Integration | Construction | Mechanical | Electrical | Structural

# GROWING POWER

## VERTICAL FARMING FACILITY


# TOTAL BUILDING DESIGN

## ENGINEERING

Architectural Engineering Institute, Annual Student Competition
Registration Number: 04-2015

GROWING POWER INC.

# EXECUTIVE SUMMARY

The structural partners of AEI Team 4 have addressed the various design challenges involved in developing the Growing Power headquarters and prototype for future expansion. This submittal contains a project overview, project goals, narrative of the design process, discussion of design decisions and justification, summaries of related analyses and modeling. In addition, the submittal includes supporting documentation and drawings presenting references, calculations, plans, elevations, sections, and modeling information.

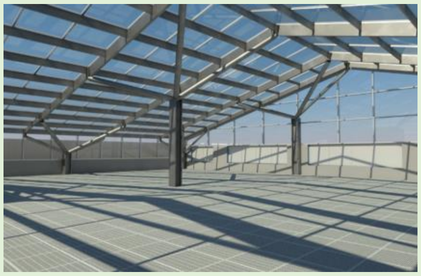
Throughout the design process, the structural team utilized BIM technology and interdisciplinary **collaboration** to develop a structural scheme for Growing Power. Structural concepts were formed by the structural partners, presented to and discussed with the entire design team, and then fully detailed by the structural partners. Input and support was also provided by the structural discipline to assist the other design disciplines in the progress of the overall building design.

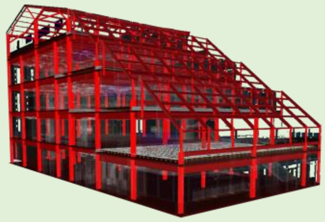
The **gravity system** was designed utilizing composite steel beams and girders in order to minimize member sizes, providing more plenum space for MEP system coordination, and minimize the self-weight of the system, which was critical given the foundation bearing capacity concerns. In order to provide a **column-free** gathering space, the structural partners developed custom transfer girders utilizing W36x361 members with cover plates to **clear-span** the building in the necessary locations. To address the low allowable soil bearing capacity issues in Milwaukee, the structural partners elected to use **Geopier® soil reinforcement** to improve the effective soil bearing capacity.

The greenhouse structures were custom-designed to reduce the conditioned volume and improve systems coordination in the growing spaces. The greenhouses feature **renewable wood framing** for the greenhouse cascading up the façade of the building and **steel tree-columns** for the top greenhouse. All greenhouses contain a **grate system** to facilitate MEP flexibility and proper water drainage.

The structural partners worked diligently with the other team members to develop a striking, integrated façade system that meets the various discipline design requirements for Milwaukee, while also consdering the other requirements for future Growing Power locations. The resulting **rain screen** system utilizes clips to attach the customizable façade components to the cold-formed steel backup studs.

Top Greenhouse Tree-Columns and Structural Model Overview





HIGHLIGHTS

High Strength, Low Weight Structural Steel System:
Composite steel members minimized sizes and subsequently weight.

Transfer Element:
In order to clear span over the gathering space, custom steel transfer girders were designed.

Geopiers®:
Geopier® soil reinforcement was utilized to as a cost-effective, efficient solution to improve the soil bearing capacity.

Wood Greenhouse Structure:
The cascading greenhouses utilize glulam framing as a renewable resource and architectural accent

Top Greenhouse Tree-Columns:
Smaller member sizes and an open floor plan were achieved through the design of tree-columns comprised of galvanized HSS shapes.

Flexible Prototype Façade:
Light-weight rain screen façade system developed through integration.

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# PROJECT NARRATIVE

## BUILDING DESCRIPTION

*Figure 1. Growing Power Milwaukee, WI*

Growing Power is a national nonprofit organization that prides itself in providing communities with healthy, high quality, safe, and affordable food. The mission of Growing Power is to promote sustainable food producing systems throughout the communities they are a part of, helping to establish food security.

The Growing Power Vertical Farm is a proposed five-story building located in the surrounding area of Milwaukee, WI. The building will have **9,000 S.F. of south facing green house space** and **42,000 S.F. of mixed use space:** office, educational, and retail. Since Growing Power operates as a national nonprofit they have a long term vision of using this vertical farm as a prototype for future locations. The challenge for AEI Team 4 is to provide Growing Power with a facility that will enable them to carry out their goals, utilizing best sustainable engineering practices.

## GOALS

Total Building Design Engineering (AEI Team 4) developed the new Growing Power headquarters in Milwaukee, WI, as a five-story vertical farm composed of greenhouse facilities, a gathering space, a marketspace, offices, and educational spaces for the community. Growing Power has also stressed that they plan to use the developed design as a **prototype** for future Growing Power facilities in other locations in the United States. AEI Team 4 investigated what makes a vertical farm successful and aligned that with Growing Power's goals to establish the goals for the project.

### PROJECT INITIATIVES

**Flexibility**

The ability for the facility to be used as a prototype for other possible sites across the country, while meeting the changing needs of Growing Power by providing options for continuous improvement.

**Community**

Strengthen the community outreach by providing ample space for education and enabling the surrounding population to participate in the growing methods used within the vertical farm.

**Sustainability**

Create a facility with a manageable lifecycle cost aided by the use and optimization of renewable energy, renewable resources, and sustainable practices in design and construction.

**Economy**

Provide the best product for the budget developed by Growing Power while continuously providing cost savings and exploring funding expansion.

The development of a facility for Growing Power involved a number of competing goals. The creation of the Vertical Farm will enable the organization to **connect** with the surrounding community in Milwaukee, research and **adapt** the concept of urban farming, **grow** quality produce in an efficient manner, and **educate** the community about various urban farming techniques.

AEI Team 4 developed a number of team goals and discipline goals, presented in Figure 2, to guide the design beyond those directly expressed in the program brief. To facilitate the ability for Growing Power to expand to other locations, AEI Team 4 developed the design as a prototype with **transferability** in mind. By creating a design that enabled the swapping of individual components or systems necessary for various locations, the basic concept of the overall building structure could be maintained. The project was also driven by selections to make the building **renewable** and **sustainable**. The project was developed based on a target value of $11 million per the AEI Competition webinar. (1) This required **economical** design decisions and choices. The **integration** of the disciplines and systems throughout the entire design process contributed to an **efficient** overall building design.

| Project Discipline Goals |
|---|
| Cost-effective, integrated structural design solutions |
| Utilize sustainable and renewable elements and concepts within the structural design |
| Develop a structural system to allow for a column-free gathering space |
| Enable Growing Power to adapt aspects of their program layout |
| Ability to place aquaponic systems anywhere within the greenhouses |
| Integration of the structural system with the mechanical and lighting/electrical systems, within the greenhouse |
| Durability of the structural system, especially in the greenhouse environment |
| Facilitate the development of future Growing Power locations by enabling the swapping of components of the lateral system for various loading conditions |
| Innovative foundation design to address the bearing capacity concerns |

*Figure 2. Project discipline goals*

The structural design partners of AEI Team 4 strived to supplement the architectural design refined by AEI Team 4, shown in Figure 1, by developing an integrated structural system to support and promote the building's operations and systems. The design was conducted and implemented with **flexibility** in mind, to enable Growing Power to experiment with various growing strategies and program layouts. To enable Growing Power to construct vertical farms in other communities, the structural system was schematically designed to be **transferable** and adaptable to resist the varying structural loads possible in other locations. Finally, the structural team strived to detail waterproofing systems and durability measures to promote the **longevity** of the structure, and the building as a whole.

