Structural Redesign of a Perimeter Diagrid Lateral System

University of Cincinnati Athletic Center
Cincinnati, Ohio

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Structural Option

Spring 2004 Senior Thesis
Architectural Engineering
Penn State University

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Project Overview

Multi-use – Includes offices, a ticket center, meeting spaces, computer labs, locker rooms, an auditorium, and gymnasium facilities
Eight stories – (5 above grade, 3 below)
Size – 220,000 ft^2 total (150,000 ft^2 above, 70,000 ft2 below)
Construction Dates – May 2003 - December 2005 (expected)
Estimated Cost – $50.7 million

Architectural Features

Unique triangulated "diagrid" exterior façade
Unusual kidney shape in plan
Soaring 5-story central atrium
Tightly integrated with surrounding buildings
Designed to be LEED certified

Project Team

Owner – University of Cincinnati
Occupant – UC Athletic Department
Design Architect – Bernard Tschumi Architects
Local Architect – Glaserworks, Inc.
Design Engineer – Arup, New York
Structural Engr. of Record – THP Limited, Inc.
MEP Engr. of Record – Heapy Engineering, LLC
CM Advisor – Turner Construction

Mechanical System

Cooling source – University central chilled water plant
Heating source – University steam system
Equipment – Double-walled Air Handling Units with economizers
Distribution - Two mechanical rooms splitting north/south sections of building servicing VAV boxes
Miscellaneous – Atrium smoke exhaust control. All equipment tied into Building Management System controls.

Structural System

Foundation – Spread footings and drilled piers
Substructure – Retaining walls braced by basement level slabs
Superstructure – Steel composite beams and composite metal decking supporting one-way slab diaphragms
Envelope – Full height trussed frame from steel wide flange and box sections, resting on V-shaped steel columns
Lateral System – Perimeter "diagrid" structure with braced frames

Lighting/Electrical System

Utility service – Taps into 12.5 kV campus loop, transformed down to 480/277V. 800kW diesel emergency generator.
Distribution – Vertical distribution to panelboards in electrical closets at each floor. Transformed to 208/120V for general service
Lighting – Primarily high-efficiency fluorescent with occupancy sensors and dimming control

E-portfolio website: www.arche.psu.edu/thesis/2004/bjg181

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Executive Summary

Innovative architecture demands innovative engineering solutions. The unusual shape and site constraints of the University of Cincinnati Athletic Center led to the initial design of a perimeter diagrid lateral system. This system has three main issues which must be addressed:

1) The original design is much heavier than a typical gravity-only perimeter system. Material costs are high.
2) Welded connections at each diagrid node are time and labor intensive. Labor costs are relatively high.
3) Very little of the usable window viewing height is glazed. Views of the surrounding landscape are limited.

This report is the culmination of a yearlong senior thesis project which researched the building and investigated the above issues. Three possible approaches to these problems, called "Solution Areas" were identified:

I) Keep the perimeter lateral system in the current configuration while changing the material of its members
II) Keep the perimeter lateral system while modifying its architectural (and hence structural) geometry
III) Move the lateral system from the perimeter to within the building, changing the envelope to a curtain wall

Analyses were performed to determine feasible alternatives in each area. Several methods of analysis were used to compare between the alternatives and the original system. These methods included hand calculations, spreadsheet tables, computer modeling, and even simple qualitative evaluations.

The results found that changing the material in Solution Area I did not produce any additional benefits over the original steel wide flange system. Modifying the geometry in Solution Area II made the system more structurally efficient, but other factors decreased its effectiveness. However, removing the diagrid in Solution Area III and replacing it with a perimeter truss and braced frame system led to significant advantages, both structurally and architecturally. These advantages include:

- Reduced structure weight and increased efficiency
- Opportunities for more usable windows by opening up the façade with a curtain wall
- Minimal impact to the interior layout
- No change in floor-to-floor height
- No impact on floor framing layout

Preliminary daylighting and construction management studies were also performed to evaluate the perimeter truss design and its effects on the rest of the building. The studies further refined the design, and found that the new curtain wall does not have any major issues which would be detrimental to its feasibility.

Overall, the structural redesign of the University of Cincinnati Athletic Center was successful. The innovative perimeter truss and braced frame system is a viable alternative to the original diagrid not only from a structural engineering standpoint, but from an architectural perspective as well.

Introduction

The University of Cincinnati Athletic Center is an 8 story, 220,000 ft^2 multi-use facility currently under construction and is located in the heart of University's "Varsity Village" athletic complex. The building is designed to house virtually all of the support services for the University of Cincinnati's intercollegiate athletic program. It will function as the social link and architectural centerpiece of a multi-stage athletic expansion plan. As such, it is situated between two main sports facilities, the Nippert Football Stadium and the Shoemaker Center, with easy access to other sports fields and areas. The Athletic Center contains a variety of spaces to accommodate the UC athletic department, including:

- Offices for all coaches and administrators
- Locker rooms for various athletic teams
- A ticket center
- Computer labs and private study spaces
- New sports medicine and athletic training facilities
- A practice gymnasium with two courts
- A university and sports museum
- New strength and conditioning facilities

This report is the conclusion of a year-long thesis studying the proposed building. It was researched, evaluated, and redesigned. This paper uses the background information and knowledge gained through the research and evaluation to present a redesign of several aspects of the building, primarily its structural system. The purpose of the report is not to mandate changes in the actual construction, rather to simply study and learn from alternative solutions to the challenges which faced the designers.

Note: In March of 2003 a donation by a Cincinnati philanthropist permanently changed the name of the building to the Richard E. Lindner Center; however its original title has been used for the entire report.

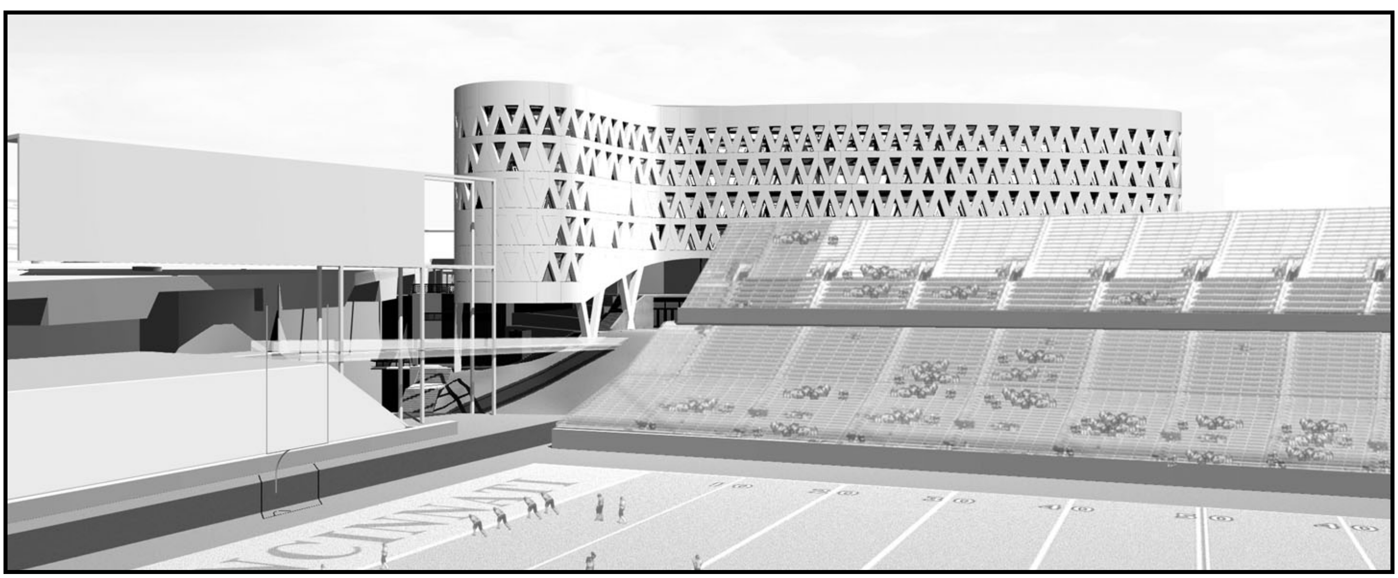


Figure 1: Panoramic view from the west

General Description

Site

The Athletic Center fits into an extremely tight space between the Nippert Football Stadium, Shoemaker Center, and Recreation Center (Figure 2). The footprint of the building turns a corner to accommodate these existing facilities. Part of the Shoemaker Center was demolished to make space for the new construction; however a portion of its below-grade spaces, namely the underground gym and locker rooms, still exists for connection to the Athletic Center. The area on which the building sits is quite populated due to neighboring athletic facilities and plans of future expansion for football and soccer fields, tennis courts, and a baseball stadium (Figure 3). Site traffic is therefore quite heavy, and pedestrian circulation paths are provided continuously around the entire building.

