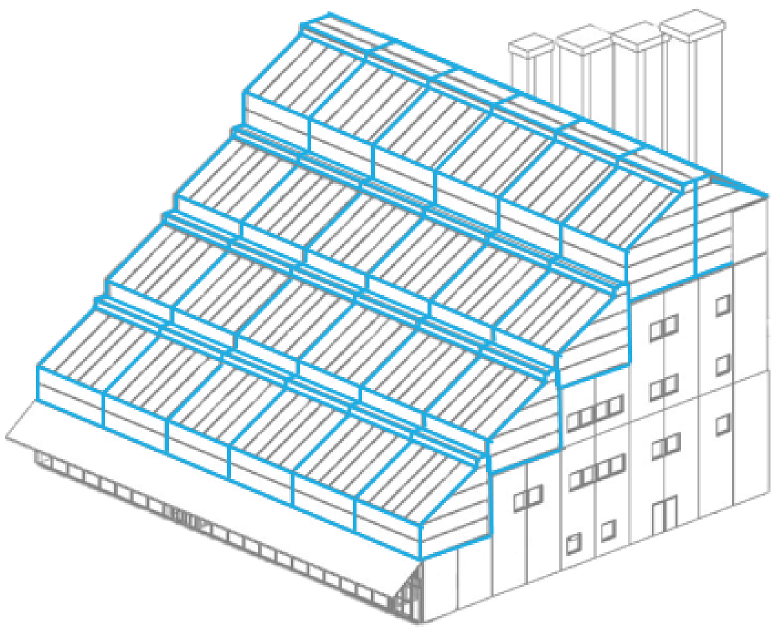
AEI STUDENT DESIGN COMPETITION

Structural Report



2-11-2015

ARCHITECTURAL ENGINEERING INSTITUTE

Synthesis
Engineering for Architecture

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Executive Summary

Having an end goal of creating an adaptable educational space capable of producing crops year round, Synthesis developed three main goals to lead the design process. These goals consisted of:

- To create an adaptable building design
- To create a self-sustaining ecosystem
- To create a great learning experience and environment

Structural Design Goals

In addition to the goals set forth by Synthesis, the structural team formulated a list of goals to achieve during the design process. These goals consisted of:

- Develop a prototype structural design, able to be used in multiple locations with minimal changes
- Develop a greenhouse design with minimal light interference
- Develop a structural layout allowing architectural freedom
- Develop a gravity, lateral, and foundation system that is efficient and economical

Gravity System

The gravity system was designed with input from multiple disciplines to ensure not only an efficient structural design, but a design that aided in the implementation of the other building systems. The building utilizes a cambered steel framed system with composite decking, allowing the structural team to design smaller members, decreases the space taken up in the ceiling plenum, and reducing the steel costs for the building.

Lateral System

The lateral force resisting system for the building utilizes Eccentrically Braced Frames (EBFs) spaced throughout the building. In areas where the EBF's interfered with the architecture, a SidePlate special moment frame configuration, was utilized. With such a unique profile, the structural design team coordinated the location of the braces with the other disciplines. The EBF's allowed for more architectural freedom in the design, without compromising the structural integrity.

Greenhouse Module

The greenhouses were an interdisciplinary collaboration between all members of the Synthesis team. A structural system satisfying the mechanical needs to create a closed loop system, while creating minimal shading in the greenhouses was necessary. By using hollow steel shape (HSS) trusses spaced at 19'-2", half a structural bay, and maximum sizes for the polycarbonate panels, shading within the greenhouses was limited.

Highlights

- *GEOPIER FOUNDATION SYSTEM*
- *ADAPTABLE LATERAL SYSTEM*
- *DEEP GIRDER FOR DIFFERENTIAL SLABS*
- *MINIMAL STRUCTURE IN GREENHOUSES*
- *HYBRID SHEAR WALLS WITHIN TOWERS*
- *REPEATABLE DESIGN*

Foundation

The building site for Growing Power consists of silty, sandy clay soils providing a very low allowable bearing capacity of 1,500 psf. To accommodate the high water table, organic material and low bearing capacity of the soil, the structural team, working closely with the construction team, implemented a soils improvement system known as Geopiers. This ground improvement led to a 400% increase in the bearing capacity, and limited the differential settlement within the building. With the increase in bearing capacity, spread and strip footings along with concrete retaining walls could be used for the foundation system.

Natural HVAC

Due to an unusual mechanical system, differential slab elevations were created on the 2nd, 3rd and 4th floors. By using a deep girder spanning between two columns, the beams at both levels were able to frame into the same member, allowing the two slabs to act as a uniform diaphragm.

The mechanical system also used air intake towers on the north side of the building. A steel structure using hybrid masonry shear walls was used to support the towers for both gravity and lateral loads.

Adaptable Design

The structural team developed an adaptable structural system through the use of:

- A Lightweight Steel Structure
- Eccentrically Braced Frames & SidePlates
- Greenhouse Modules/Structural Grid (Repeatability

1.0 Project Introduction

Project description - The 2015 AEI Student Design Competition addresses a five-story vertical farm that is being designed and constructed for a local nonprofit urban farming organization, Growing Power, Inc. The building is located at 5500 W Silver Spring Drive, Milwaukee, Wisconsin. A vertical farm is created using a tiered greenhouse approach on the southern façade of the building. Each floor steps back **(see Figure S.1)** and utilizes the available southern light in order to house aquaponic systems and grow crops which are used to sell to the surrounding neighborhoods in the retail market on the ground floor. Aside from the year round production of plants and vegetables, the facility houses classrooms, conference spaces, and a demonstration kitchen designed to further Growing Power's expanding mission to become a local and national resource for learning about sustainable urban food production.

The design of the building addresses the following challenges proposed in the 2015 AEI Student Design Competition:

1. Design and develop a sustainable building that optimizes construction, design, and lifecycle cost concepts.
2. Consider architectural and engineering modifications for a prototype building to be built in Miami, FL and possibly elsewhere
3. Provide a detailed analysis demonstrating the integration of all systems required for operation of the vertical farm

These requests, in conjunction with preliminary information provided regarding Growing Power, Inc. and its needs, led to the development of preliminary goals and design criteria for the entire Synthesis team.

FIGURE S.1: EAST FACADE SHOWING THE BUILDING STEPPING BACK

At Synthesis, the structural design was developed with the goals set forth by Growing Power as well as the goals set forth by the structural design team to create an integrated building. The structural team focused on creating an adaptable building capable of moving to differing regions and microclimates with a uniform structure that is easily moved throughout the country with minimal design changes. There was also a focus on developing a modular structural design that could create a self-sustaining ecosystem by limiting the amount of sunlight interference for the crops within the greenhouses. To create a good learning environment, floor vibrations were evaluated and limited within educational and office space to avoid distractions.

2.0 Project Goals

The Synthesis Structural team emphasizes engineering systems and spaces that are not only functional, but also align with the projects overall shared goals. They include:

Educational

Synthesis is committed to engineering an environment for Growing Power that promotes a meaningful learning experience for everyone who visits the Vertical Farm.

Ecological

The structural system should consider its internal impact on other building systems and occupants while also taking into account the external effect it has on the environment.

Adaptable

Strong emphasis has been placed on designing a prototype building that is easily adjusted to new building conditions, emerging technologies, and geographical environments.

3.0 Integration

Throughout the project, the structural team was an integral part in the entire design of the building. The structural team was relied upon to deliver an efficient structural system that brought out the features of the other building systems, and eliminated architectural interference. Major areas of integration involving the structural team include the architectural redesign, greenhouse design, natural HVAC system, and the building enclosure. Detailed information on how the structural team collaborated with all of the other design teams at Synthesis can be seen in the **[Integration Report]**.