## IDENTIFIED STRUCTURAL SYSTEM DEMANDS

The structural partners identified several challenges and aspects that the structural design would have to address and solve in order to contribute to the overall design and operation of Growing Power.

The basic operations of a vertical farm necessitate that equipment and tools related to growing plants are located on the step-backs and top of the building per the architectural plans. This results in **high loads from water tanks,** estimated to be up to 250 psf for 4' deep tanks, which needed to be designed and accounted for in any greenhouse locations and addressed throughout the rest of the structure. These loads had to be explicitly addressed in order to achieve the desired architectural openness in the gathering space, requiring the removal of columns, and subsequently, the transfer of high loads. The greenhouse design also included a raised floor grate system, which required that the structural slab be lowered 14" below the greenhouse areas. The geotechnical report found on-site soil conditions with an allowable bearing capacity of 1,500 psf, causing a refocus on total building weight, and created complications late in the structural evaluation process.

Furthermore, since Growing Power's Milwaukee campus will be used as a prototype for future building in many other locations, the structural design strived to address the variation in structural loadings and conditions, such as snow, wind, seismic, and soil, possible at numerous locations, such as Miami, Florida. Thus, Growing Power can more easily transpose the building design, enabling them to focus more on their mission to educate, connect, engage, and grow.

# SYSTEM SELECTIONS

## CODE ANALYSIS & DESIGN LOADS

For the design of Growing Power's headquarters, the structural team utilized the applicable codes and standards for the location in Milwaukee, while also considering controlling factors for other potential locations, such as Miami. (2)(3)(4)(5) A complete discussion of these codes and standards, and the building design loads, is provided in the Supporting Documentation (SD|III). The structural system was developed utilizing loading conditions for Milwaukee and considered other potential locations to facilitate the transferability of the system.

## GRAVITY SYSTEM DESIGN

The structural team for AEI Team 4 determined a number of desirable characteristics and criteria for selecting a structural gravity system, presented in Table 1. A full list and evaluation of the considered system options is available in the Supporting Documentation (SD|X). By evaluating the various system options against these measures, concrete and steel were identified as the leading candidates for the final system selection using the decision matrix presented in the supporting documentation. At this point, more in-depth research, analysis, and design was conducted focusing on rigid frame structural steel and two-way mild reinforced concrete, which is discussed in the following sections.

Table 1. Gravity System Selection

**Project Decision Matrix**

| Option | Goals | | | | | | | | | | Risks | Select |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 4 | 7 | 9 | 10 | 2 | 3 | 5 | 6 | 8 | | X |
| **Gravity System** | | | | | | | | | | | | |
| Steel Noncomposite | 4 | 2 | 3 | 3 | 3 | 3 | 3 | 2 | 5 | 2 | | |
| Steel Composite | 4 | 2 | 2 | 3 | 3 | 4 | 3 | 3 | 5 | 2 | | X |
| Concrete Two-way Slab | 2 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 5 | 2 | | X |
| Concrete Post Tension | 3 | 3 | 3 | 3 | 3 | 5 | 4 | 4 | 3 | 2 | | |
| Concrete Bubble Deck | 2 | 4 | 5 | 3 | 4 | 4 | 3 | 2 | 1 | 5 | Extremely specialized market | |

*The options were rated on a scale of 1-5 based on how they met each goal. Coloring corresponds to the four project initiatives: Flexibility, Sustainability, Economy, and Community. A complete list of goals is available in the Supporting Documentation.*

## STRUCTURAL STEEL

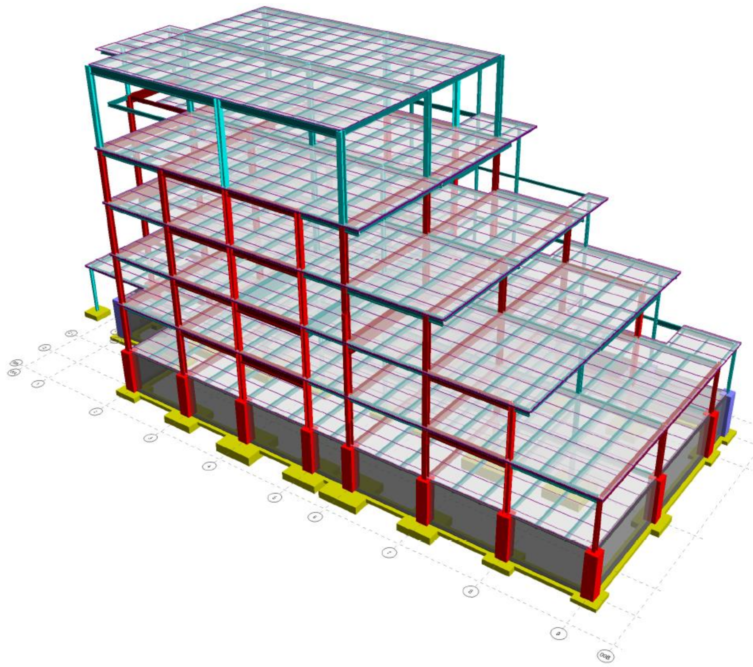

Figure 3. Structural model in RAM Structural System

The structural steel gravity load system design is comprised of **composite** deck and steel wide-flange beams to achieve lighter self-weight than concrete and thinner total system depths than non-composite steel beams, which aided coordination within the ceiling plenum. Due to the anticipated high live loading, especially in the greenhouse areas, the composite behavior of the structure will be more efficient. The structural team aimed to utilize AISC Economy W-shapes, however, certain instances, such as the transfer element, necessitated non-economical sizes. RAM Structural System was utilized to analyze and verify the design and selection of members within the structural system. Given the limitations of RAM SS with bi-level framing and tree columns, the structural partners found it necessary to utilize alternative analysis and design software in these areas. Because these areas required more attention, a more in-depth discussion occurs in the greenhouse section. The resulting reactions of each of the analyses were applied to the RAM model, in order to account for the behaviors induced by the systems. An image of the 3-D model is shown in Figure 3. Hand calculations were conducted to spot-check and verify the design, examples of which are presented in the supporting documentation.

Beam framing for all floors is oriented in the plan north-south direction, as indicated in the example floor plan in Figure 4, with deck running plan east-west in a typical bay (30'-6" x ~21'-0"). The structural partners' goal of allowing Growing Power the flexibility of placing aquaculture tanks throughout all greenhouses caused significant extra live load for the floors in those areas. This resulted in a typical bay, shown in Figure 5, containing composite W18x35 beams with 28 studs. To achieve a two hour fire rating for the floor composition and utilize composite action, **Vulcraft 3.0VL18 with 3 ¼" light-weight concrete topping** was selected (SD|XI). [(6)] Spot checks were conducted to verify the composite beam design (SD|XI). The reduction in depth due to composite action made steel framing in this area more feasible for integration with other options since each greenhouse floor is dropped to allow for a secondary floor system in the greenhouse, discussed in greenhouse. The non-composite design would have necessitated the use of W24's, which would have occupied too much of the reduced ceiling plenum, hampering the integration of the various systems.