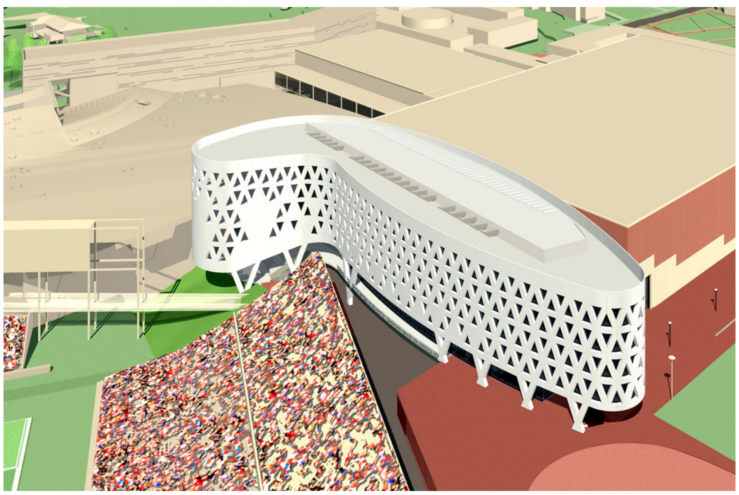


Figure 2: Site context rendering

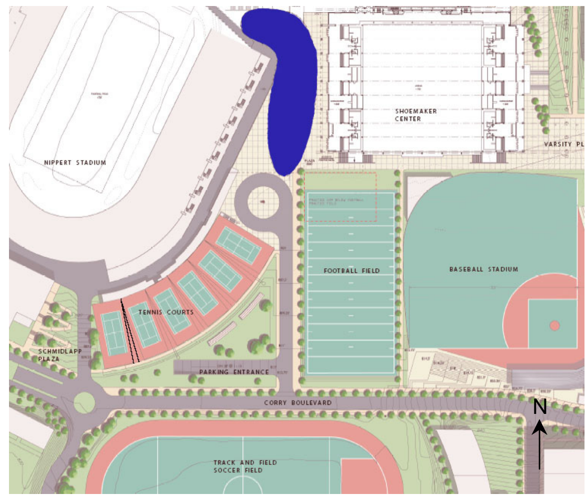


Figure 3: Expanded site plan

Architecture

Architecturally, the design is characterized by its unique exterior façade (Figure 4). The façade consists of a triangulated "exo-skeleton" of concrete-covered steel. This skeleton, referred to as a "diagrid", forms a visually dominant shell around the building. The heaviness of this exterior system is offset by its light color and appears to be lifted off the ground by a series of v-shaped columns.

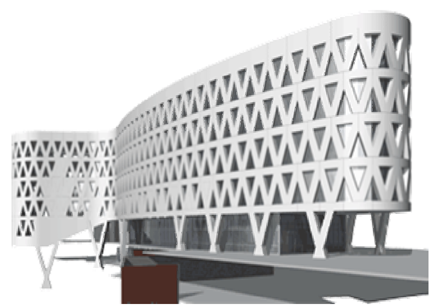


Figure 4: Façade close-up

Also unique to the building is its curved shape. There are no corners in above-grade plan, creating a rather unusual kidney or "link-pin" shape (Figure 5). The interior space of the building itself is divided by a 5-story atrium running down the middle of its main section. To each side are offices, meeting rooms, and administrative areas. Below ground is a more conventional rectangular footprint, with mainly sports facilities and locker rooms. Horizontal movement through the building is kept simple by its compact design, however vertical movement is facilitated by a set of elevators and a grand staircase in the atrium.

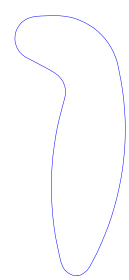


Figure 5: Plan outline

Building Systems

Electrical

Power for the building is taken from a 12.5 kV campus loop. Medium voltage switchgear in a redundant double-ended unit substation transforms the utility tap down to 480/277V. A 480V switchboard located in an adjacent room distributes power to each floor's electrical closet vertically via cable feeders in conduit. Voltage is then transformed down to service 208/120V panelboards, where it is fed to branch circuits. Sufficient spare capacity is provided for future loads. Typical 20A grounded power receptacles are placed in each room. Isolated circuits are provided for computer equipment outlets to reduce detrimental harmonic effects. An 800 kW diesel generator supplies four hours of autonomous backup.

Mechanical

The building is fully air conditioned and heated. The mechanical system is served by low velocity double wall air handling units in two equipment rooms. Chilled water for cooling is supplied by a University of Cincinnati central chilled water plant. The 45 degree water is metered upon entrance to the building. Two secondary, variable speed pumps sized for 100% of the 720 ton cooling load circulate the water. The building heating taps into the University's campus steam system. Two parallel pressure reducing valves reduce the loop's high pressure steam to low pressure steam. The steam is also converted to hot water by two straight-tube heat exchangers, operating independently or together. Perimeter fin tube radiation and VAV boxes with hot water reheat condition each individual space. Zone carbon dioxide sensors connected to the Building Management System control indoor air quality.

Lighting

The majority of luminaires are high-efficiency fluorescent modular ceiling recessed fixtures, predominant in the office and non-public areas. Compact fluorescent with rapid start electronic ballasts are also used. Local switches and occupancy sensors provide their control. In more specialized spaces, such as kitchens and multi-purpose rooms, tungsten accents lights and track lighting combine with time programs and scene set dimmers to allow detailed control. In the atrium, linear fluorescent lamps with louvers respond to daylight levels in the atrium through the use of an array of light level sensors. The exterior diagrid facade is floodlit in an upward direction by luminaires with changeable optics. Emergency lighting is provided as specified by code.

Fire Protection

Active fire protection occurs through the fire alarm and sprinkler systems. The fire alarm system is fully addressable and networked throughout the building. Remote annunciation panels are provided. Horns, strobe lights, smoke detectors, pull stations, and door release are integrated into the system. The entire building is served by an automatic combined sprinkler and standpipe system, connected to the 12" campus water main. It is a wet system, with quick-response fusible link or frangible bulb sprinkler heads. Areas where freezing occurs are protected by an automatic dry type system. Pressure-reducing valves regulate smoke buildup pressures on each sprinkler connection. Standpipes are equipped with 2.5" hose valves, but no hoses. In the case of fire during power loss, 1250 gpm fire and jockey pumps are connected to the emergency power supply.

Structural System Description

Gravity System

The floor framing system consists of typical steel composite wide flange beams with composite metal decking supporting one-way slab diaphragms. Most connections are shear only, though some elements framing into full height columns near the atrium are designed with moment connections to support atrium walkways. The layout is irregular due to the highly curved shape of the building; however, the N-S direction spacing is typically 9' o.c. within 27' bays. A representative above-grade framing plan is shown in Figure 6.