An area where all disciplines came together to create a fully integrated building was with the architectural redesign. The plans from the original design were reviewed by each discipline to determine if the engineering systems being implemented would work with the current floorplans. From here, the plans were altered while keeping the original program to create a building where all of the engineering systems could be optimized within the architecture. An area of the redesign that the structural team had major input on was within the gathering space. The structural team was adamant on having this space fall between two column lines to give more view lines to the front of the room. The full architectural optimization and plans can be seen in the **[Integration Report]**.

4.0 Codes & Standards

Prior to design, local building codes for Milwaukee and Miami were researched to find that both areas followed the 2009 International Building Code (IBC). From the 2009 IBC and the special local codes in Miami, many other codes and manuals were referenced to be used during design in these jurisdictions. These codes and manuals include, ASCE 7-05, ACI 318-08, AISC 13th Edition, and MSJC 2008. For a further break down of the codes and standards used, please refer to Appendix B.

5.0 Computer Software

For the structural design of 5500 W. Silver Spring Drive, multiple programs were used throughout the design process along with hand calculations to supplement and verify the outputs. To start, Microsoft Office was used to develop preliminary dead, live, wind, and seismic loads. A basic structural layout was then developed through Revit by laying out possible beam and column locations on the architectural model. Once this layout was established, it was recreated in RAM Structural System to analyze and verify the gravity, lateral, and footing design. To aid in further refinement of the lateral system, the lateral force resisting elements were input into and analyzed using ETABS. RISA 2D was then used to start developing an efficient truss for the greenhouses. Subsequently, STAAD was being used to analyze the towers on the north side of the building. Revised structural plans were updated in the Revit model as different aspects of the design were completed to keep all design disciplines collaborated. A breakdown of the programs and their uses/purposes can be seen in Table S.1.

TABLE S.1: COMPUTER PROGRAM USAGE AND PURPOSES

Software	*Usage/Purpose*
Microsoft Excel	Dead Loads
	Live Loads
	Wind Loads
	Seismic Loads
Revit	Initial Structural Layout
	Final Structural Layout
RAM Structural System	Gravity System Analysis & Design
	Lateral System Analysis &Design
	Footing Analysis & Design
ETABS	Lateral System Analysis & Design
RISA	Truss Analysis
STAAD	Chimney Analysis

6.0 Structural System

By working with the other design disciplines at Synthesis, an effective structural system was developed to maximize the benefits for all designers involved. With this in mind, a composite steel superstructure with 3-¼" of lightweight topping on 2" metal decking was used to establish to:

- Reduce Costs
- Create Extra Plenum Space for the Mechanical Return Air Plenums
- Provide Fireproofing within the Decking
- Reduce the buildings weight.

The steel superstructure then carried over to the structural design of the greenhouses. With steel in the greenhouses member sizes could be reduced allowing more light transmittance and lower costs. By using steel coated with intumescent paint to provide fireproofing and reduce corrosion the structure could tie directly into the main buildings superstructure without corrosion issues that occur with aluminum tying into steel.

To resist lateral forces, a combination of eccentrically braced frames, moment frames, and hybrid shear walls were used in design. Eccentrically braced frames were used within interior partitions where the architecture allowed because of their high response modification factor when placed in seismic regions. Moment frames were then used to supplement the eccentrically braced frames in areas where the architecture could not be interrupted. Hybrid shear walls were used in the towers since the steel superstructure was already being infilled with CMU block for insulation purposes.

For the substructure of the building, a system of Geopiers to increase the bearing capacity along with spread and strip footings were implemented. By using Geopiers the bearing capacity of the soil could be increased from 1,500 psf to 6,000 psf, greatly decreasing the size of the footings. To resist the high lateral pressures experienced due the high water table, concrete retaining walls were used around the perimeter of the basement.

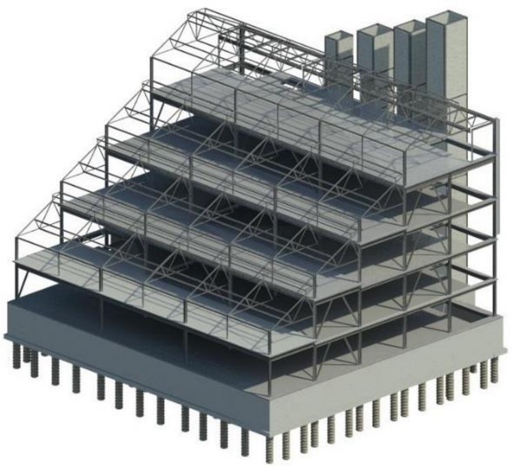

FIGURE S.2: OVERALL BUILDING STRUCTURE

7.0 Design Process

To create an adaptable building, the structural engineers decided a light-weight structure was needed to ensure the building was capable of moving to areas with high seismic activity. It was also important to limit the impact of the structural system on the architecture and other systems in the building. Thus allowing for more freedom with the layout of the interior spaces of the building when moving from site to site. Upon review of the geotechnical report, it was confirmed, due to the low bearing capacity of the soil that a light-weight structure was advantageous, if not a necessity. After looking at the main structural systems, a steel superstructure was selected.

To develop the best structural system, a structural layout with limited architectural interference of the structure was placed on the architectural floor plans. After the layout was developed with all other design disciplines in mind, hand calculations were done on a typical bay in wood, concrete, and steel. Wood was quickly ruled out due to its inability to span large distances efficiently, poor performance in areas with high heat and humidity, and for code purposes. Once wood was eliminated, further analysis on a concrete, a precast, and a steel super structure was done for a typical bay and they yielded similar member depths for beams and girders. It was found that concrete and precast would be more economical for the overall super structure, but weighed significantly more and would increase the construction schedule. With all of these considerations in mind, a steel superstructure was decided upon to achieve a light weight structure that could be constructed in seven months, minimizing the need for exterior construction during winter time. For more information on the schedule of the building, see Appendix E in the **[Construction Report]**.

As the structural team at Synthesis began developing a lateral force resisting system for the building, the goal was to hide the elements within the existing architecture. Four main ideas were developed for resisting the lateral forces in the beginning of design. These included 1) concentrically braced frames, 2) eccentrically braced frames, 3) moment frames, and 4) hybrid shear walls. Through early design, it was found that with eccentrically braced frames, the building could easily be moved to seismic regions, due to the higher response modification factor, while having minimal effects on the architecture as compared to concentrically braced frames while performance was maintained. Moment connections were found to be the least efficient and most expensive method of resisting the lateral loads but they had no interference with other systems within the building. Shear walls were found to be the most efficient but were also the most obtrusive to all of the other systems and spaces.

After deciding the best placement for lateral force resisting elements by reviewing the floor plans, the structural team decided that implementation of three of the original four systems was most effective for all design teams on the project. A combination of eccentrically braced frames and moment frames were strategically placed to eliminate any clashes with the architecture and mechanical equipment. Since moment frames were determined to be the least efficient method to resist lateral loads, they would only be used in open areas such as the gathering space. To allow for reduced loads in seismic regions, it was decided that the ordinary moment frames could be switched to special moment frames as needed. Since the steel in the towers on the north side of the building needed to be infilled with masonry blocks to raise the insulation value, it presented an opportune place to implement hybrid shear walls. By using the infill walls to resist lateral loads in the towers, braces were not needed, this made it easier to construct the masonry without having to work around a brace.

Another major structural design process that occurred for the building was the foundation system. Even with the poor bearing capacity from the soil, the geotechnical report recommended using typical spread and strip footings to support the superstructure. Through analysis and preliminary sizing of these footings, it was found that due to the high gravity loads in the building, and the poor bearing capacity the footing sizes were large and overlapped with one another. Due to the inefficiency of the spread footings, the structural team looked into a mat slab foundation to support the building. The idea was then proposed to the construction team at Synthesis for their opinion on the situation. From research, it was found that the mat slab was going to be expensive due to the amount of concrete needed for the foundation, and a more economical solution would be preferred. Therefore, more research was done which established the idea of ground improvement techniques through soil strengthening (namely Geopiers). After an investigation into the idea of ground improvement, it was determined that the initial bearing capacity of 1500 psf could be increased to 6000 psf. This large increase in the bearing capacity allowed for the economical use spread and strip footings.