An example typical bay from the base building is shown in Figure 5, which utilizes W16X26 beams with 14 studs. Because the floor exhibits a high span to depth ratio, a preliminary vibration analysis was performed which determined the floor meets not only the gathering space and classroom thresholds but also the office threshold of 0.005g.

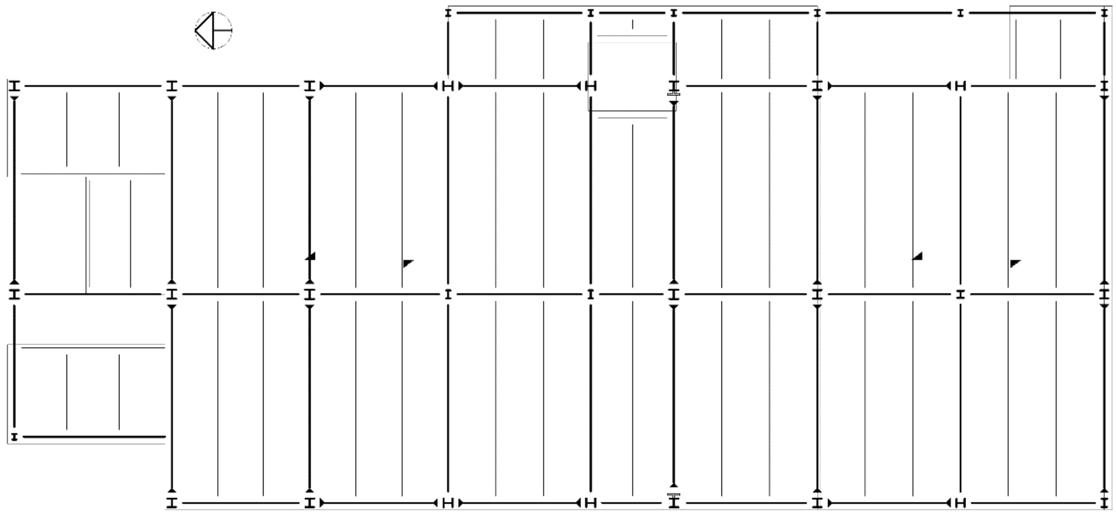

*Figure 4. Representative steel plan*

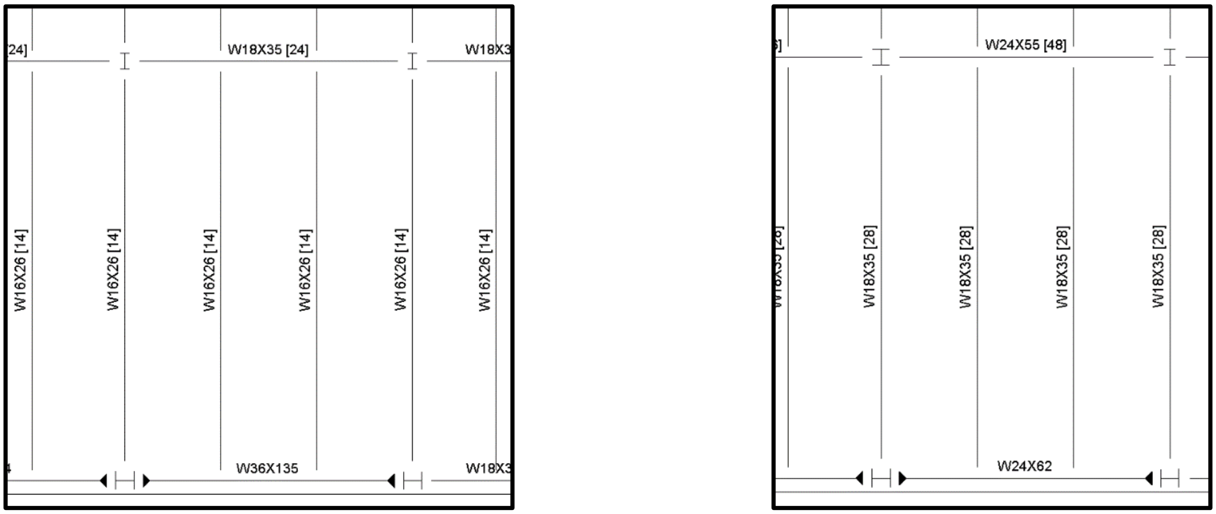


*Figure 5. Typical steel bay supporting base building (left) and greenhouse (right).*

## CONCRETE ALTERNATIVE

Cast-in-place two-way mild-reinforced concrete was selected as a finalist candidate for the gravity system design for a number of reasons. The concrete design was expected to provide a more durable option, which was necessary given the moist environment of the greenhouses and the desire for structural system longevity. In addition, the anticipated structural depths would be less than the other options, providing the most plenum space for MEP systems and easing coordination. The concrete system would provide a continual, inherent diaphragm despite the drop-down for the greenhouse areas. The concrete design was also anticipated to be relatively easy to adjust for future locations, contributing to the flexibility and transferability of the overall structural design. However, there were several concerns and drawbacks to a concrete design as well. The self-weight of the concrete design was a potential issue during preliminary selection, especially given the in-situ soil conditions. In addition, the reinforcement in concrete could hinder the flexibility of the program layout, as any **future cores and penetrations** would have to be placed as to not greatly reduce the structural capacity of the system.

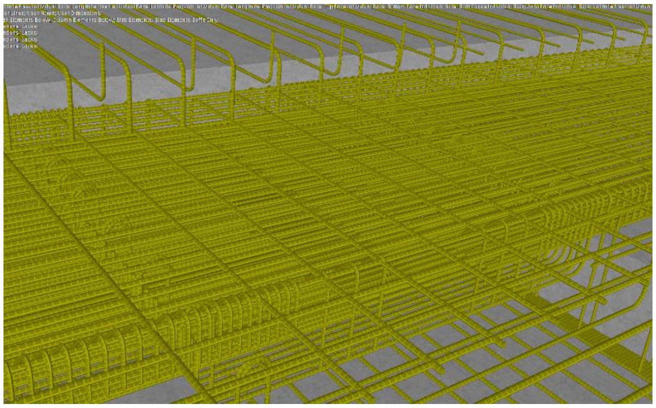

*Figure 6. Excessive shear reinforcing*

The anticipated floor system depth (8”-10”) was thinner than those in other systems, which would ease interdisciplinary coordination and facilitate the implementation of a raised grate system within the greenhouses. While the RAM Concept model indicated a slab depth of 8”-10” was possible, exploration of the CRSI Design Handbook(7) indicated a slab depth of 12” for preliminary design to control punching shear. However, the larger impact this would have on the plenum space, especially in the greenhouse drop downs was considered unreasonable.