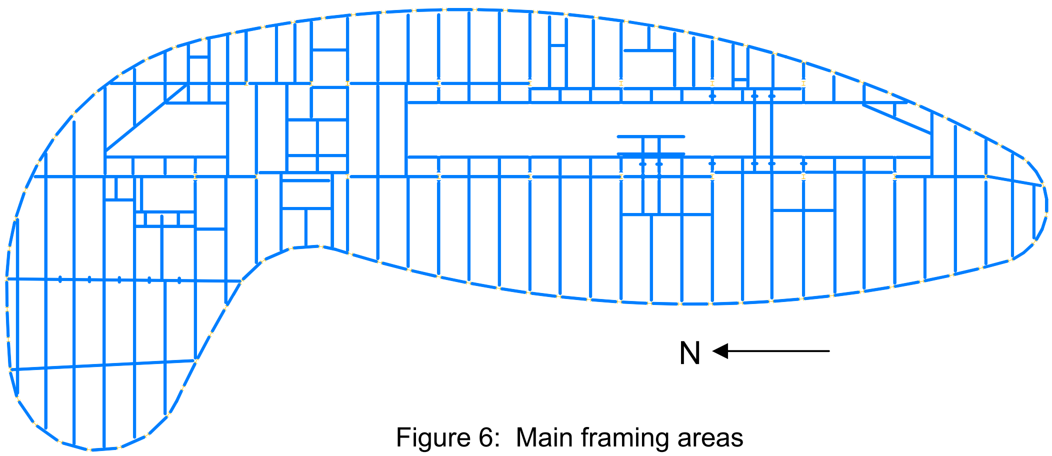


Figure 6: Main framing areas

Lateral System

Diagrid and Diaphragms

The above-grade enclosure of the Athletic Center is a triangulated, curved perimeter frame system called a diagrid. The diagrid acts as a rigid shell, and for structural purposes can be considered a very thin, deep beam. It is composed of wide flange rolled sections welded or bolted for full restraint. The steel is covered with precast concrete cladding to produce a monolithic appearance. Between the beams are triangular window glazings. A rendering of a typical diagrid connection is shown in Figure 7. The above-grade diaphragms are 6.5" reinforced concrete slabs on metal deck, supported by steel framing. There are numerous slab openings, including the main atrium and several elevator and stair shafts.

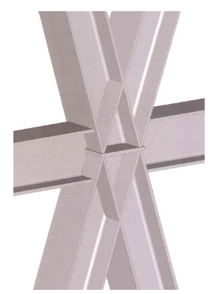


Figure 7: Diagrid connection

Braced Frames

There are four types of braced frames. Two of them, labeled BF2 and BF3, are light braced frames around the atrium staircase. They both span from Level 100 to Level 400 (ground floor) and provide lateral support for the staircase only. The other two, labeled BF1 and BF4, are heavy braced frames to resist lateral movement for the entire building. Two BF1s brace against E-W deflection around an elevator shaft in the northern half of the building, while the lone BF4 braces against East-West deflection in the southern half. Frame elevations are shown below in Figure 8.

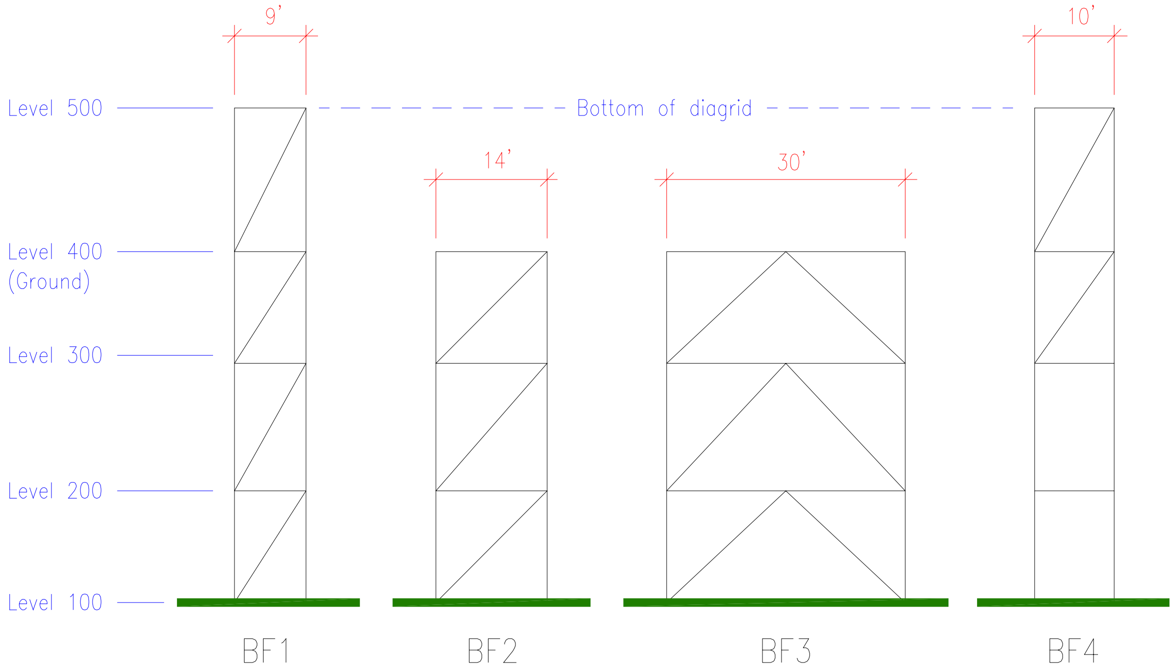


Figure 8: Braced Frame Elevations

Columns

There are two kinds of columns found in the Athletic Center. Within the perimeter of the building are two rows of full height vertical columns, supporting the floor and partition gravity loads of the interior bays. Between Levels 300 and 500 are large "V" columns which are rigidly connected to both the diagrid and the substructure. Though their primary function is to carry gravity load from the diagrid, they also play a significant role in the transfer of lateral forces from the bottom of the diagrid to ground level. They are made of either heavy wide flange rolled shapes or built-up boxes, and sit on single below-grade columns. A rendering of a V column is shown in Figure 9.

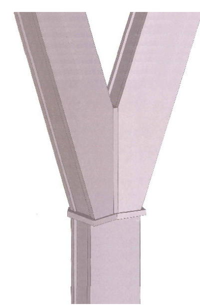


Figure 9: V column

Foundation

The foundation utilizes a combination of spread footings and drilled piers, set into gray shale. Reinforced concrete shear walls below grade serve as the retaining walls as well and are typically 1'6" thick. They are rectangular in plan and therefore do not carry the loading from the curved above-grade floors. They do, however, work with the below-grade diaphragms to resist shear forces. There are 16 threadbar anchor rods embedded in the foundation walls to resist shear. As in the upper floors, the foundation diaphragms are 6.5" reinforced concrete slabs on metal deck.

Problem Statement and Solution Overview

Problem Statement

The largest, most visible architectural and structural component of the Athletic Center is its perimeter diagrid system. It is arguably the most unique aspect of the building, and presented quite a challenge to both the architect and the structural engineer. Though the diagrid was certainly a sound and acceptable choice for the cost, schedule, architectural, and other constraints given to the structural team, it was not the only available solution to the design parameters of the project. In fact, three main issues were identified which are potential drawbacks to the current design. They are presented below:

1) The perimeter diagrid lateral system is much heavier than a typical gravity-only perimeter system. Material costs are relatively high.
2) Welded connections at each diagrid node are time and labor intensive. Labor costs are relatively high.
3) Very little of the usable window viewing height is glazed. Views of the football stadium and surrounding buildings are limited and unusual.

These three issues alone represent significant disadvantages to the Athletic Center's budget and performance. They have warranted further investigation into alternative solutions to the perimeter lateral system. As a result, research concentrated on identifying all potential weaknesses in the diagrid system, proposing viable options to those weaknesses, and ultimately determining which option, if any, is most appropriate.

Solution Overview

Structural Redesign

The Athletic Center's unusual perimeter lateral structural system did not lead to a standard, "cut and dry" solution to the design requirements. It was unlikely that any one option would perform optimally in all performance considerations. Therefore, three distinct Solution Areas labeled I, II, and III have been investigated and evaluated. Each area varied in its degree of deviation from the original design.

I) Keep the perimeter lateral system in the current diagrid configuration while changing the material of its members
II) Keep the perimeter lateral system while modifying its architectural (and hence structural) geometry
III) Move the lateral system from the perimeter to within the building, changing the envelope to a curtain wall

Solution Area I addressed issues 1 and 2 from the problem statement. Changing the material or detailing of the diagrid impacted both the material and labor costs associated with its construction. Solution Areas II and III also addressed the cost concerns of issues 1 and 2; however, because of their potential to drastically change the structural design of the building they impacted issue 3 as well.