8.0 Load Analysis

8.1 Gravity

By breaking the building into two sections (non-greenhouse and greenhouse) in combination with using ASCE 7-05 and IBC 2009, gravity loads were developed for the building. The non-greenhouse portions of the building were designed for a minimum reducible live load of 80 pounds per square foot (psf) for a typical bay since code requires this load for a corridor above the first floor. While 80 psf is conservative in some areas, a typical office has a load of 50 psf with an additional load of 20 psf for movable partitions, which is only slightly less than the 80 psf used for a typical floor. This also allowed for changes within the floorplans without compromising the structural integrity. In areas, such as the gathering space and breakout space, a higher unreducible live load of 100 psf was used to allow for assembly with movable seating. The design dead load for the non-greenhouse portion was a total of 67 psf with a 1 kip per linear foot load along the perimeter for the architectural precast building façade. Table S.2 shows a further breakdown of the components contributing to the dead load for the non-greenhouse portion on the building.

To allow for the movement and incorporation of aquaponic tanks in all greenhouses, a higher unreducible live load of 150 psf was used. Thus giving the owner of Growing Power the option to add more or move the tanks during the lifetime of the building. The dead load within the greenhouses was also determined to be 150 psf due to the increased weight of the structural members, and the additional loads due to equipment needed for multiple purposes within the greenhouses.

TABLE S.2: DEAD LOAD FOR NON-GREENHOUSE PORTION OF THE BUILDING

Component	Weight
Beam Self Weight	7psf
Concrete and Metal Deck	42 psf
Mechanical Allowance	5 psf
Lighting/Electrical Allowance	5 psf
Floor Allowance	8 psf
Total	67 psf

8.2 Wind

To determine the initial wind pressure experienced by the building, Main Wind Force Resisting System (MWFRS) was used with the parameters specified in Table S.3:

TABLE S.3: WIND LOADING PARAMETERS

Milwaukee Wind Parameters	Value
Risk Category	III
Importance Factor	1.15
Basic Wind Speed, V	90 mph
Wind Directionality Factor, K_d	0.85
Exposure Category	C
Velocity Pressure Coefficient, K_z (At top roof level)	1.20
Topographic Factor, K_{za}	1.0
Gust Effect Factor	0.85
Enclosure Classification	Enclosed
Internal Pressure Coefficient, GCpi	$\pm$ 0.18

Once a structural system was selected, further wind analysis was done through computer modeling.

8.3 Seismic

To determine the initial magnitude of the seismic loads, Equivalent Lateral Force (ELF) procedure was adopted. This analysis was done using the parameters in Table S.4 on the following page:

Table S.4: Seismic loading parameters

Milwaukee Seismic Parameters	Value
R	7
S_s	0.107
S_1	0.045
S_{ms}	0.168
S_{m1}	0.105
S_{ds}	0.179
S_{d1}	0.104
T_L	12
T_s	0.581
I_e	1.25
Seismic Design Category	B

8.4 Comparison of Lateral Loads

After developing the lateral system and structure of the building, final lateral loads for seismic and wind were calculated, as shown in Table S.5. Through comparison it was determined that wind loading controlled for the Milwaukee site in both the N-S and E-W directions.

Table S.5: Comparison of factored story forces

Un-Factored Story Forces			
Level	Wind (N-S)	Wind (E-W)	Seismic (R = 7)
1	26.86 kips	22.70 kips	0 kips
2	49.26 kips	24.88 kips	19.61 kips
3	51.77 kips	21.73 kips	26.09 kips
4	54.26 kips	18.30 kips	28.43 kips
5	33.19 kips	11.26 kips	21.75 kips
Top Greenhouse	28.81 kips	9.78 kips	0 kips
Base Shear	244 kips	109 kips	95.9 kips
Overturn Moment	14,038 ft-k	6,254 ft-k	6,596 ft-k

9.0 Greenhouse Design

9.1 Overview

A modular design was implemented for the greenhouse spaces to create a repeatable and adaptable design (see Figure S.3). This allows for more flexibility in the structural design of the prototype structure.

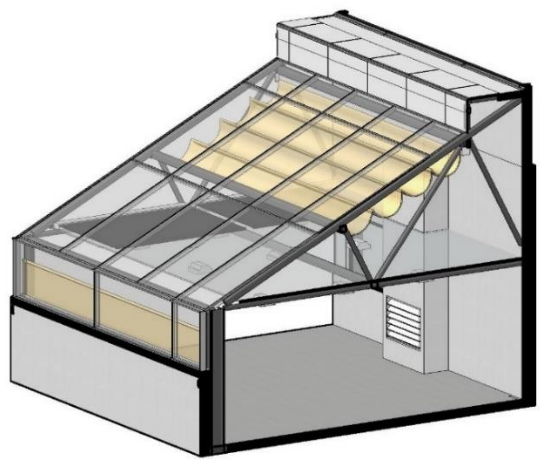

Figure S.3: Greenhouse Module

Growing Power plans to utilize all five levels of the greenhouse space, with the intent to maximize growth potential in these spaces. The structure was designed to maximize the open area and crop output for these spaces. The overall design of the module was a collaborative process between all options and is outlined in detail in the **[Integration Report]**.

9.2 Truss Design

With the greenhouses employing a modular aspect, in heating, cooling, lighting and construction, the structural team wanted to carry this over to the structure**.** The trusses are design to support not only polycarbonate panels that make up the roof glazing system, but also the polycarbonate ceiling that acts as a divider for the mechanical system in the greenhouse modules (see Figure S.4).

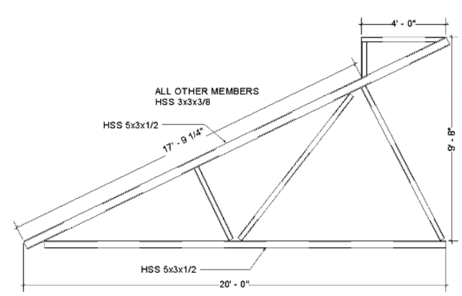

Figure S.4: Greenhouse Truss

The trusses are spaced at 19'-2", half a structural bay in the east-west direction. This spacing corresponds to the size of one module, as determined by the mechanical and structural limitations. If the building were to move to a more constrained site, a structural bay on the building could simply be removed/added without the need to redesign the greenhouse spaces to accommodate this. The amount of greenhouse modules can be adjusted accordingly. See **[Integration Report]**

The truss design went through a number of configurations before settling on the current configuration, a modified Fink truss. The structural team worked with the construction and lighting teams to come up with a design that was cost effective, as well as minimal in the amount of shading it created, and structurally adequate. For more information on the design process, see Appendix D**.**

9.3 Aquaponics

Knowing that flexibility is an important part of the greenhouse layout at Growing Power, the structural team designed the greenhouse bays to support high live loads to accommodate aquaponics tanks. The structural team designed for up to one 500 gallon tanks for every two modules, with the ability to be placed anywhere in the greenhouse.

9.4 Glazing System

For the glazing system, the structural team wanted something lightweight, as well as durable, and strong enough to span the entire greenhouse module. A polycarbonate panel system was decided on with a flush glazing mullion system. Flush glazing is a system in which the framing members are set entirely behind the panes to create a flush exterior face. The panels are attached to the framing through the use of structural silicone sealant. The flush glazing allows for a more architecturally pleasing appearance, as well as allowing for easy maintenance, should a panel ever be damaged. For more on the glazing system, see Appendix D.