Therefore, the structural partners proceeded with the 8”-10” slab and explored various solutions to the issues that accompanied that selection. The high floor loading conditions of the greenhouses necessitated excessively large drop panels and shear reinforcing that eventually became extreme and unfeasible. The addition of wide beams (6’ wide x 2’ deep) and other elements proved fruitless in the attempt to support and control the effects of the high floor loads in the greenhouses. In non-greenhouse applications, the drop panels were 12’x12’ and 8” deep. The columns were sized at 24”x24” and although increasing their size would aid in solving the punching shear problems, this would become an architectural plan issue.

The progressive thickening of the concrete floor system and **tight spacing of shear reinforcing** (#4 @ <1.0”), as observed in Figure 6, confirmed concerns related to the possibility of future slab penetrations that frequently accompany building renovations and retrofits, thereby inhibiting the flexibility needed for Growing Power to alter and update their facilities.

The structural step-down for the greenhouses was another area of complication, as longitudinal reinforcing was so congested that improper consolidation was anticipated during concrete placement. Several locations required reinforcing (#6 @ <1.0”, <0.25” clear spacing) that was not even constructible, let alone meeting code.

The concrete system would not require additional fire protection measures, which was a major advantage due to the prevalence of fire separations indicated in the architectural drawings that result from the various space occupancies.

The inherent lateral stiffness of the concrete system would reduce the financial impact that would accompany rigid frame steel connections. However, the locations of elevator cores lead to the realization that more moment frames would be required than originally thought. The concrete floor system would help prolong the life span of the structure in the moist environment of the greenhouses, where it may also be exposed to corrosive chemicals from fertilizer and the aquaponic processes.

The team’s original revised architectural layout of the design resulted in bay proportions that enabled two-way concrete slab designs with a typical bay proportion of 1:1.7 (Int|9). Some bays exceeded 1:2.5 with smallest proportion equaling 1:1.3. However, refinement to the team’s architectural layout and corresponding column layout led to one-way behavior tendencies as the **bay size approached 2:1**, making the two-way concrete slab system inefficient.

As the preliminary designs progressed, it became increasingly evident that the allowable soil bearing capacity recommended in the geotechnical report would not permit the selection of a concrete system for the Milwaukee location. After evaluating possible solutions to the various issues and consulting the full design team, the structural partners decided that the concrete design was not feasible for the situation and conditions, as summarized in Table 2. Therefore, the **structural steel composite design** was selected as the structural system for the building.

Table 2. Steel vs. Concrete Comparison

| System | Pro | Con |
|---|---|---|
| Composite Steel | • Light weight<br>• More shallow<br>• Smaller sizes<br>• Quicker construction | • Susceptible to water damage<br>• Fireproofing required<br>• Potential material cost (studs)<br>• Longer lead time |
| Two-Way Concrete | • Good for heavy LL<br>• Inherent Fireproofing<br>• Vibration Control<br>• Durability | • Span limitations<br>• Bay Ratio Limitations<br>• Cost |

### TRANSFER GIRDERS

In order to achieve the project goal of an open, **column-free** second floor gathering space, transfer elements were necessary to **clear span** the building below the third floor (Int|14). Several different structural concepts were explored for transferring the column loads out across the 61' span.

The use of castellated beams was initially explored to achieve lighter members and ease the integration with MEP systems. However, the design revealed that no single castellated member could achieve the necessary strength and deflection requirements, while meeting the requirement of a maximum member depth of 42". Two transfer girder members would be adequate when working in tandem. However, this idea was discarded when considering the necessary connection in comparison to the alternatives, as it would involve framing two members in at a single column where there would be inadequate space.

Another considered option was the use of story deep trusses, essentially using the third floor level as a truss. While the members could be hidden in walls, this would contradict the goal of flexibility as it would limit Growing Power's ability to adjust the program layout in the future in Milwaukee and in other locations.

Therefore, the most critical transfer girder is designed as a **W36x361 with 2"x30" steel plates** (A527 Gr. 50) welded to each flange with a ¾" camber[8], as depicted in Figure 7, to achieve the necessary moment of inertia (74153 $in^4$) to limit net deflection to 1" and to provide the column-free gathering space desired in the project goals. The other transfer elements utilized W36x361 members, to achieve economy of roll, with various cover plate sizes to achieve the necessary member properties for their respective loading conditions. The member size was selected based on availability & cost and to balance the ratio of member size to flange plate size.

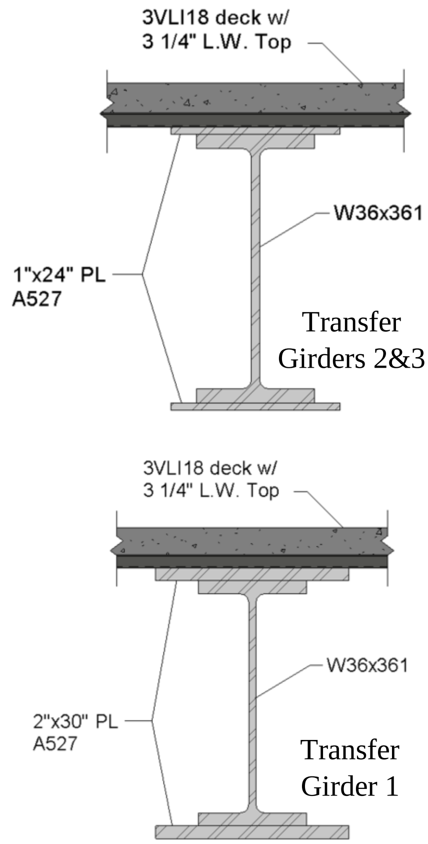


*Figure 7. Cross-sections of transfer elements*

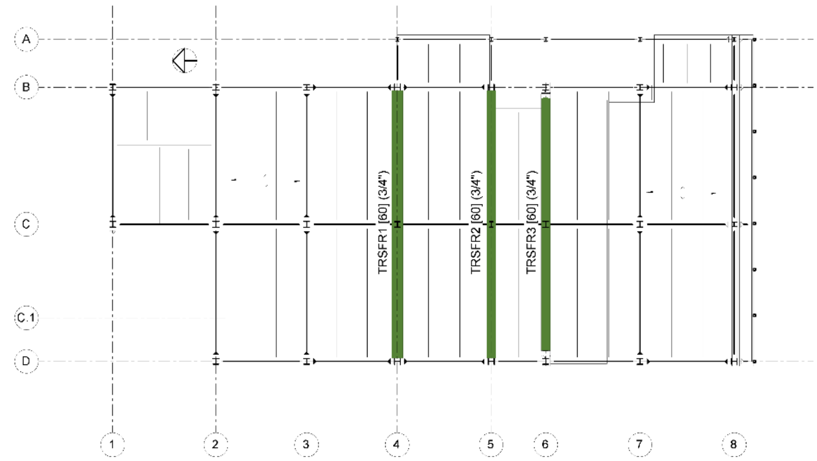


*Figure 8. Structural plan with transfer girders*

Composite design was not included in the transfer girder design to ensure deflection was properly controlled. However, the transfer girders include 60 shear studs along their length to provide additional deflection control through composite action.

