement \, is \, required.$$

LRFD Design Load Applied to the Slab Calculations

<u>Calculate the Uniformly Distributed Factored Load</u>

$$slabWeight = \left(\frac{ts}{12}\right) * wc = \left(\frac{8}{12}\right) * 115 = 76.667 \, psf$$
$$\text{Superimposed Live Load}, ll = 61.7 \, psf$$
$$\text{Distributed Dead Load}, wd = \frac{(slabWeight) * 1}{1000} = .0767 \, kip/ft$$
$$\text{Distributed Live Load}, wl = \frac{ll * 1}{1000} = .0617 \, kip/ft$$

$Distributed\ Factored\ Loading, wu = 1.2 * wd + 1.6 * wl\ kip/ft$

Use the ACI coefficients to determine the Design Moments and Shear Force

$$Maximum\ applied\ positive\ moment, MuPos = wu * \frac{15.83^2}{11} = 4.35\ kip - ft$$

$$Maximum\ applied\ positive\ moment, MuPos = wu * \frac{18.83^2}{12} = 5.64\ kip - ft$$

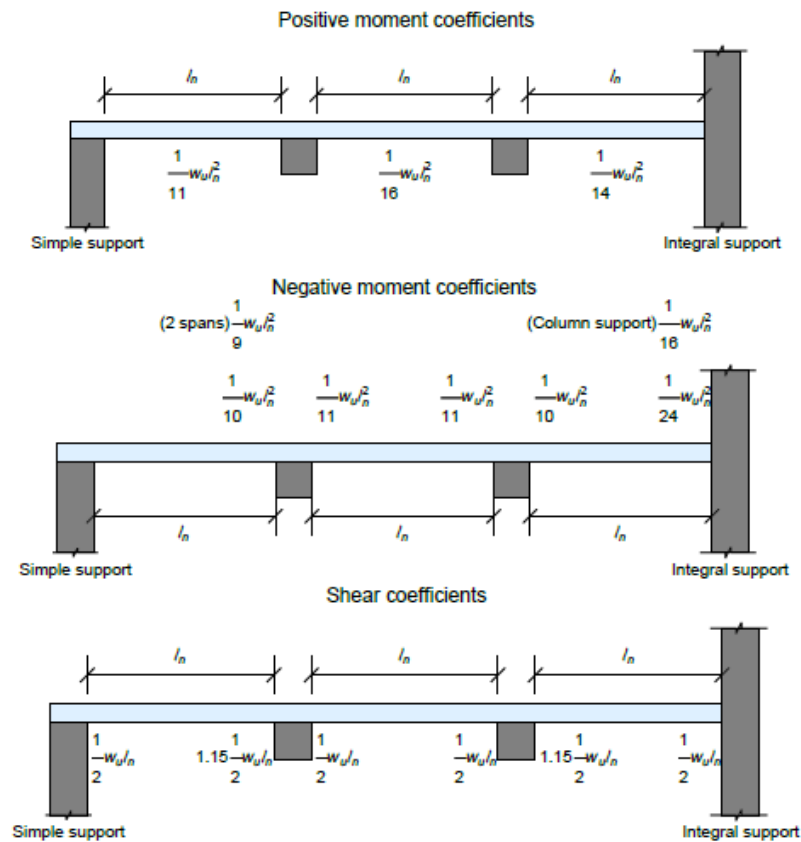$$Maximum\ applied\ shear\ force, Vu = \frac{1.15 * wu * 15.83}{11} = 1.74\ kip$$