9.5 Lateral Design

The greenhouse structure is tied into the main Lateral system for the rest of the building, eliminating the need for a separate system. The trusses are attached at the upper level's diaphragm, sending all wind load directly into the building's main LFRS.

10.0 Gravity Design

10.1 Overview

In the beginning of design the structural team at Synthesis completed analysis to develop an efficient gravity system. Through research, it was found that a lightweight gravity system was going to be beneficial for a prototype building such as the one presented at 5500 W. Silver Spring Drive. Therefore, a layout utilizing a cambered composite steel superstructure with typical bay sizes of 20' x 38'-4" (see Figure S.5) was generated, creating uniform beam sizes throughout the whole building. Due to the ceiling plenum being used to exhaust air, a size restriction of 16 inches was placed on the beams and girders in the portion of the building utilizing a raised access floor. A minimum member depth of 12 inches was used due to allow for three bolt connections. Thus creating a range of member sizes from W12x16's to W16x40's within a typical bay in the non-greenhouse portion of the building and a range of W21x44's to W24x62's in a typical bay within greenhouse portion of the building. Due to stair openings and a difference in slab elevations, larger members were used where necessary. Throughout the gravity design, there were regular conversations with the construction team to ensure that the design was constructible, and that beams did not exceed the capacity of the crane. For a full crane analysis, see Appendix H in the **[Construction Report]**. A full gravity layout can be seen in drawings S1.10 through S1.50.

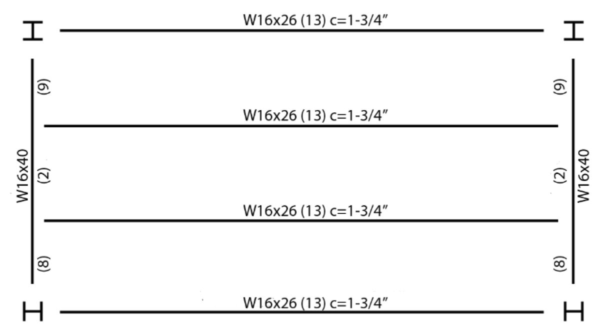

FIGURE S.5: TYPICAL BAY

10.2 Composite Design

By using a composite deck system, member sizes were able to be reduced, allowing the structural team to meet its maximum member size limitations easier. Vulcraft's 2.0VLI18 composite decking with 3 ¼" of lightweight concrete topping along with 4 inch composite studs were used to reduce the overall weight of the building. By using 3 ¼" of lightweight concrete on 2" deck a total slab thickness of 5 ¼" was developed, providing the system to have a 2-hour fire rating with no additional fireproofing.

10.3 Cambers

To reduce member sizes cambers were applied to many deflection controlled members within the building. By implementing cambered beams, it saved a significant tonnage of steel needed for the superstructure by not having to bump member sizes up to meet the deflection criteria of L/360. Also, with cambered beams, it allowed for construction to be done without having to shore the beams. Without shoring, the cost and schedule of the building cost be greatly reduced.

10.4 Raised Access Floor

Due to the unconventional mechanical system being used on the 2nd, 3rd and 4th floors of this building, differential slab elevations were created along column line 2 as well as between the greenhouse and non-greenhouse sections of the building (see Figure S.6).

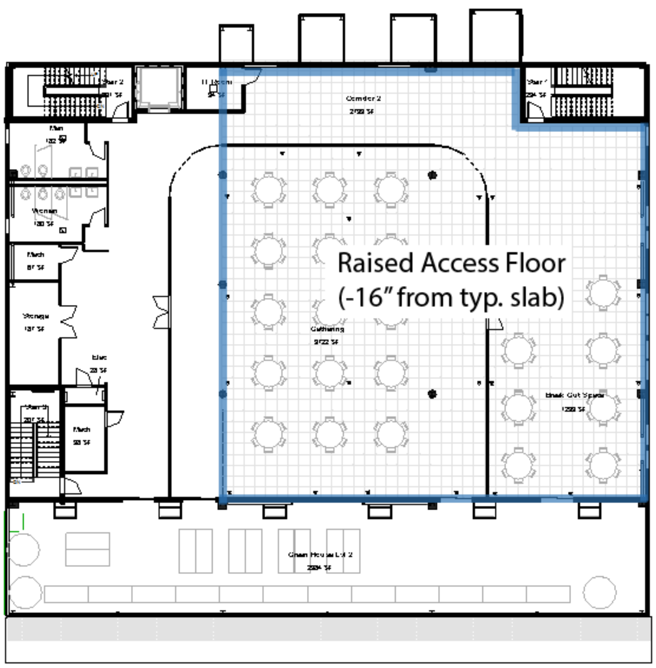

FIGURE S.6: RAISED ACCESS FLOOR LOCATION

This created a preferred column line capable of picking up the load from each elevation. Once the column lines were developed and optimal beam placement was selected, the structural team had to develop an effective way to pick up both beams. Through multiple design iterations and conversations with the construction team, it was found that a deep beam (W33x118) along column line 2 was the most economical solution to the problem. In the transition from the greenhouse to the non-greenhouse portion of the building, the designed beam (W21x44) was capable of supporting both slabs. A detail showing how the differential slabs are supported at each transition can be seen in Figure S.7 and Figure S.8.

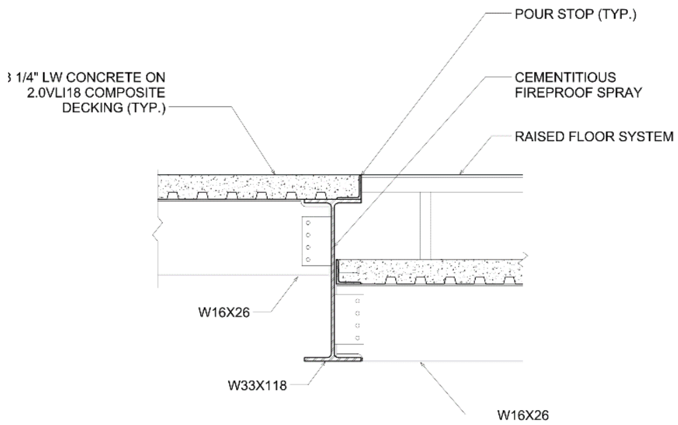

FIGURE S.7: DIFFERENTIAL SLAB ELEVATION NORTH-SOUTH

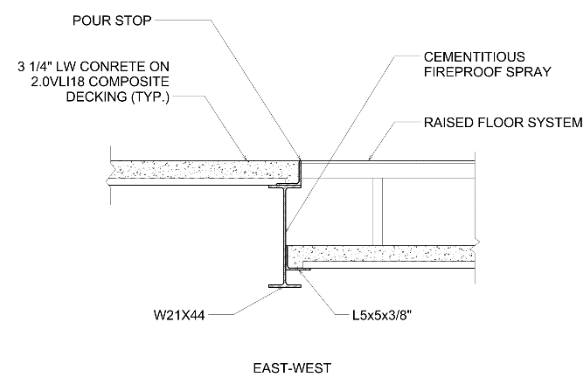

FIGURE S.8: DIFFERENTIAL SLAB ELEVATION EAST-WEST

10.5 Connections

When designing the member connections for the building, the structural team wanted to design an efficient and constructible connection. Working closely with the construction team, it was determined that shear end plate connections with coped beams would be the best choice to meet these goals. To reduce labor cost in the connections, bolted connection were used as opposed to field welds. In instance where a welded connection was needed, a majority of them would be done off site to ensure labor efficiency. With these considerations in mind, the structural team at Synthesis designed and detailed a number of typical connections. An example of a connection within the greenhouse can be seen in Figure S.9.