Per AISC Design Guide 3[(9)], 50% of the live load was utilized in deflection calculations since the member deflection was limited to 1" or less. Engineering judgment also rationalized that there was a low probability that an entire bay would be filled with 4' deep tanks, as the specified tanks are only 3' tall. In addition, it was presumably necessary for there to be walkways and growing beds in the growing areas. The design also enabled the MEP systems to run through the transfer girders where needed. As not every transfer element required the same capacity, the flange plates varied by element to customize the transfer elements, while maintaining the use of W36x361 beams, shown in Figure 8.

The column design was conducted utilizing RAM SS, with a minimum size of W10's to facilitate connections with the members framing in. Although smaller sizes could be selected, it was anticipated that the savings of reducing the size would be outweighed by the cost, labor, and general inconvenience of the connections. However, a number of the columns were utilized in the lateral system, and therefore upsized to W14's. Columns were typically spliced 30" above the top of slab on the third floor level (per standard practice).

The selection of the composite structural steel system resulted in a **60% reduction** in structural weight when compared to the preliminary two-way concrete design. The steel sizes selected for the design can be obtained from mills within 500 miles of Milwaukee, so that Regional Materials LEED credit could be attained if Growing Power desired.

## LATERAL SYSTEM DESIGN

The lateral load resisting system is comprised of **steel moment frames** located in a pattern to achieve uniform distribution of lateral stiffness. The elevator cores were initially planned to be part of the lateral system. The design worked well for Milwaukee, with better drift values than the use of moment frames, shown in Figure 10, however, the non-symmetrical layout in conjunction with the variation in requirements that accompany a design for numerous locations, especially seismic zones, ruled out the use of the cores. Braced frames were deemed unfeasible in order to facilitate the flexibility and open layout desired for Milwaukee and any future locations. Moment frames, displayed in Figure 9, also enabled the design team to eliminate them where possible as the building mass decreased with each progressive level. This was key in producing a flexible design that would be versatile and easily adapted for many locations.

Following the design of the gravity elements, a preliminary lateral analysis was conducted using the designed gravity members. From the initial output, W14 columns were selected based on an effective axial load. The W14's were intended to aid in controlling drift since drift was identified as a critical state early on in the design process, From that point, virtual work methods were used to identify critical elements that were contributing the most to the lateral system (SD|XIV). Utilizing that output, only specific members were resized to produce the most economical, efficient design. Within the lateral system, the column sizes range from W14x82 to W14x257, while beam and girder sizes range from W21x55 to W36x135. Throughout the iterative design process, P-Δ effects were included through the Direct Design Method.

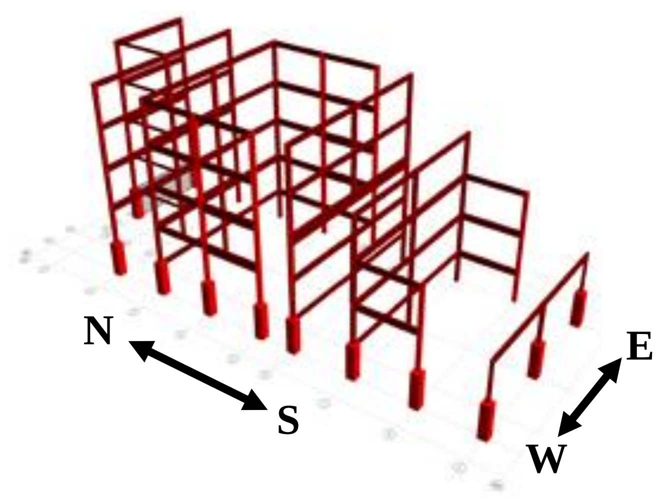


*Figure 9. Steel lateral system - Milwaukee*

The top of building greenhouse lateral system makes use of the 8 lateral columns that act as tree columns (p. 12). The loads that feed into the greenhouse framing ultimately distribute into the 8 columns. Since the building column sizes are maintained for the entire height of the building, each column has enough stiffness and strength to act as a cantilever from the 5th floor to pick up any additional load. The load transfers were determined using SAP2000. The base reactions were input into RAM Structural System's Frame module to design the remaining lateral system.

The layout of the moment frames in the East-West direction, which is the critical wind loading direction, posed a challenge when trying to avoid placing any of the transfer elements in the frames which would cause a soft portal. Due to the building setbacks it was desired to place a moment frame at the front of the top greenhouse. Not only would that aid in controlling the 5th floor lateral drift, but the tree columns supporting the roof could be tied in as well. However in this location, one of the transfer elements was located in the moment frame. This instance could not be avoided without causing major eccentricity problems on the roof. The transfer element selected to act in the moment frame was the lightest gravity loaded transfer element, allowing more capacity for use in the moment frame. Because the transfer element had such a large moment of inertia to prevent a soft story in the frame, the columns needed additional stiffness around the portal. Basing the desired moment of inertia on the most economical shape in the RAM model, a WT7x171 was selected to stiffen the gravity load designed W14x176 by welding it to each column flange. To ensure stiffness of the portal across the connection area the WT7x171 was extended a half story above and below the portal (SD|XIII).

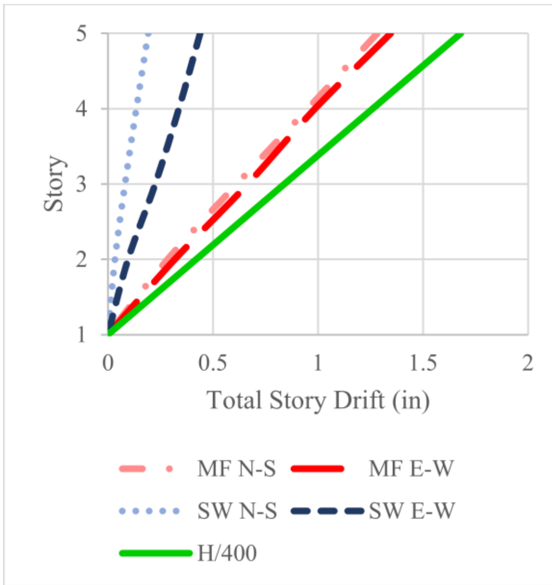


*Figure 10. Shear Walls vs. Moment Frames Drift Comparison. The graph indicates the drift values for each option and each direction.*

The layout in the North-South direction was designed to limit the number of columns in biaxial bending. This decision was made to limit multiple moment connections on all lateral columns. The chosen location of the moment frames allows all but one greenhouse, the 4th floor, to tie into moment frames in both directions which places less stress on the members at the structural drop down. In the cases of Milwaukee and Miami, where wind controls, the drop down was determined to not cause significant diaphragm discontinuity. After conversing with a high-rise structural engineering expert, the configuration of the girders was deemed feasible of transferring any load from the greenhouse slab into the main building slab. If the building were to be placed in a high seismic zone in the future, the drop down would require minor additional detailing and alterations to ensure diaphragm continuity.