Figure 12: ACI Design Shear and Moment Coefficients

LRFD Design Load Applied to the Slab Calculations

Appendix B – Construction Cost Estimate Details

Materials				
Item	Quantity	Unit	Cost Estimate ($) per unit	Total Material Cost ($)
Loose Soil Material and Delivery*	1,350	CY	$150.00	$202,500
Prairie Smoke	1,000	SF	$0.02	$20
Black-eyed Susan	5,000	SF	$0.02	$100
Little Bluestem	10,000	SF	$0.02	$200
Turf	12,000	SF	$0.80	$9,600
Mulch	150	CY	$30.00	$4,500
PVC Waterproofing Membrane	40,000	SF	$1.50	$60,000
Stone walkway	9,755	SF	$4.00	$39,020
Landscaping Bricks (retaining Wall)	5,700	Per	$4.50	$25,650
Landsaping caps	1,300	Per	$4.23	$5,499
Base of Multipurpose area	2,000	SF	$5.00	$10,000
Picnic Tables	6	Per	$300.00	$1,800
Benches	6	Per	$415.00	$2,490
				$361,379

Labor (time based on crew and days spent)**				
Item	Quantity	Unit	Cost Estimate ($) per unit	Total Labor Cost ($)
Waterproofers	80	Team hrs	365	$29,200
Planting (Plants / grasses / mulch)	8	Team hrs	365	$2,920
Laying Stone	60	Team hrs	365	$21,900
Assembling Terraces	95	Team hrs	365	$34,675
Installing tables / benches	4	Team hrs	365	$1,460
				$90,155
			TOTAL SUBCOST	$451,534
			TOTAL COST W/ 15% CONTINGENCY	$519,264

*includes cost of pnuematic placement

**Assuming 4 Laborers and 1 Supervisor working at $70 and $85 per hour respectively

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Appendix C – Supplemental Drawings
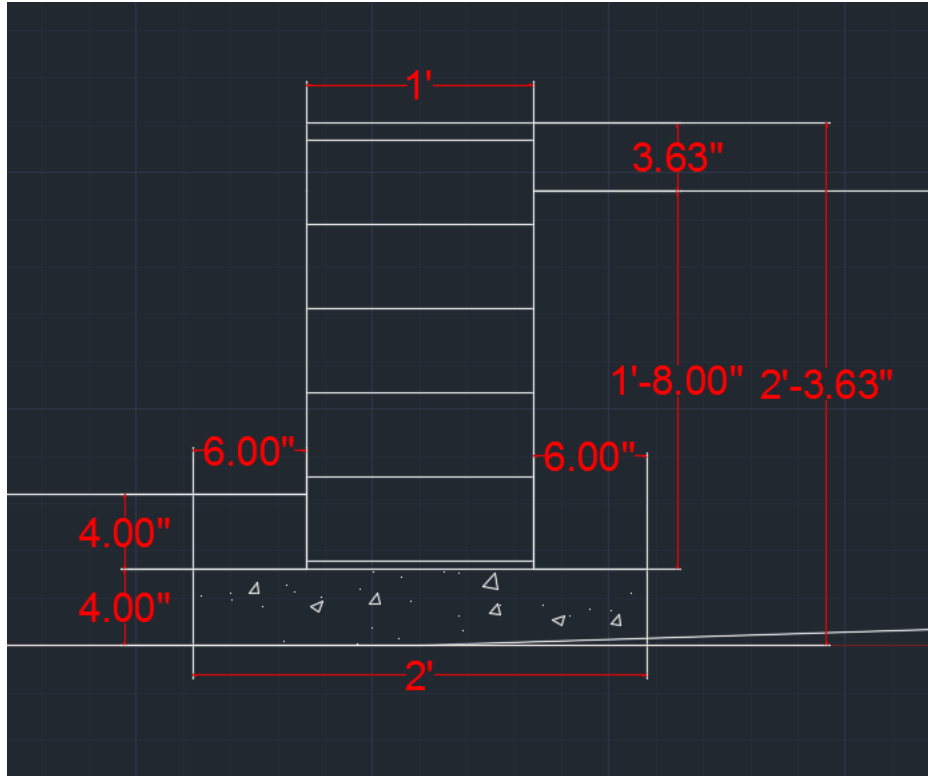