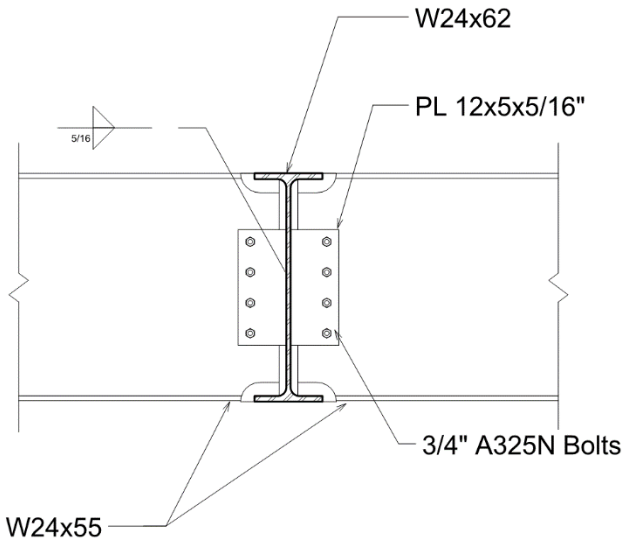

FIGURE S.9: TYPICAL GREENHOUSE BEAM TO GIRDER CONNECTION

10.6 Equipment Access Panel

To create a serviceable building, access to the equipment in the basement of the building was a necessity. Therefore, since it could not be accessed from the exterior of the building, a panel needed to be designed to allow for the large equipment to be removed and replaced at some point during the lifetime of the building. To service this equipment, a 12'x13' removable section of the floor was framed just inside the loading dock for equipment to be lowered into, or removed from the basement (see Figure S.10). By using a 12' dimension, three four foot wide by eight inches thick prestressed precast panels could be placed over the opening, allowing for them to be lifted out of place when needed. With the precast panels being thicker than the decking system, the beams within this bay were lowered to support the precast panels and built up to support the floor decking. A 2-¼" topping was then be placed over the panels to bring the levels back to the same elevation, and give the panels a finished look (see Figure S.11).

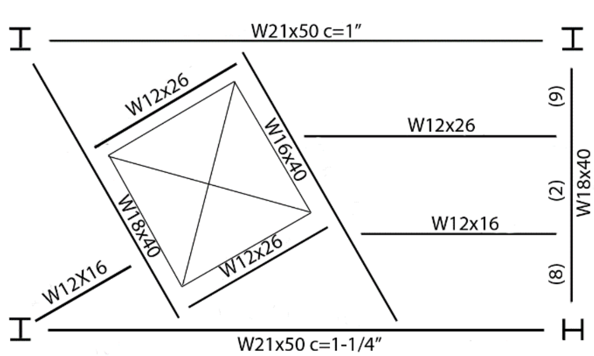

FIGURE S.10: EQUIPMENT ACCESS PANEL FRAMING

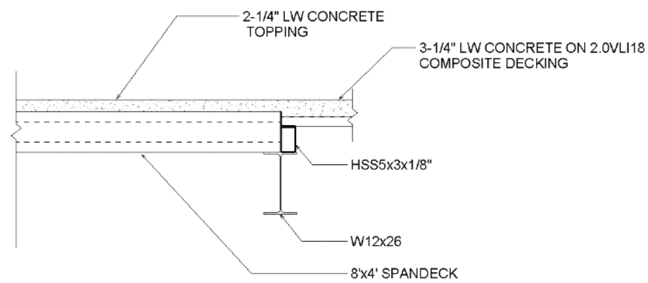

FIGURE S.11: EQUIPMENT ACCESS PANEL

10.7 Vibrations

Since member sizes were reduced by using a lightweight composite deck, floor vibrations were a major concern for areas such as the classrooms and offices. Therefore, having the chance of making the spaces unusable due to the distractions possible in these areas. Vibrations analysis was done using Design Guide 11 on a typical bay within the classrooms and offices. It was found that the most efficient gravity design, with a W16x26 beam framing into a W16x40 girder limited the amount of vibrations to an acceptable range. For calculations on vibrations analysis, see Appendix F.

11.0 Lateral Design

11.1 Overview

The structural team focused on designing an adaptable lateral system for this prototype building. The structure needed to be able to be moved to high wind and seismic regions with minimal changes needed in the design to have an adaptable lateral system. Therefore, since it is rare for a building that is less than 10 stories tall to be greatly affected by wind, a lateral force resisting system consisting of eccentrically braced with supplemental moment frames was implemented. With a total of three frames in the east-west direction, and a total of four frames in the north-south direction the maximum drift the building experienced during wind or seismic conditions was 1.53". To eliminate architectural interference, brace sizes were limited to 5" wide so they would fit within an interior stud wall. The locations of the lateral force resisting system elements were laid out to eliminate as much additional torsional loads by limiting the eccentricity (See Figure S.12**)**. Elevations and member sizes can be seen in the structural drawing on S2.00.

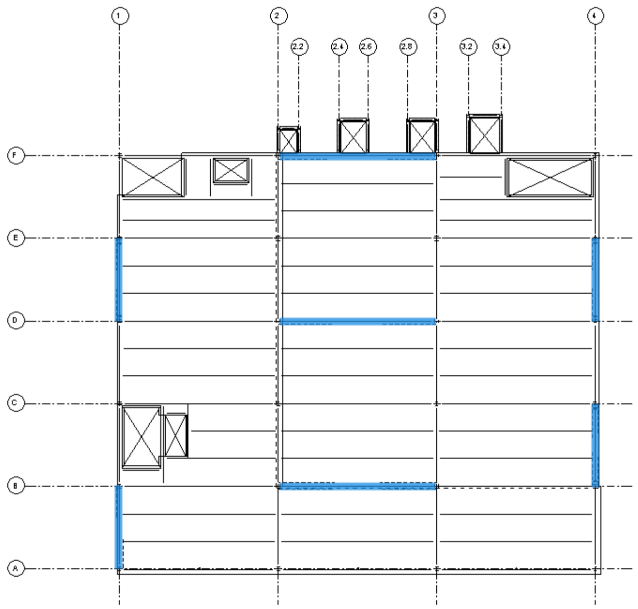

FIGURE S.12: PLAN OF LATERAL FORCE RESISTING FRAMES

11.2 Eccentrically Braced Frames

From preliminary calculations, it was found that seismic loading would control if a lateral system utilizing a lower response modification factor was used. Therefore, eccentrically braced frames without a moment connections away from the link were used. With these frames, less space within the partitions was taken up, allowing more flexibility for the placement of window and door openings. These frames were also able to be hidden within the architectural stud walls by limiting the width to 5". With a high response modification factor of 7, eccentrically braced frames have been found to perform admirably in seismic regions. For the Milwaukee site, the braces connected to the beams at 1/3 the distance of its span. This configuration created beam sizes ranging from W16x40's to W24x62, braces sizes ranging from HSS 3x3x3/8" to HSS 7x5x½", and column sizes ranging from W10x39 to W10x88. When moving this building to seismic regions, the braces could be made more efficient by shrinking the size of the link between the two braces. However, it will have more of an impact on the openings within the architectural design.

11.3 Special Moment Connections

In certain areas, such as the gathering space, and loading docks, braces could not be used since they would block views and openings within the building. Therefore, moment frames needed to be utilized to avoid interrupting the everyday operation of the building in these areas. The only problem was that a typical moment frame only has a response modification factor of 3.5. Dropping the response modification factor from the highest ordinary moment frame down to the lower of the two response modification factors. To increase the R-factor to 8, a complicated connection needed to be designed to be deemed a special moment frame. Therefore, research was done on connections that could achieve a minimum factor of 7 so that they would be at the same value as the eccentrically braced frame. Through this research, it was found that SidePlates (See Figure S.13), a newer technology, could achieve an R-value of 8 without the cost and construction implications of a special moment frame. Therefore, the ordinary moment frames were replaced with SidePlate connections without compromising the effectiveness of the eccentrically braced frames. The beams columns on bays utilizing these special connections ranged from W16x26 to W24x55. On sites where seismic loading won't control, such as Miami, SidePlate also produced a more economic connection with an R-value of 3.5 which can be utilized to save construction costs.