## FOUNDATION DESIGN

Once the structural team completed the design of the superstructure, focus was turned to the foundation system. The structural partners explored a number of different options for the Foundation system, several of which are presented in Table 3. The Geotechnical Exploration Report provided by Geotechnical and Environmental Services, Inc. found organic fill to a depth of 3' to 5.5' and recommended the use of "conventional spread and/or strip footings to bear on the natural alluvial soil" located below. The recommended net allowable soil bearing capacity of 1,500 psf would cause the use of numerous combined spread footings. A mat foundation was also considered in order to create a "bath tub" due to the high groundwater level. However, this was a less of a concern for the structural design once a groundwater drainage system was developed (CM|8). Therefore, the structural team explored the concept of **Geopier® soil reinforcment** in order to avoid the need for combined spread footings by improving the allowable soil bearing capacity and reduce the plan size of spread footings.

Table 3. Foundation System Selection

| Project Decision Matrix | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Option** | **Goals** | | | | | | | | | | **Risks** | **Select** |
| | **1** | **4** | **7** | **9** | **10** | **2** | **3** | **5** | **6** | **8** | | **X** |
| **Foundation System** | | | | | | | | | | | | |
| Mat Foundation | 4 | 3 | 3 | 3 | 3 | 2 | 4 | 3 | 5 | 3 | | |
| Spread/Strip Footing | 4 | 4 | 3 | 3 | 3 | 5 | 4 | 4 | 5 | 3 | | |
| Deep Foundations | 2 | 2 | 3 | 3 | 3 | 2 | 3 | 2 | 2 | 4 | Expensive, invasive, slow | |
| Geopiers | 4 | 4 | 4 | 3 | 4 | 5 | 4 | 4 | 2 | 5 | | X |

Geopier® foundation systems use Rammed Aggregate Piers® to improve the effective bearing capacity for foundation systems. The Rammed Aggregate Piers® are constructed by augering a hole to the necessary depth, placing a lift of aggregate in the hole, then ramming the aggregate. The piers are completed by continuing the cycle of placing lifts of aggregate and ramming each lift. This process increases the lateral pressure around the hole, improving the effective bearing capacity for footings, as detailed in Figure 11.

The use of Geopier® soil reinforcement improved the estimated useable bearing capacity to **6,000 psf** based on correspondence with Ground Improvement Engineering [10], which was critical given the high building loads. The foundation situation also was improved through the composite selection of the steel structural system, as the gravity loading was **reduced by 60%.**

The reinforced spread footings for the columns and strip footings for the basement walls utilize the soil reinforcement provided by the Geopiers®. RAM Structural System was used during the design of the column spread footings and basement wall strip footings

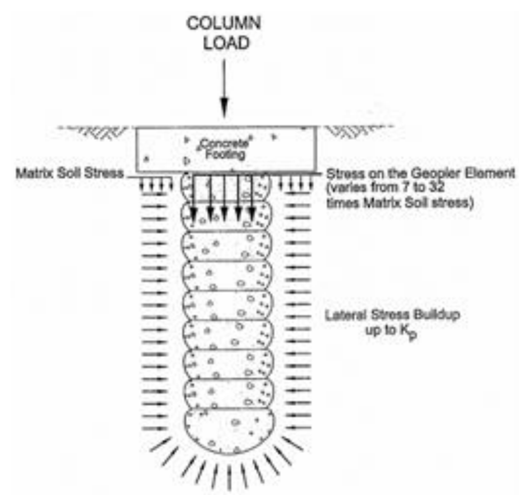


*Figure 11. Geopier® Soil Reinforcement [11]*

(SD|XVI). Several standard foundation sizes were utilized for repetitive construction, which aids the schedule and budget.

The 12'-6" foundation wall design was conducted accounting for the possibility of lateral fluid pressure up to 5' below grade. This resulted in a 12" thick, 3,000 psi concrete foundation wall.

Piers were designed as part of the foundation walls to transition the steel superstructure to the concrete substructure. Based on preliminary design, the steel columns connect to 20"x24"x1 ½" base plates, which are then anchored into 28"x32" piers, for the columns contributing to the lateral system, which are integrated into the foundation wall. This design was completed by importing the structural model from RAM Structural System into RAM Connections. Interface details were developed to address this situation, as displayed in Figure 12.

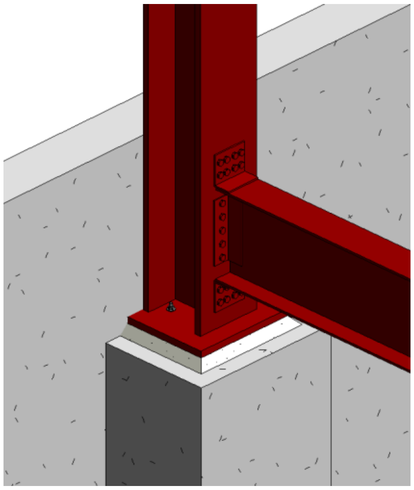

*Figure 12. Interface of steel superstructure and concrete foundation system*

## GREENHOUSE DESIGN

Rather than relying on pre-manufactured greenhouses, as was the original intent, AEI Team 4 designed **custom greenhouses**, for a number of reasons (Int|12). The pre-manufactured greenhouses were designed to be supported above a 20' height to avoid fire-rating requirements, thereby only needing to use non-combustible materials per IBC 2009. As part of the team effort to improve the quality and efficiency of the greenhouses, the roof systems were redesigned to satisfy the required fire-rating allowing almost the entire structure to be below 20'.

Table 4. Greenhouse Roof System Selection

| Project Decision Matrix | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Option | Goals | | | | | | | | | | Risks | Select |
| | 1 | 4 | 7 | 9 | 10 | 2 | 3 | 5 | 6 | 8 | | X |
| Green House Structural System | | | | | | | | | | | | |
| Wood | 2 | 2 | 4 | 3 | 4 | 5 | 1 | 2 | 5 | 4 | | X |
| Steel | 5 | 4 | 4 | 3 | 3 | 5 | 4 | 4 | 5 | 3 | | X |

In addition, a **raised floor grate system** was developed to improve drainage and de-clutter the greenhouse floor area (Int|13). The grate system enabled the MEP systems to run beneath the grate, keeping the floor unobstructed, which is critical for Growing Power to operate the greenhouses efficiently and guide tours through the space. The structural design for the greenhouse roofs utilized both engineered wood and steel, as outlined in Table 4.