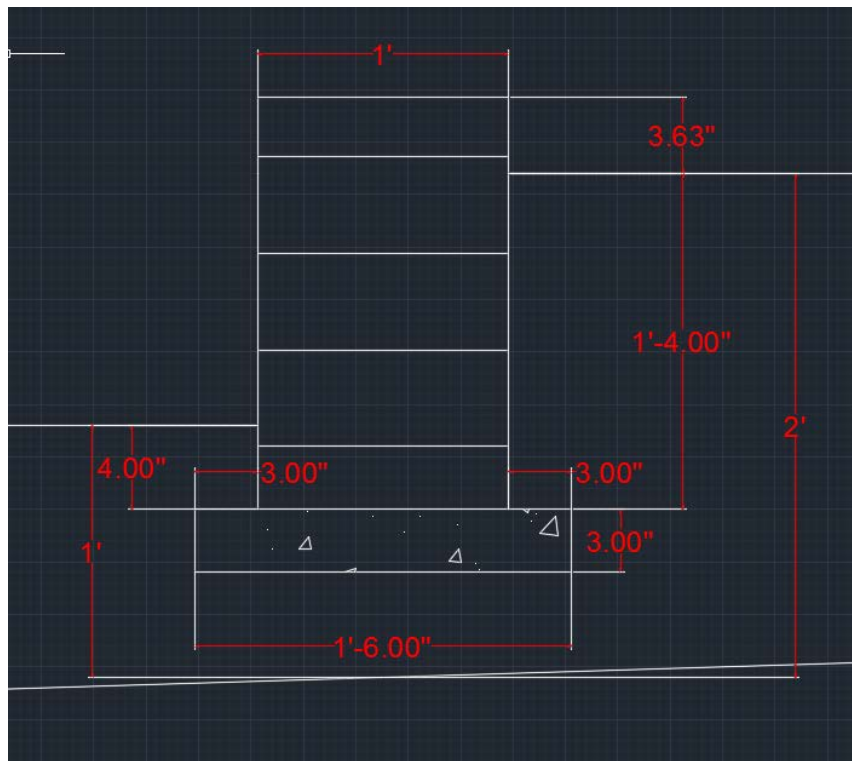Figure 13: Retaining Wall structure between end terraces and turf areas