FIGURE S.13: SIDEPLATE CONNECTION (COURTESY OF SIDEPLATE)

11.4 Deep Beam

With differential slab elevations on the 2nd, 3rd and 4th floors, a monolithic slab was not created to transfer the lateral loads into the lateral force resisting elements. Therefore, it was a necessity to ensure that these slabs work together to get the loads to the resisting elements. This was a major deciding factor when choosing a deep beam to pick up the deck from each elevation. With both slabs connecting into the same beam, lateral loads could be transferred from one slab to the other through the beam. Thus generating proper diaphragm action on these floors allowing for the load to properly get to the lateral frames. On sites where high seismic loads are experienced, a kicker would be introduced to aid in the transfer of lateral forces to avoid the deep beam from rolling. Reinforcing within the slab would also be introduced in areas of high stress for regions that experience excessive lateral loads.

11.5 Drift

While the code does not state any drift requirements for structure under wind loading, the structural team wanted to use a standard practice of limiting the building deflections to h/400 for the building as a whole, and for each story. From chapter 16 in the IBC it was found that the allowable drift due to seismic loads is equivalent to $0.015h_x$. The allowable and actual drifts for each story and shown in Table S.6. As seen in the table, the allowable story drifts were met for the building.

TABLE S.6: DRIFT REQUIREMENTS

Drift Control			
Story	Allowable Wind Drift	Allowable Seismic Drift	Worst Case Drift
2	0.43”	2.58”	0.39”
3	0.41”	2.46”	0.32”
4	0.41”	2.46”	0.34”
5	0.41”	2.46”	0.28”
Top Greenhouse	0.36”	2.16”	0.19”
Total Structure	2.02”	12.12”	1.53”

11.6 Hybrid Shear Walls

Originally, it was believed that by using the infill walls within the stair and elevator towers as hybrid masonry shear walls was going to be an effective way to resist lateral loads. Due to the desire to keep the center of rigidity close to the center of mass it was found that braced frames and SidePlates were the most efficient lateral system for the Milwaukee site. To incorporate shear walls, additional connections needed to be done, increasing the duration of the schedule unnecessarily when the loads could be taken care of efficiently through other means. While the Milwaukee site does not incorporate hybrid masonry shear walls, it is an option to include on other sites to resist higher lateral loads with little changes needed to the original lateral design of this prototype building. More information on hybrid shear walls in 13.4 for the tower design.

12.0 Foundation Design

12.1 Geotechnical Report

From the geotechnical report, it was found that through multiple borings drilled to 15’ that the soil on site was not desirable. Many of these bores experienced water levels as high as 5’ below surface level. Meaning a high water table was present at the site. Through soil analysis, it was also found that the bearing capacity present on site was only 1,500 psf. The soil was also found to have as much as 80% organic material in some areas, leading to possible settlement issues if all of the organic material was not removed and filled with new material. With the basement of this prototype building being close to the depth of the borings it was a concern that more organic material could be present below the 15’. Considering all parameters in the geotechnical report, the report recommended using a system of spread and strip footing with a minimum dimension of 24” to support the building.

12.2 Overview

Once the gravity and lateral systems were designed, the loads experienced by the foundations could be developed. With large bays and high dead loads in the greenhouses, a considerable amount of load was being transferred to the foundation of the building. The poor soil conditions presented in the geotechnical report did not allow for typical spread footings to be used because they overlapped with one another. Through many design iterations, as explained in the design process, it was deemed that utilizing ground improvement through Rammed Aggregate Geopiers was the most economical solution for the foundations system. With improvement in bearing capacity through employing Geopiers, typical spread and strip footings could be used to support the column and concrete foundation wall loads. A typical spread footing ranged in size from 4’x4’x1.5’ to 11’x11’x3’, and a typical strip footing was 2.5’x1.5’ deep. Due to the high water table present on site, the foundation walls experience a large hydrostatic pressure, producing foundation wall ranging from 16” to 19” thick.

12.3 Ground Improvement

With the poor bearing capacity of the soil present at the site it was advantageous to increase the soils strength through ground improvement. Thus meaning a system of 30” Geopiers would be placed underneath the spread and strip footings, quadrupling the usable bearing capacity from 1,500 psf to 6,000 psf with minimal impact on the cost and schedule of the project. With this increase in capacity, spread and strip footings were the most economic choice.

Geopiers are an intermediate foundation that uses rammed aggregate to increase the bearing capacity on site. Through research, it was found that the building site was an optimal place to utilize Geopiers.

For the installation of Geopiers, the process begins by drilling a hole in the soil. Once the hole is drilled, 12" lifts of aggregate are placed into the hole and rammed into place to develop lateral stresses. This process is then repeated until the cavity is completely filled, building up stresses within the component (See Figure S.14). This increase in lateral stresses improves the strength of the soil considerably (See Figure S.15). Once all Geopier elements are then in place, shallow foundations can be poured over the intermediate foundation system.

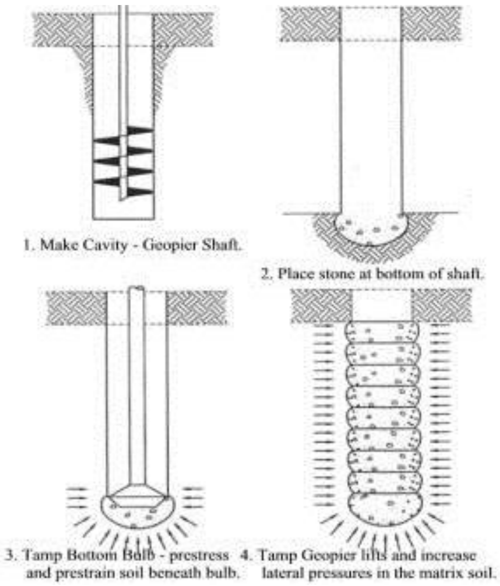

FIGURE S.14: INSTALLATION PROCESS OF RAMMED AGGREGATE GEOPIERS (COURTESY OF FARREL DESIGN-BUILD COMPANIES INC.)

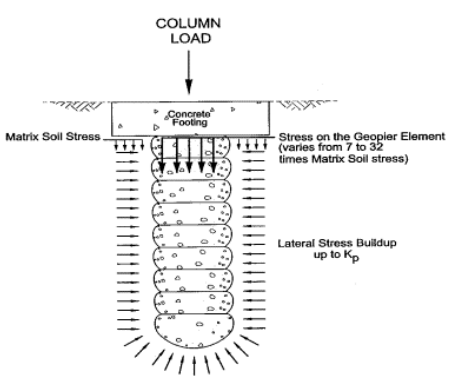

FIGURE S.15: BUILD-UP OF STRESSES IN RAMMED AGGREGATE GEOPIERS (COURTESY OF GEOPIER.)

It was found through research that to achieve a bearing capacity of 6,000 psf a Geopier was going to be needed for every 100 kips of load, or a 12' maximum spacing on strip footings. An overall load for each column was calculated and divided by 100 kips to determine the number of Geopier elements needed for each spread footing, ranging from 1 to 9. For the total amount of ground improvement elements for each specific column see Appendix I. A total of 131 Geopier elements, costing about $65,000, were needed for this building based off of the column loads, and a 12' maximum spacing of the components for strip footings.