Daylighting Study

All of the proposed options for the perimeter lateral system affected the building's enclosure properties, including the amount and position of glazing required. In addressing the third issue from the problem statement, it was a natural extension of the structural research to perform a qualitative daylighting study. The study considered several factors for potential daylighted private office spaces along the western side of the Athletic Center. These factors were developed into a curtain wall façade intended to work with the redesigned structural system. The results from this study were integrated into the overall final considerations and recommendations.

Construction Study

Naturally, changes to the structure and architecture of the perimeter lateral system had a substantial impact on several construction issues. A construction management study of two of these issues, erection sequencing and site layout, helped determine whether the proposed system alternatives were feasible.

Structural Redesign

Theory

Innovative architecture demands innovative engineering solutions. The unusual design of the Athletic Center presented a substantial challenge for the engineering team to find a creative answer. Often when a building exterior is as unique as the Athletic Center the structural engineer must assume more responsibility for the architectural design. In this way they become more of an architect-engineer, attuned to the aesthetics of shape, form, and balance, while maintaining a firm grasp on the practical requirements of safety, economy, and constructability. The primary goal of the structural redesign was to take advantage of the opportunities which exist in the original design to develop a creative yet sensible alternative.

Therefore, there was no hesitation to alter the architectural look and feel of the building. Liberties were taken in changing the façade to meet demands of the new structural designs. However, complete disregard of the Athletic Center's contextual and programming requirements would be irrational and irresponsible. The general shape, height, and space layout was kept consistent with the original intent of the architect and owner. This restraint also helps reduce the scope of research and focuses the redesign on more comparable alternatives.

In order to further refine the above theory and to provide a base by which designs can be evaluated, the following specific goals are outlined below:

- Increase overall structural efficiency.
- Decrease the cost of the building as a whole, not just structure.
- Keep the design feasible from a construction standpoint.
- Reduce system complexity if possible.
- Limit redesign to the diagrid system only, however, check major effects that the changes will have on the rest of the building, such as foundation overturning and torsion

The Solution Area approach was developed to obtain a complete picture of the available alternatives to the diagrid system. It starts with a relatively non-disruptive replacement of the diagrid material, moves to a visibly changed exterior geometric change, and ends with the total discarding of the diagrid itself. Therefore, there are three progressive levels of architectural deviance.

For each Solution Area the general method was threefold:

1) Research – Available options were obtained through background research
2) Design – Those options were analyzed to find size, efficiency, feasibility, etc.
3) Select – The most reasonable option (if any) is chosen for comparison to the others

Specific selection criteria for comparison between alternative systems and the original system vary by Solution Area. They are identified and explained within each section.

The structural design of the Athletic Center utilized the 1998 Ohio Basic Building Code. Other major codes and standards used for the redesign are ACI 318-02, AISC LRFD Design Manual 2001, NDS 2001, and ASCE 7-98.

Solution Area I – Changing the material of the diagrid

The purpose of Solution Area I was to keep the perimeter lateral system in the current diagrid configuration while changing the material and/or detailing of its members. Before undertaking this task, examples of other diagrid systems were found. It was determined that 5 alternative materials have been or could be used in such a configuration. Those 5 alternatives are rectangular HSS, round HSS, glulam timber, precast concrete, and cast-in-place concrete.

Procedure

The alternatives were evaluated through a wide spectrum of categories. Each alternative in every category was rated on a scale of 0-100 by either an analytical procedure or simple educated assumptions. The categories which used an analytical procedure are:

- Weight – Force output from a computer model was used with a spreadsheet to find a typical axial to moment force relationship. This relationship was found to be about 2. A representative load of 200 kips (compression)/100 ft-kips was employed to size members using the respective design methods for each material. The sizes multiplied by material density gave approximate weights per foot of diagrid member.
- Cost – Once the members were sized, basic costs from Sweet's Unit Cost Data converted the weights or lengths to cost per foot. This cost was used with the consideration of fireproofing, insulation, etc.
- Size – The force output used to determine typical member weights was also used to find the most loaded member (475 kips/550 ft-kips). This member was sized in each material by the same design method as above.

The categories rated using educated assumptions were weighted for importance according to their contribution to the material's overall feasibility. They are:

- Availability
- Lead time
- Erection time
- Flexibility
- Durability
- Labor cost
- Fire resistance

Results

All of this information above was tabulated in Excel. The resulting spreadsheet indicates that no single system performs head and shoulders above the rest (Appendix A.1). Summaries of the ranking and scoring are shown in Table 1 and Chart 1.

Material	Rank
Wide Flanges	1
Rectangular HSS	3
Round HSS	2
Glulam Timber	6
Precast	5
Cast-in-place	4

Table 1: Alternative Diagrid Material Ranking

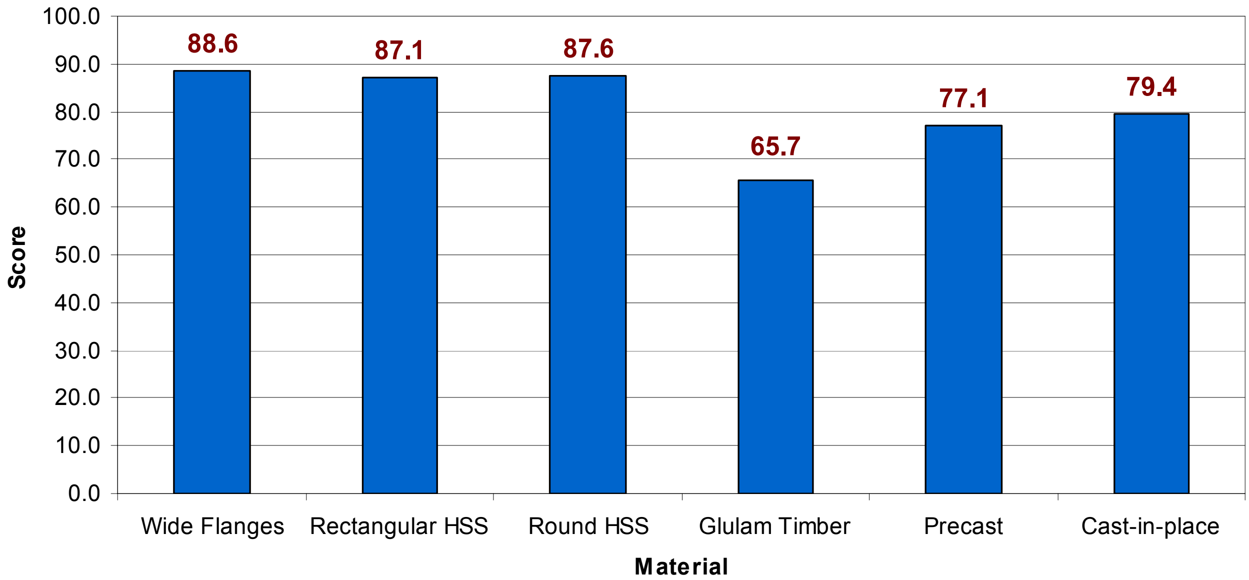
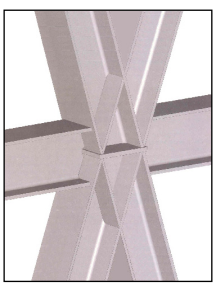


Chart 1: Alternative Diagrid Material Scoring

The original steel wide flange diagrid slightly edged out rectangular HSS and round HSS. In general, the steel options scored better than the concrete or wood options. An overview of each alternative's advantages and disadvantages are explained below.



Steel Wide Flange

Advantages – The weight and size of wide flanges are optimized to resist the high bending loads many of the members experience. This results in reduced structure weight and flexibility of size.

Disadvantages – Pre-fabrication of the diagrid sections requires a longer lead time. Careful planning can overcome the additional scheduling time.

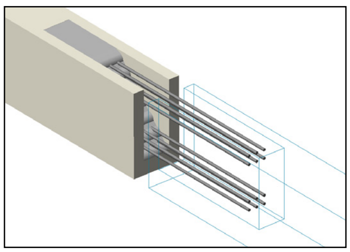
Rectangular and Round HSS

Advantages – As with wide flanges, HSS sections can be prefabricated in multi-panel sections, which would allow quick erection by crane. The quick erection also reduces labor costs in the field.