Figure 14: Retaining wall structure between terrace levels
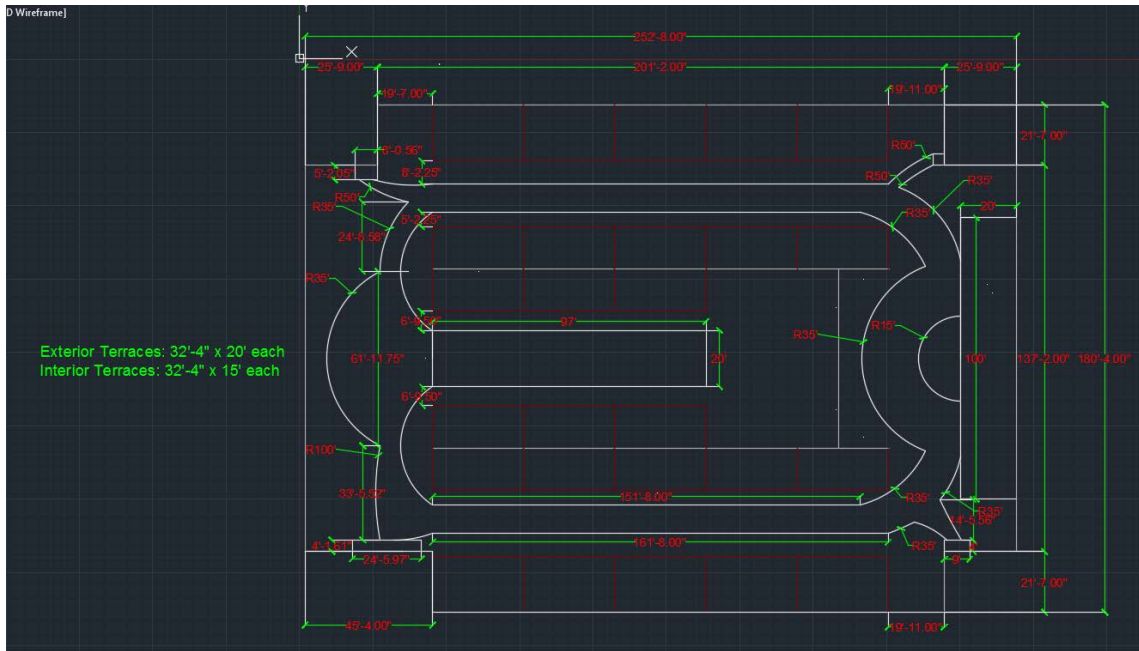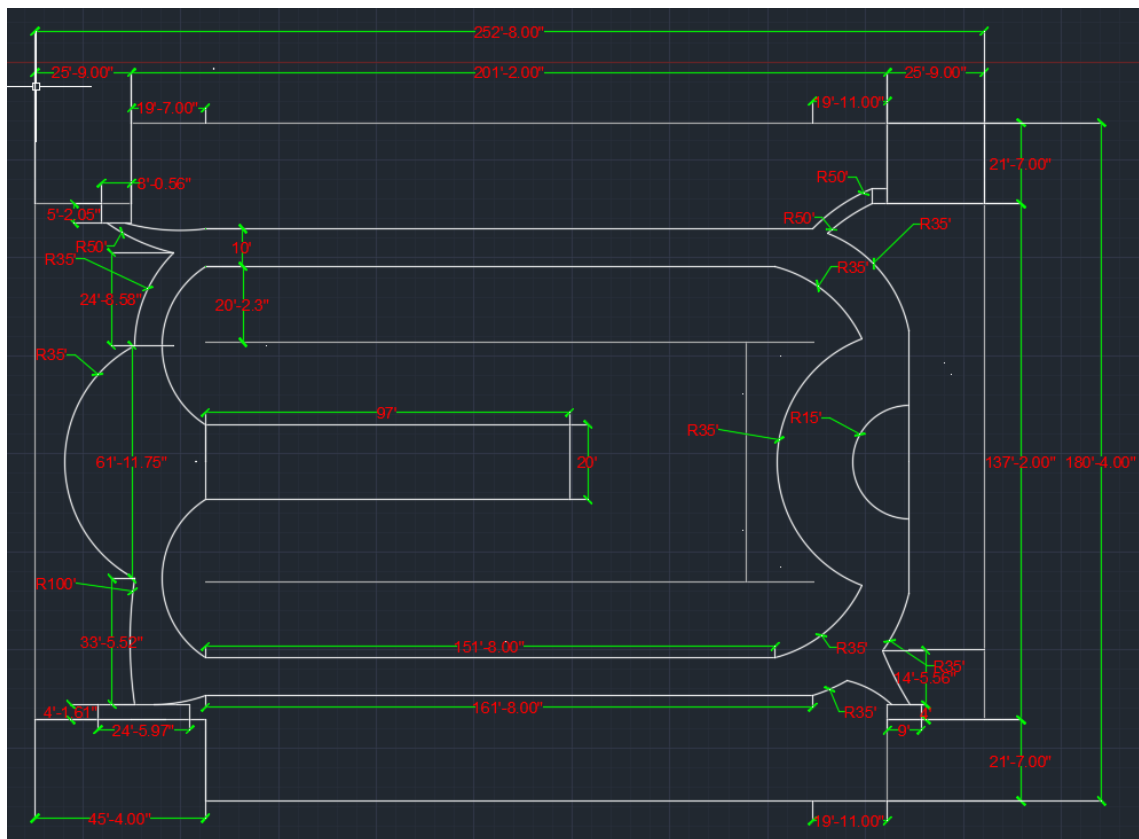
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Figure 15: Garden Design Alternative 1

Figure 16: Garden Design Alternative 2