Geopiers have also been found to help limit the amount of settlement present within buildings. With organic materials present on site, there was an increased chance of differential settlement. This was extremely important for this site because the borings were at the same level as the foundations. Therefore, with the unknown nature of the soil lower than 15' below grade the structural team assumed that organic material was still present and could lead to differential settlement if not dealt with.

12.4 Spread and Strip Footings

With ground improvement increasing the bearing capacity of the soil to 6,000 psf, the original foundation recommendation from the geotechnical report was plausible for this prototype building. Therefore, typical spread and strip footings were used to support the superstructure of the building.

Once the overall loads and moments entering each spread footing was developed, overall dimensions for the foundations were developed. Then through the 2008 version of the Concrete Reinforcing Steel Institute (CRSI) design handbook, the amount of reinforcing needed to achieve a capacity of 6,000 psf was developed. While all footings will not be maxed out at 6,000 psf, standard practice was met by designing spread footings to the same bearing capacity as the soil it is placed on. See Figure S.16 to see a typical spread footing supported by Geopiers. All spread footing sizes and the amount of reinforcing can be seen on Appendix I.

FIGURE S.16: TYPICAL SPREAD FOOTING SUPPORTED BY GEOPIERS

For the strip footings supporting the foundation walls, a minimum of 30” was used due to Geopiers diameter being 30”. This ensured that the Geopier elements would be used to their maximum capacity. All footings were designed using the worst case experienced which occurred on the West side of the building at the loading dock. Using 3000 psi normal weight concrete, all strip footings were 3’-0” wide and 1’-6” deep with # 8 rebar spaced at 8” along the member and #6 rebar spaced at 12” longitudinally (see Figure S.17 in the Retaining Walls section). By keeping the same strip footing sizes, the productivity could be increased while having minimal impact on the budget of the project.

12.5 Retaining Walls

Due to the high water table present on site, the foundation walls were prone to developing a high amount of hydrostatic pressure. Even though the water pressure would not always be present the retaining walls were designed as such. The foundation walls fell into two major categories due to the surcharge experienced on the site outside of the wall.

The larger of the two foundation walls was on the West side of the building due to the location of the loading dock. With trucks regularly making deliveries, a surcharge of 250 psf was assumed due to the weight of the trucks and equipment they are carrying driving along this foundation wall. Therefore, with the a large surcharge and hydrostatic pressure, the wall needed to be 19” with #8 rebar spaced at 10” vertically on the interior wall, #4 rebar at 12” vertically on the exterior side of the wall, and #4 rebar spaced at 12” horizontally on each side for shrinkage and temperature purposes with 2” of clear cover on each side.

On the other three sides of the building, a surcharge of 100 psf was assumed due to the possibility of people gathering in these spaces, especially in the Grand Outdoor Central on the south side of the building. By using a lower surcharge for these foundation walls, a 16” normal weight concrete wall with #8 rebar spaced at 10” vertically on the interior of the wall, #4 rebar spaced at 12” vertically on the exterior of the wall, and #4 rebar spaced at 12” horizontally on both sides of the wall for shrinkage and temperature purposes. For a detailed section of a retaining wall, see Figure S.17. For calculations on the retaining walls, see Appendix I.

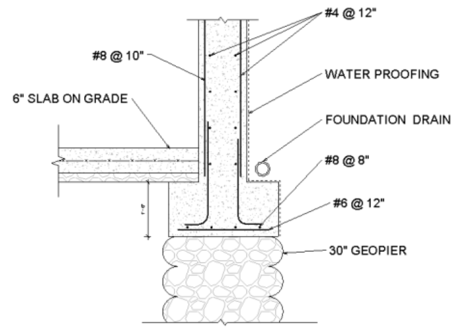

FIGURE S.17: RETAINING WALL AND STRIP FOOTING DETAIL

12.6 Water Control

Even though all retaining walls were designed to be able to withstand the pressures developed from the high water table present on site, it was preferred that this pressure be reduced as much as possible. Therefore, a drainage system utilizing sump pumps was introduced to alleviate the water present within the soils. This water is utilized by the mechanical team as a source of greywater to flush toilets and water crops. While the walls may be overdesigned when the hydrostatic pressure is not present, they are designed for situations where the sump pumps fail and the pressure is introduced upon the retaining walls. For further information on how the water is removed, see Section 6.0 in the **[Construction Report]**.

12.7 Slab on Grade

With the large amount of mechanical and electrical equipment being housed in the basement of Growing Power, an analysis of the loads imposed on the slab on grade needed to be conducted. Consulting the supplied geotechnical report for the building, it was recommended that a 6” slab on grade be implemented based on the soil conditions for the site.

After analyzing the equipment loads on the slab, it was determined that a 6” concrete slab on grade was required with only shrinkage and temperature reinforcement was needed (see Figure S.17).

13.0 Tower Design

13.1 Overview

With the natural HVAC system being employed by the mechanical engineers at Synthesis, three air intake towers, and one exhaust tower were needed on the north side of the building (see Figure S.18). With this mechanical system relying on wind pressure to push air throughout the building, square chimney like structures needed to be constructed above the top greenhouse to maximize the area normal to the wind direction. Since the towers needed to have good thermal properties, a CMU shaft was desired so the amount of additional insulation could be limited. Therefore, a steel superstructure for these towers was infilled with CMU, and covered with an exterior insulation finishing system (EIFS) to get the desired R-value for the mechanical engineers and give the towers a finished look. Since masonry infill walls were already going be used, hybrid shear walls were utilized to resist lateral forces and limit the amount of drift at the top of the towers. Tower dimensions can be seen in Table S.7.

FIGURE S.18: TOWERS ON THE NORTH SIDE OF THE BUILDING

TABLE S.7: MECHANICAL TOWER DIMENSIONS

Tower Dimensions		
Tower	Plan Dimension	Height above Top Greenhouse
2nd Story Supply	6’-5” x 6’-9”	9’-4”
3rd Story Supply	8’-5” x 8’-9”	15’-4”
4th Story Supply	8’-5” x 8’-9”	21’-4”
Exhaust	9’-5” x 9’-9”	28’-4”

13.2 Code Considerations

To analyze the towers, ASCE 7-05’s section on components and cladding (chimneys) within the wind load chapter was used to formulate pressures. While a round tower would be ideal to reduce the amount of wind pressure experienced to a minimum of 16 psf, the mechanical needed square towers to allow maximum air intake. By using square towers, the pressures experienced where about double that of a round tower. A comparison of these loads can be seen in Table S.8.

TABLE S.8: WIND PRESSURES EXPERIENCED BY SQUARE AND ROUND TOWERS

Tower – Wind Forces				
Tower	Pressure		Force (F)	
	Square	Round	Square	Round
2nd Story Supply	33.2 psf	13.0 psf	0.72 k	0.28 k
3rd Story Supply	31.9 psf	12.9 psf	2.31 k	0.94 k
4th Story Supply	33.0 psf	13.3 psf	3.78 k	1.52 k
Exhaust	33.1 psf	13.4 psf	5.91 k	2.39 k

13.3 Superstructure

With a desire for thermal resistance within the towers, solid grouted masonry was needed to provide a better R-Value for the mechanical engineers. To reduce the size of the masonry walls at the base of the towers, a lightweight steel structure was designed to alleviate the CMU infill walls at each story of the building. Thus creating a steel superstructure with masonry infill walls. The infill walls were designed assuming that the wind was perpendicular to the wall and it would be connected to the steel at the top and bottom of the wall. Using these parameters along with the wind loads calculated, it was found that a fully grouted 12” CMU wall was needed in the portion of the towers extending above the building, and a fully grouted 8” CMU wall needed at all other sections.