Disadvantages – Floor layouts will be changed because beams will need to frame into node points. This reduces floor flexibility and efficiency.

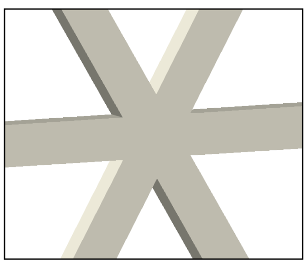
Glulam Timber

Advantages – Multi-panel sections can reduce erection time.
Disadvantages – Timber costs, both for material and connections, are much higher than the traditional structural materials of steel and concrete. The large sizes required by strength design (not even considering deflection and creep) prohibit its use in this application. Additionally, durability and weathering of the timber are issues.



Precast Concrete

Advantages – The flexibility of precast allows it to fit the curved form of the building. Concrete is also an extremely safe material against structural fire damage.
Disadvantages – Additional dead weight due to the large cross sections impact the foundations below grade, as well as increasing deflections of the long spans. Concrete creep is also an issue.



Cast-in-place Concrete

Advantages – Material cost is excellent, due to the low pound-for-pound concrete/steel cost ratio. Lead time is virtually nothing because cast-in-place is available on demand.
Disadvantages – Counteracting the nonexistent lead time is a lengthy erection time, complicated by the need for unusual formwork shapes and rebar splices. Labor costs will reflect the increased field time.

Discussion

Overall, wide flange steel is still the most reasonable choice. None of the other choices seem to offer substantial benefits over the original diagrid material. It must be concluded that this solution area did not produce a reasonable alternative to the current system, and therefore the original design will be kept. Consequentially, wide flange steel will continue to be used in the upcoming redesigns.

Solution Area II – Modifying the geometry of the diagrid system

Although the perimeter diagrid system functions as both the gravity and lateral load carrying system for the above grade levels, it is not an exceptionally efficient structure. The dense array of this virtual "wall of steel" uses relatively little of its potential strength. Many members are barely stressed under factored loads while a select few approach their practical load limits. The obvious solution would be to adjust the size of each individual diagrid segment to more fully utilize its strength capacity and/or deflection contribution. Unfortunately, this creates fabrication, erection, and cladding complications, increasing cost and scheduling of the building simultaneously.

The purpose of Solution Area II was to maintain the perimeter gravity and lateral system while taking liberties to modify its architectural (and hence structural) geometry. The goal was to develop a more efficient structure similar in concept to the original diagrid which would overcome weight, complexity, deflection, and drift issues.

There are two main ways to modify the geometry of the structure. They can be executed alone or in combination:

1) Open up the grid
   This can be accomplished by either removing members in a consistent fashion along the entire façade or by reducing the density of the grid in certain sections only, such as on the upper stories. One of the most well-known examples of this approach is the architecturally and structurally acclaimed John Hancock Center in Chicago. Its characteristic diagonal bracing was derived from a fine diagrid mesh on each face. The grid was made progressively coarser (Figure 10), increasing its structural efficiency while creating the clear X shapes the skyscraper is associated with (Iyengar, 47).

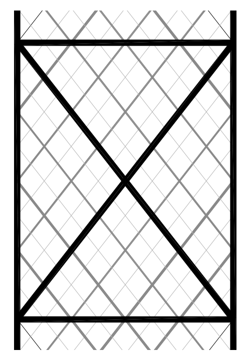


Figure 10: John Hancock Center grid

2) Adjust configuration
   The arrangement of the diagrid can change by either reorienting the members to different slopes or by letting the members "follow the load path." The latter option is well documented in engineering literature and sometimes produces unpredictable yet elegant results. An example of this theory is the Central China Television (CCTV) tower currently in development by the Office for Modern Architecture and Ove Arup engineers (Figure 11). The daring expressed design allowed the structural team to modify its diagrid configuration to accommodate areas of high load flow. (Reina, para. 7)

Figure 11: CCTV

To assess and compare the performance of the various options which were developed, the following categories were taken into consideration:

- Structural Efficiency – weight of superstructure
- Structural Stability – strength through redundancy, deflection
- Architectural Impact – geometry of the plan, V column layout
- Floor Framing Impact – orientation of framing members, connection ability
- Material Cost – steel, glazing, insulation, cladding
- Complexity – labor and connection material cost

In selecting the most desirable system, more emphasis was given to the structural categories of efficiency and stability.

Procedure

Structural Efficiency and Structural Stability

Using the structure modification techniques above, alternative geometric configurations of the diagrid were developed. Initially, these were drawn in two dimensional views (see Appendix B.1), which seemed to be the easiest way to visualize the patterns and proportions. It was determined that analyzing these representative 2D elevations would be much more efficient than analyzing the actual 3D shells. Although this approach is a simplification of the actual curved façade, the inaccuracies were assumed to be negligible. Furthermore, the alternatives could be easily evaluated for major axis bending and axial forces, the two most prevalent member forces in the original diagrid structure.

In order to choose a section of the perimeter for analysis, moment and axial force diagrams of the original diagrid system were studied. Looking at Figures 12a and 12b below, the areas of highest force occur at the northern end of the building. A section centered at the Northeast corner which includes two of the greatest areas of stress and the longest span was chosen. It is highlighted in green.

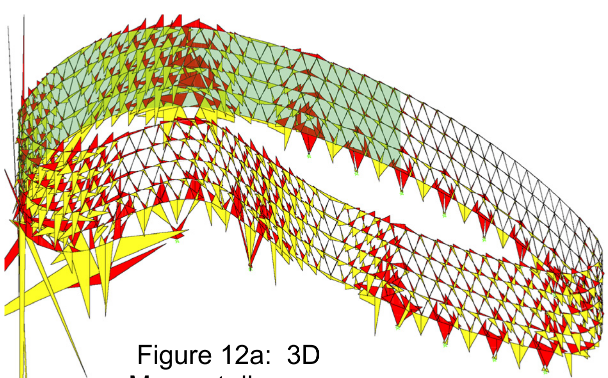


Figure 12a: 3D Moment diagram

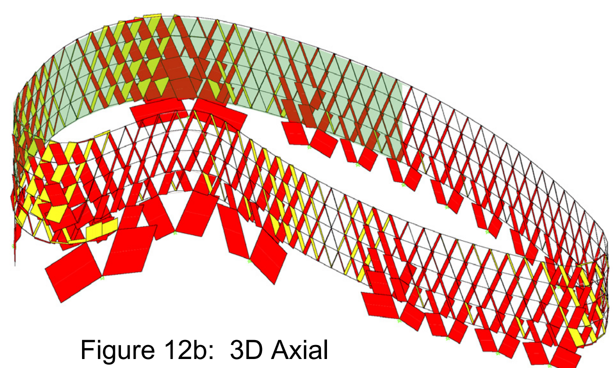


Figure 12b: 3D Axial Force diagram

The final elevations for all of the options, or cases, were set using this Northeast section. Support conditions were modeled to be as close to the original V columns as possible. Cases 1, 2, 3, 4, 5a, 5b, and 5c are shown in Figures 13a through 13h. For Case 6, the technique of following the flow of forces was used. To do this, the section was modeled in the STAAD structural analysis program as a uniformly loaded simple beam with relative support conditions similar to the elevation. The moment diagram of the beam (Figure 14) gave insight as to how the diagrid members could be oriented more efficiently. The new orientations allow members to carry primarily tensile load. Case 6 configuration is shown in Figure 15, with the “tendon” members highlighted red.