### CASCADING GREENHOUSES

The structure of the cascading greenhouses was formulated utilizing **renewable engineered wood** products, as seen in Figure 13. A comparison was conducted between structural steel and engineered wood. The renewability of the wood sources typically used to manufacture the engineered wood products reflects the environmental friendly goals for this

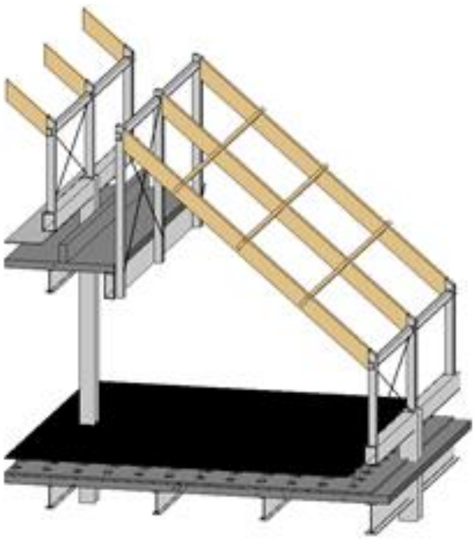

*Figure 13. Cascading greenhouse structure*

design, which contributed to the decision. Engineered wood products contain a fraction of the embodied energy present in steel and concrete, while utilizing wood from second- and third-growth forests. (12)

The selected glulam members (24F-V4 3 $^{1}/_{8}$”x 7 $^{1}/_{2}$” purlins and 5 $^{1}/_{8}$”x12” rigid frames(13)) are classified as achieving 1 hour fire rating as heavy timber per IBC 2009 Table 601 Note C and Table 602.4, which requires glulam members to be larger than 3”x 6 7/8”. Therefore, additional fire protection was not required despite lowering the heights of the cascading greenhouses to improve the space utilization within the greenhouses. The applicable moisture factor was used during wood design, however, the moisture levels in the greenhouse environment were not anticipated to be an issue in relation to wood deterioration, especially when utilizing preservative treatment (Mech|5). However, to ensure durability and longevity of the structure, non-toxic pigmented acrylic latex paint or pigmented alkyd paint(14) shall be applied.

For the cascading greenhouses, ½”ϕ galvanized steel tension rods were used to provide lateral support via X-bracing between every other frame, as depicted in Figure 13.

### TOP GREENHOUSE

The top roof greenhouse was designed in structural steel due to the larger spans and strength limitations of wood (SD|XVIII). The design was completed utilizing **tree-columns**, shown in Figure 14, to maximize spans, while minimizing the number and size of members. In addition, the number of columns impeding the space was limited. This helped improve daylighting levels in the greenhouse (Elec|5) and enabled the floor plan to remain more open and flexible.

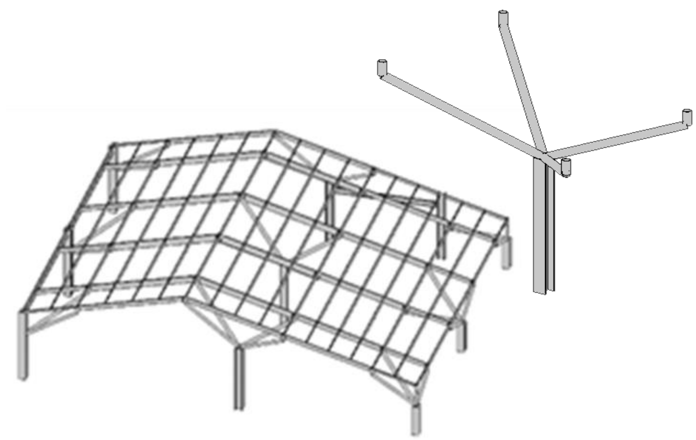

*Figure 14. Top greenhouse structure (left) and tree column (right).*

The **grate system** in the greenhouses enables piping to be run below the architectural floor level, decongesting the growing space floor without blocking light. The system is designed as a raised-access floor system with corrosion resistant cast aluminum 2’x2’ grates to enable the easy removal and rearrangement of the system components. (15) This is achieved by dropping the structural level down 14”, then placing a waterproofing membrane and a 2” light weight fiber reinforced weathering slab on top of the structural slab (SD|XVII).

This design also enables proper drainage in the greenhouses, as **bi-level drains**, detailed in Figure 15, are below the grate system such that water can flow unobstructed to the drain on the topping slab. The bi-level drain also collects any water that passes the **topping slab** and reaches the **waterproofing membrane**. This helps improve the durability and lifespan of the structure and building

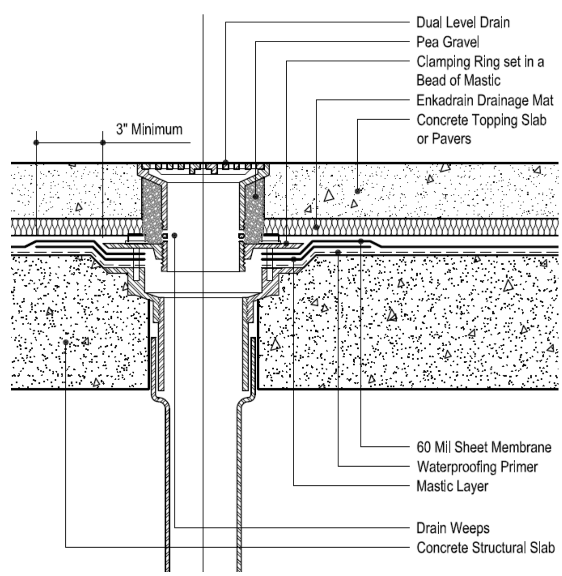


*Figure 15. Bi-level drain in greenhouse floor and rainwater collection trough (16)*

The **rainwater collection trough** (SD|XVII) between the greenhouses was designed to support a ponding load in the event that the drains become clogged, and the water cannot drain (Mech|6). The trough was also designed for impact loading that could occur should snow slide off of the upper roofs (SD|VI). Although the greenhouses would typically be heated, preventing snow build-up, the structural design partners deemed it appropriate to design for a case where snow would build up if greenhouses were closed, and therefore unheated, for maintenance or during construction.

## FAÇADE

The selected **rain screen system** is advantageous for all portions of the design team for a numerous reasons (Int|10). The rain screen system, shown in Figure 16, enables various finishes, in this instance terracotta, to be attached to clips which tie back in to **galvanized cold-formed steel studs**. The structural load of this system (25 psf) is less than the loads of other typical façade systems, such as brick veneer (~40 psf).

*Figure 16. Rain screen facade mock-up*

Cold-formed steel studs (6” deep, 16 gage Clark Dietrich 600S @ 16” o.c.[17]) were selected as the back-up system for the façade over CMU due to the lighter system weight, lower cost, shorter construction duration, and ease of construction (SD-XIX). As the perimeter beams were typically upsized to facilitate connections, there is adequate capacity should CMU be deemed appropriate for other locations, such as where the acoustic characteristics of CMU are needed. The use of CMU backup structure would result in 71% utilization of the perimeter members vs. 58% with studs. However, the resulting building mass increases the seismic weight by 32%, thereby intensifying base shear accordingly. The rain screen also poses opportunities for creating a proper moisture barrier and variation in architectural aesthetics (Int|10). This prevents water penetration that can damage the façade, in addition to potential corrosion of the façade back-up structure.

## PROTOTYPING

The structural design was conducted in a manner that facilitates the **transferability** of much of the building design by addressing aspects of the code that vary throughout the country. The intent was to provide Growing Power with a template for expanding and spreading to other communities.