Due to the short spans within the towers, it was found that W12x19’s could support the wall loads and still meet the deflection criteria of L/600 used for masonry. The only issue with using a W12x19 was the width of the flange for the masonry to sit on was not 12 inches. To get a member wide enough for the masonry to be able to sit on, the beams needed to be extremely overdesigned for the load that they were carrying. Therefore, since the beams already needed prefabricated studs attached to them to make the steel engage the masonry, it was determined that the best solution was to have the beams shipped to site with a 12” plate and studs already attached (See Figure S.19 in the Hybrid Shear Walls Section).

13.4 Hybrid Shear Walls

With infill walls being attached to the steel above and below within the towers on the North side of the building, it presented a perfect opportunity to use hybrid shear walls. To determine that amount of lateral resistance that these walls can be assumed to provide, a calculation determining the equivalent steel area of the infill walls strut was computed (see Appendix H). By inputting these equivalent braces into an ETABS model along with hand calculations, it was determined that the hybrid masonry shear walls limited the amount of drift within the towers to an acceptable range. By using the infill walls for lateral resistance, braces were not needed, making the walls more constructible since blocks did not have to be cut around any braces. To create a hybrid system a detailed connection between the steel and CMU needed to be developed for them to work together (See Figure S.19).

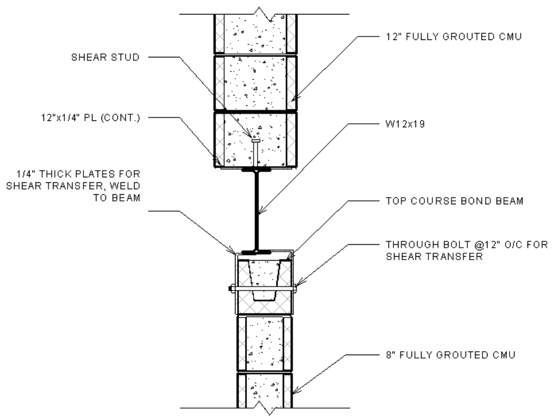

FIGURE S.19: HYBRID SHEAR WALL CONNECTIONS

Since the masonry in the towers is used for structural purposes, the maximum drift allowable by code if h/600. Since this allowable drift is stricter than the parameters used for the rest of the building, a slotted connection was used to isolate the movement of the towers from the main superstructure. For slotted connections details, see S3.00.

14.0 Considerations to Move

One of the main considerations for the structural team at Synthesis was the idea that Growing Power wanted this building to be a prototype to be able to be moved to other regions with minimal changes needed. With modular greenhouses and uniform bay and member sizes, the building could easily add or subtract a bay depending on the needs of the building being constructed in a specific region without drastically changing the gravity design.

A major consideration when moving this prototype to another location is the foundation of the building. Due to the poor soil conditions in Milwaukee, a specialized foundation to allow spread and strip footings was needed to be implemented and develop an efficient substructure. In other areas throughout the country, the soil conditions vary drastically. Many of these locations will have a bearing capacity that is better than those present on our site Milwaukee. Therefore, many sites may still be able to implement spread and strip footing without the use of Geopiers to improve the soils properties. In Miami, a proposed location for this building, it is common to have sandy soils with poor bearing capacity. Thus meaning, a Geopier system could be utilized for ground improvement to raise the bearing capacity to the point where spread and strip footings could be used. Prior to the use of Geopiers, an expert should review the site to determine if the site is ideal. In situations, where Geopiers are inefficient to include, other foundation systems should be explored.

Another crucial issue that needs to be considered when moving this building to another location is the lateral system. Since buildings can experience lateral loads through two different means, seismic and wind, a building will act differently depending on which load controls. The main lateral system for the Milwaukee location consists of eccentrically braced frames and ordinary moment frames. When moving to an area with high seismic loads, the eccentrically braced frames are ideal due to their high response modification factor(R-factor) and can be made more efficient for seismic regions by shrinking the link between the two braces with a few architectural changes. To reduce the high forces experienced in seismic regions, the ordinary moment frames within the design for Milwaukee would need to be changed to special moment frames to increase the R-factor to the same value as eccentrically braced frames. In high wind areas, such as Miami, eccentrically braced frames and ordinary moment frames would still be used but the member sizes included within these frame would need to increase to resist the loads entering the building. If not enough additional load resistance cannot be satisfied by increasing the member sizes or change the moment frame type, the stair towers and elevator tower can provide additional lateral resistance by connecting them to the steel and turning them in hybrid shear walls. In regions with small lateral loads, the size of the braces within the structure can be reduced or removed completely depending on the amount of lateral forces entering the building.

A large change that would need to occur in some windy areas due to local codes, such as Miami, is with the polycarbonate panels within the greenhouses. These panels would need to be increased in thickness or decreased in size to be able to handle impact forces when wind turns loose object into missiles.

Prior to this prototype building being constructed in any other area, a design professional would need to review the building to ensure that all local codes are met for the area. The design professional would also need to review the geotechnical report and determine the lateral forces on the building and adjust the foundation, lateral system, and code issues accordingly.

15.0 Summary

The structural team at Synthesis aimed to meet the goals set forward by the owner, by Synthesis, and their own personal goals for the building. Through collaboration with all other design disciplines, the structural designers were able to meet all guidelines, requirements, and goals set forth in the executive summary to create a successful structural design. An efficient and innovative lightweight composite steel superstructure was developed to operate smoothly with all other systems within the building, including, the architecture, lighting/electrical design, mechanical design, and the construction teams.

To achieve the goal of adaptability for multiple locations throughout the US, an efficient gravity, foundation, and lateral system were developed for 5500 W. Silver Spring Drive. By having a uniform bay size, with two greenhouse modules per bay, this prototype can easily add or subtract an extra bay when moving from area to area while using the structure from a typical bay in the added bays. Also, the gravity system within the main building was designed so interior partitions and floorplans can change from area to area depending on the needs of the specific site. All of the greenhouses were also designed to be able to hold aquaponic tanks so that if owner wants to move or add additional tanks, they could without having to worry about the impact on the structural system. To help lower lateral forces experienced in seismic regions, a lightweight structure with eccentrically braced frames along with ordinary moment frames that could be switched to special moment frames were used to develop a higher response modification factor. The foundation is also adaptable to move from site by implementing Geopiers with spread footings in low bearing capacity regions, and eliminating the Geopiers and using typical spread footings in areas with good bearing capacity.

To achieve an educational environment, expected floor vibrations were taken into account for areas such as the classrooms, offices, and gathering spaces, since light-weight composite structures are prone to vibrations. By changing member sizes, distractions for employees and students in important spaces due to vibrations were eliminated.

To help achieve a self-sustaining ecosystem, the trusses within the greenhouse were design to block minimal amounts of sunlight. By spacing the trusses at the same spacing as the greenhouse modules, and having the polycarbonate span further distance, there were less structural members and mullions blocking the light necessary for plant growth.

By using BIM software, the structural team along with all other design disciplines were able to accomplish an innovative and efficient integrated building for Growing Power. The full use BIM software, allowed for a quality, functional and constructible building to be a prototype for Growing Power to move throughout the country.

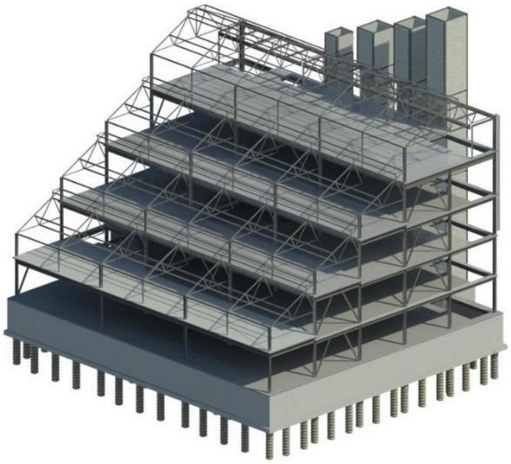

FIGURE S.2: OVERALL BUILDING STRUCTURE