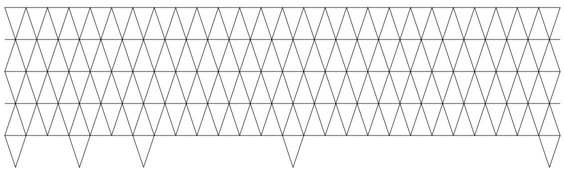


Figure 13a: Case 0 elevation

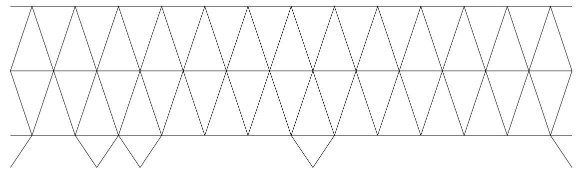


Figure13b: Case 1 elevation

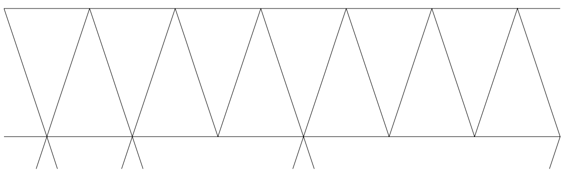


Figure 13c: Case 2 elevation

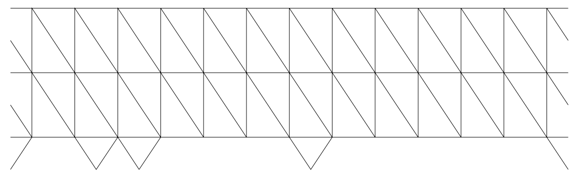


Figure 13d: Case 3 elevation

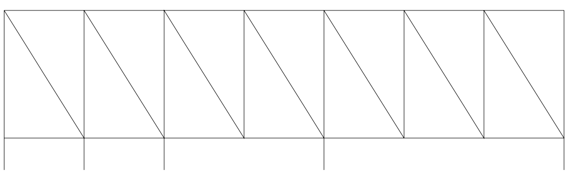


Figure 13e: Case 4 elevation

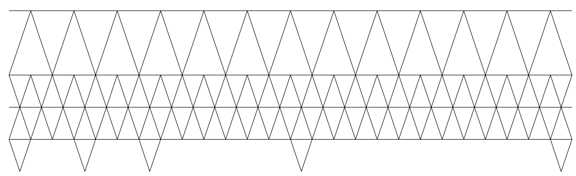


Figure 13f: Case 5a elevation

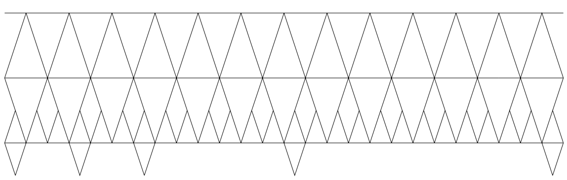


Figure 13g: Case 5b elevation

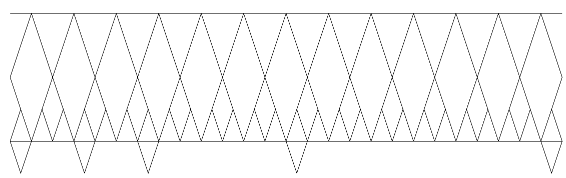


Figure 13h: Case 5c elevation

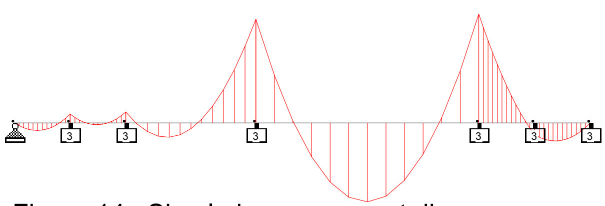


Figure 14: Simple beam moment diagram

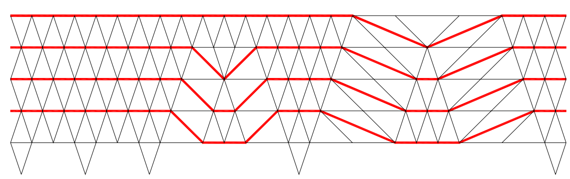


Figure 15: Case 6 elevation with highlighted tendons

With the elevations set, a STAAD analysis of each case was undertaken. An AutoCAD drawing was imported as a 2D plane model. Pinned support was placed in the lower left corner, while roller supports were placed along the bottom and left edges. All members were assigned the same member section. A W14x53 was chosen as the approximate average member in the original diagrid. Each node was loaded for gravity according to its tributary floor width. Live load reduction was not taken into consideration. In the interest of developing feasible construction techniques, members were grouped by similar function in order to size that particular function only. The system was then analyzed, and output for midspan deflection and member stress was recorded.

It is important to note the inherent inaccuracies of such a model. Because of the simplified loading scheme, systems with larger tributary widths, especially Cases 2 and 4, will seem more inefficient than in actuality. Using the same section properties for all members creates a distribution of forces slightly different than one using final member sizes. The exclusion of lateral wind forces can also affect the results. Additionally, no load was put directly on the horizontal members. This may or may not be the case, depending on how the floors are constructed at levels with horizontals. Even with these shortcomings, this modeling method is justified by its ability to provide relative conclusions rather than absolute approximations.

In order to compare the performance of every case, resulting data from the STAAD models were analyzed with Excel spreadsheets. Each member group was tabulated to find the average and maximum stress for that group. From these stresses the relative weight of every case was obtained. An example of the spreadsheets used to calculate these values is found in Appendix B.2. Summaries of all cases are in Appendix B.3. Table 2 was prepared to directly compare the structural properties of the cases against each other.

	Str. Efficiency	**Redundancy**	**Deflection**
Case	**Weight**	**%**	**in.**
0	42170	71.6	0.029
1	36192	54.4	0.059
2	51648	42.5	0.079
3	33417	53.4	0.044
4	65833	46.0	0.095
5a	40845	64.3	0.037
5b	45110	58.8	0.057
5c	68016	66.3	0.074
6	33176	69.0	0.029

Table 2: Structural properties comparison

In the table above, the relative weight of the structure corresponds directly to its structural efficiency. The lower the weight, the more efficient the configuration. Redundancy is its reserve strength, calculated by dividing the average member stress by the maximum member stress and subtracting from 1. A higher redundancy percentage is desirable. Deflection values at the midpoint of the largest span were taken directly from STAAD. These are not actual deflections because unit loads were used in the model as opposed to real loads.

Architectural Impact

The architectural impact considers the effect of the changed geometry on the building footprint and on its V column placement. The original diagrid has a standard grid width of 9 feet. Although the horizontal members are slightly curved to match the smooth perimeter, the diagonal members cannot economically be modified in the same way. Therefore, any diagonal member of the alternative structures is out of plane with the perimeter. This is barely noticeable for a 9 foot grid width, more visible for an 18 foot grid width, and problematic with a 36 foot grid width. Examples of the effect of grid spacing are shown below in Figure 16. The structure profile is black while the actual smooth perimeter is red.

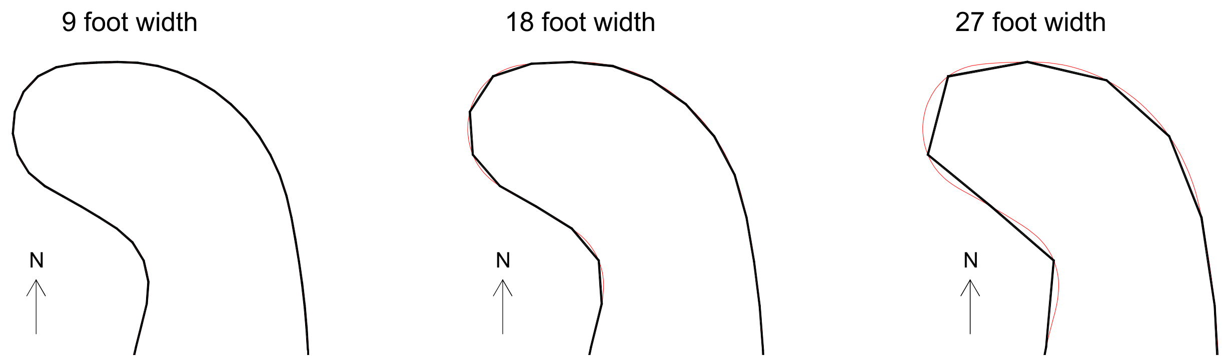


Figure 16: Grid spacing comparison

Cases where the spacing is 36 feet will significantly alter the aesthetic continuity of the Athletic Center design. Spacings of 18 feet will have a few negative effects on the cladding installation and interior layout, but they are not as severe as with 36 feet. Spacings of 9 feet will have little or no impact at all.