Obviously, the foundation portion of the design is not completely transferable as soil conditions will vary with every new site. However, the site soil properties in Milwaukee are very poor, so soil properties should ideally only improve. Even within the Greater Milwaukee Region, USGS maps indicate a high frequency of soil compositions that would offer improved bearing capacity over those indicated in the geotechnical report. Improved soil conditions could enable the use of simple spread and/or strip footings, as recommended in the geotechnical report.

The greenhouses were designed to be easily transferable to other locations, by easily changing member sizes as necessary. For

[MIAMI HIGHLIGHTS]

Transferable Lateral System:
Lateral system designed for Miami, by upsizing structural elements while maintaining the same configuration.

Flexible Prototype Façade:
Rain screen system can be adapted to Miami wind loadings and requirements by adjusting clip and stud specifications.

Greenhouse Structures:
The greenhouse roofs are transferable to Miami with adjusted sizes for new loading conditions

example, in **Miami**, the **glulam members** of the cascading greenhouses and **steel members** of the top greenhouse would **increase in size** due to the **higher wind loading** conditions based on procedures from ASCE 7-05. The lower-cost option of mass-manufactured greenhouses was available, however, AEI Team 4 decided to design custom greenhouses to provide Growing Power with a striking, durable, efficient, and high-quality integrated product.

If Growing Power wanted to sacrifice durability, aesthetics, and quality for a cheaper option, the custom-designed glulam-framed cascading greenhouses and steel-framed top greenhouse could be replaced with basic mass-manufactured greenhouse structures, pending code compliance of those selected. The custom greenhouses were designed in a manner to lower the roof heights to decrease the volume of conditioned space, while meeting code requirements as discussed earlier.

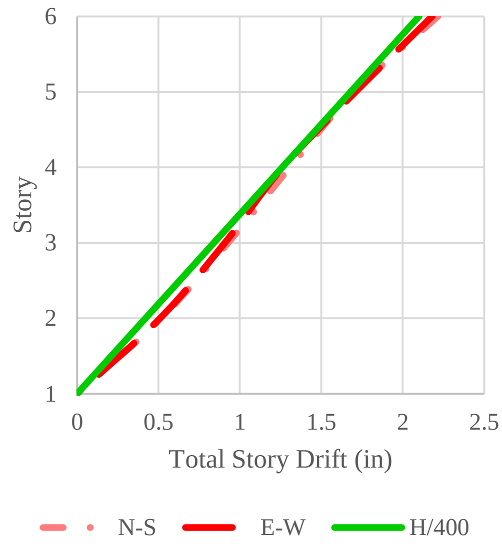


*Figure 17. Miami drift comparison*

For Miami, the wind load values were derived using **Exposure C** because a specific site was not selected, so the surrounding surface roughness was unknown. In addition, a **partially enclosed** structure was assumed in the event that debris in a hurricane were to damage the greenhouse glazing, causing the pressurization to change. By making these assumptions, the structural design for cladding and the lateral system may have been conservative, but alterations could be made once a specific site were selected for Miami or other locations.

The façade design was also conducted to enable easy relocation to future sites, as discussed in the façade section. For Miami, the cold-formed steel studs would need to be re-specified to **6" deep, 12 gage Clark Dietrich 600S @ 12" o.c. to address the increased wind loading**.

The lateral system for Miami utilized the **same configuration of moment frames**, while select **members were up-sized** for the new unfactored loading conditions, although the drift values were closer to the minimum requirement (Figure 17). This verified the structural partners' intent to make the structural design **transferable** to new locations by exchanging member sizes as required.

## CONCLUSION

The design of the Growing Power headquarters in Milwaukee, and desire for a prototype for future locations starting with Miami, presented the structural partners of AEI Team 4 with a number of assorted, complex challenges. The team examined the project requirements and challenges to develop goals to guide and drive the design process and decisions to create integrated systems that comprise a building that satisfies Growing Power's needs and goals.

With the various goals in mind, the structural partners developed a **cost-effective, integrated** structural design that utilizes a **composite structural steel** floor gravity load resisting system to minimize member sizes and structural self-weight. The **sustainable** ideals of Growing Power and AEI Team 4 were incorporated through the use of **renewable wood products** in the cascading greenhouse roofs, which also act as an **architectural accent**. Custom **transfer girders** were designed to **clear-span** the building in select locations to create a **column-free gathering space**. In the building as a whole, the structural partners strived to minimize the encroachment of the structural system upon the floor plan in an effort to enable Growing Power to adjust and alter the program layout in future locations. To provide Growing Power with the **freedom to adapt** their operations, the structure supporting the greenhouses was designed for **4' water tanks in any location** such that the aquaponic systems can be rearranged and relocated within the greenhouses as necessary without requiring additional structural evaluation. The greenhouses provided a fantastic opportunity for **systems integration**, to which the structural discipline contributed the development of the **tree-columns and grate system**. To promote the **durability and longevity** of the structure, especially in the greenhouses where water will be continually present, **waterproofing and drainage** concepts were developed. As a whole, the structural design was conducted to create a **prototype** for Growing Power to utilize for any future locations, namely Miami. The prime example of this concept is the **lateral system** design, where the arrangement remains untouched, while member sizes are adjusted as needed. Upon reviewing the Geotechnical Exploration Report, the structural partners became concerned with the recommended allowable bearing capacity and sought out **innovative foundation system** methods to assuage the challenge at hand. The solution was the implementation of **Geopier® soil reinforcement** to improve the effective soil bearing capacity for the Milwaukee site.

Table 5. Goals and Solutions Summary

| Project Goals | Design Solution/Outcome | Project Initiatives |
|---|---|---|
| Cost-Effective, Integrated Structural Design | Composite Steel Floor System | Economy, Flexibility |
| Sustainable & Renewable Elements and Concepts | Glulam Greenhouse Roof Members | Sustainability, Community |
| Column-Free Gathering Space | Clear-Span Transfer Girders | Flexibility, Community |
| Adaptable Program Layout | Minimize Structural Footprint in Floor plan | Flexibility |
| Ability to Place Aquaponic Systems Anywhere in the Greenhouses | Structural System Designed for 4' Tanks | Flexibility, Sustainability, Community |
| System Integration in the Greenhouses | Tree-columns and Grate system | Flexibility, Sustainability, Community, Economy |
| Durability of the Structure, Especially Greenhouses | Waterproofing and Drainage Detailing<br>Galvanization of Greenhouse Steel Elements | Economy |
| Facilitate the Development of Future Locations | Lateral System Configuration Remains Intact While Sizes Change | Flexibility, Economy |
| Innovative Foundation Design Addressing Bearing Capacity | Geopier® Soil Reinforcement | Economy |

The structural discipline has succeeded in providing Growing Power the means with which to further their mission. The composite structural steel gravity system was designed to enable Growing Power to vary the layout of growing systems, providing **flexibility**. The steel lateral system was developed to ensure that the design is **transferable** and adaptable to other locations and other loading conditions. The waterproofing of greenhouses and the façade protect the structure and promote the **longevity** of the building. Through collaborative process and utilization of BIM technology, the structural team was able to accomplish the various discipline goals by developing solutions that also addressed the project goals and initiatives, as presented in Table 5, in order to deliver Growing Power the building that fits their needs.