As for V column placement, new supports were designed for each case. These supports were evaluated for how well they would perform structurally, how well they fit into the geometric pattern of the building, and how close their bases are to the original base placement. The overall combination of the footprint and support considerations determined the index value for architectural impact (Table 3). The higher the number the better the case fit with the original design intent.

	Architecture
Case	**Index**
0	100
1	90
2	75
3	90
4	75
5a	95
5b	95
5c	95
6	90

Table 3: Architecture impact

Floor Framing Impact

The structural reconfigurations of the alternatives present complications to the original floor layout. Because the perimeter diagrid is meant to handle gravity as well as lateral forces, dead and live loads from the interior spaces are transferred through floor beams to the horizontal members of the grid, which then pass these loads to the diagonal members and eventually to the V columns below. The problem which arises from the geometric change to the structure is that some or all of the horizontal members are now removed. Load-carrying floor beams now have no where to frame into, especially in the office bays on the west side of the building. There are two potential solutions to this situation. They are:

1) Change the direction of beam span, allowing the beams to frame into girders attached to the exterior structure.
2) Maintain the span direction, but provide a heavy cross beam which will support the original beams.

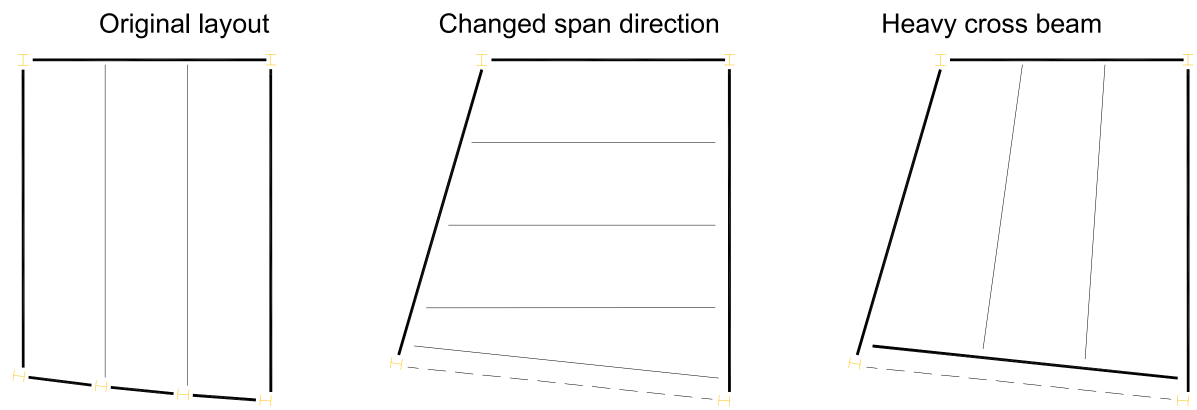


Figure 17: Floor framing schemes

It is apparent from Figure 17 above that the original floor scheme is the simplest, most consistent layout. The other two options create unnecessary steel or inconsistent tributary widths. Therefore any of the cases which require the use of these options do not perform as well as cases with horizontals at every level. The floor framing index (Table 4) takes this idea into consideration and subtracts 10 for every floor which lacks horizontal members. A higher index is desirable.

Case	Floor Framing Index
0	100
1	80
2	70
3	80
4	70
5a	90
5b	80
5c	70
6	100

Table 4: Floor framing impact

Material Cost

An estimate was made that the cost of steel and its related fireproofing, insulation, and cladding is more expensive per square foot than its glazing counterpart. Therefore, each case has been indexed based on its relative structure-to-window percentage (Table 5). The index was taken out of 100. The higher the index value the higher the material cost.

Case	Material Cost Index
0	100
1	80
2	70
3	80
4	70
5a	90
5b	85
5c	80
6	95

Table 5: Material cost

Complexity

Connection material and labor cost can be a significant portion of the overall structure cost of a building. The fewer pieces to join together and the less welds or bolts to secure the less expensive the system. This is especially important for a connection-intense structure such as a diagrid. Any reduction in the number of nodes or the members framing into them would be beneficial. Each case was indexed based on its number of nodes and members (Table 6). A lower index value is more desirable.

Case	Complexity Index
0	100
1	75
2	50
3	75
4	50
5a	85
5b	80
5c	75
6	100

Table 6: Complexity

Results

In order to compare the overall picture between cases, tables were used to collect the individual considerations into a logical scoring system. Table 7 scores the cases for each consideration, and then weights those considerations. Chart 2 calculates the final score, while Table 8 ranks each case from 1 through 9.

	Str. Eff.		Redundancy		Deflection		Architecture		Flr. Framing		Mat. Cost		Complexity	
Case	**Weight**	**Score**	**%**	**Score**	**in.**	**Score**	**Index**	**Score**	**Index**	**Score**	**Index**	**Score**	**Index**	**Score**
0	42170	0.79	71.6	1.00	0.029	1.00	100	1.00	100	1.00	100	0.70	100	0.50
1	36192	0.92	54.4	0.76	0.059	0.49	90	0.90	80	0.80	80	0.88	75	0.67
2	51648	0.64	42.5	0.59	0.079	0.37	75	0.75	70	0.70	70	1.00	50	1.00
3	33417	0.99	53.4	0.75	0.044	0.66	90	0.90	80	0.80	80	0.88	75	0.67
4	65833	0.50	46.0	0.64	0.095	0.31	75	0.75	70	0.70	70	1.00	50	1.00
5a	40845	0.81	64.3	0.90	0.037	0.78	95	0.95	90	0.90	90	0.78	85	0.59
5b	45110	0.74	58.8	0.82	0.057	0.51	95	0.95	80	0.80	85	0.82	80	0.63
5c	68016	0.49	66.3	0.93	0.074	0.39	95	0.95	70	0.70	80	0.88	75	0.67
6	33176	1.00	69.0	0.96	0.029	1.00	90	0.90	100	1.00	95	0.74	100	0.50
Weight		1.0		0.8		0.8		0.7		0.3		0.5		0.4

Table 7: Alternative diagrid scores

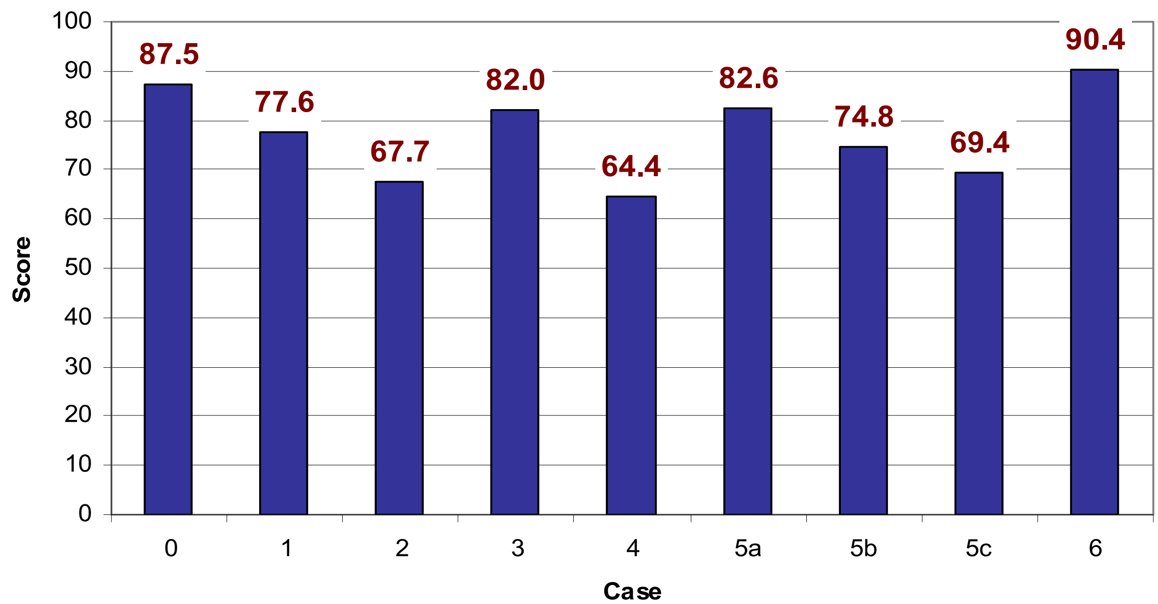


Chart 2: Alternative diagrid final scores

Case	Rank
0	2
1	5
2	8
3	4
4	9
5a	3
5b	6
5c	7
6	1

Table 8: Alternative diagrid rankings

Discussion

A few interesting observations and conclusions can be inferred from the results of the structural analysis and the final scores.

1) Varying member lengths and heights has substantial impact on structural efficiency.

   Alternatives with medium height members (Cases 1 and 3) weigh considerably less than single story alternatives (Cases 0 and 5a). The longer lengths of their members are optimized to the loading conditions they must carry. Continuing this trend, it would be expected that alternatives with large height members (Cases 2 and 4) weigh even less. However, this is clearly not true. In fact, the system weights of the large member cases are nearly twice as much as the medium cases. This is because the long unbraced lengths of Cases 2 and 4 cause column buckling failure to occur well before material yielding. It must be noted that the floor slabs at each level could potentially provide lateral support for the members, especially in Cases 3 and 4 which have vertical truss elements. This bracing would certainly help reduce member sizes, making large member cases more efficient than what is represented above.

2) In general, there is a noticeable tradeoff between architectural impact and cost.

   The configurations which minimize floor plan and floor framing impact tend to have higher material and complexity scores. Conversely, configurations which create large bays and column spacings (Cases 2 and 4) also reduce cladding, insulation, and labor costs. This tradeoff virtually negates any of the scores from the four leftmost columns in Table 7. Because of this, final scores, and ultimately system selection, are primarily dependent on structural performance considerations.

3) High system redundancy helps control deflection.

   There is one exception to this general observation. Case 5c has relatively high redundancy, yet it performs poorly in deflection. This is due to its inefficient diamond-shaped configuration. Without the cross beams to tie opposite corners of the diamond together it becomes unstable. This is clearly shown in a deflection diagram from STAAD (Figure 18).

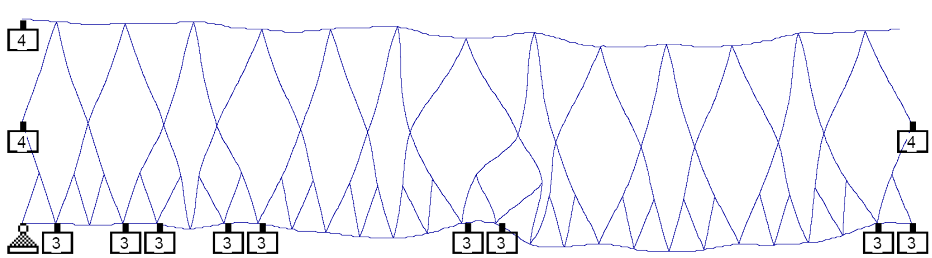


Figure 18: Case 5c deflection

Overall, Case 6 is the best geometric configuration out of the proposed alternatives. The combination of small bay spacing and floor beams at each level keep architectural impact to a minimum. Structurally, its “tendons” over the long spans are highly effective in limiting midspan deflection, all while providing adequate redundancy and weighing less than every system. It outperforms the other options in many categories.

Even with its advantages, Case 6 is only marginally better than the original diagrid system. Though the alternative may result in nearly a 25% reduction of steel weight, all the other criteria for evaluation do not justify a replacement of the diagrid system. Its score is simply too close to the original system score.

Therefore, an entirely new approach to the structural redesign of the Athletic Center is necessary. The concepts which have been exploited so far should be taken further. A more unique treatment of the diagrid must be addressed.

Solution Area III – Removing the diagrid to bring the lateral system inwards

The conclusions of the previous two sections made it quite clear that another approach was necessary to obtain a valid redesign of the Athletic Center. Changing only the material was not advantageous at all. Modifying the diagrid geometry had benefits, but not enough to substantiate a redesign. A whole new design approach, one which eliminates the concept of a diagrid, would have to be used. In this way the lateral system would be moved from the perimeter inward, and a new gravity system would need to be developed to replace the diagrid. A curtain wall would become the new vertical building envelope. Rethinking the entire above-grade load carrying structure would be considerably more difficult than either Solution Area I or Solution Area II.

The primary goals of the diagrid removal were as follows:

- Change the façade's architectural look and feel. In an interview with Charles Thornton, the Athletic Center's architect, Bernard Tschumi, leans toward a theoretical view of not expressing or exposing structure if it is not required (Thornton, 73). Though the original design expresses the structural system of the Athletic Center, it is out of necessity rather than intent. In keeping with Tschumi's perspective on expressed structure, the aesthetic look of the building was intentionally modified to hide the structure. This would be relatively easy due to the ability to add a curtain wall around the perimeter.
- Keep the shape of the building intact. Changes to the plan would mean changes to space layout and programming characteristics.
- Reduce structure weight and complexity. Structural efficiency remained a key indication of the feasibility of a redesigned system.
- Provide as much glazing opportunity as possible. As indicated in the problem statement, very little of the usable window viewing height is glazed. Opening the façade to views of the football stadium and surrounding landscape would be desirable.
- Minimize impact to the interior layout. The redesigned structure should not have major negative effects on the amount or quality of interior space.
- Maintain floor height. Added floor-to-floor height generally equates to added cost.

Several additional considerations were taken into account:

- Placement of columns. According to architect David Zelman, existing spaces from the adjacent facilities could not be compromised by the construction of the Athletic Center (para. 4). The diagrid was developed to span over these spaces. It successfully allowed only one column to be brought through the existing space. More than that would have forced closure of Shoemaker Arena. The redesigned system had to solve the same problem, maintaining the relative positions of Level 500 support columns.
- Penetration of open spaces. There are several vertical openings such as atriums, stairwells, and elevators through which beams cannot pass.
- Lateral system placement. Location of any braced or moment frames must be invisible to the occupants.
- Floor system impact. Because the floor system originally framed into the perimeter diagrid, it would be beneficial to require the new perimeter to allow similar framing opportunities.
- Foundation impact. Gravity and lateral load flow should follow a path as in the original system in order to retain foundation design applicability.

Procedure

The redesign of the structural system followed the same development phases as a typical new construction project: Conceptual Design, Schematic Design, Design Development, and Construction Documents.

Conceptual Design
Initially, conceptual ideas of potential gravity-carrying structural systems were drawn up. These drawings are shown below in Figures 19a through 19f. The building outline is blue, the proposed structure is yellow, and the main supports are represented by maroon pyramids. The light blue line in Figures 19b and 19c represents the edge of existing facilities below the Athletic Center. No columns except for the existing perimeter column may extend past this line.

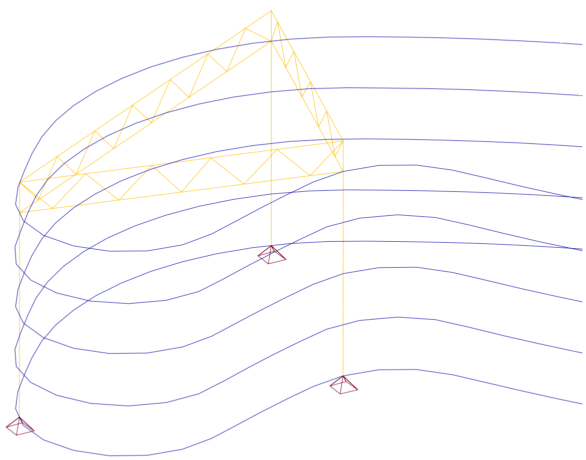


Figure 19a: Interior hat truss

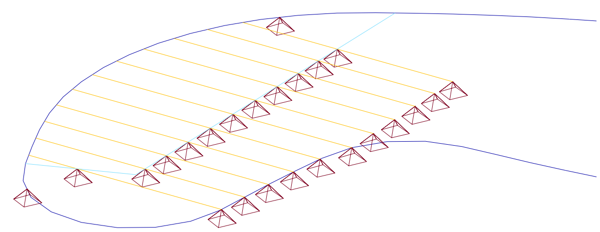


Figure 19b: Cantilevers over columns

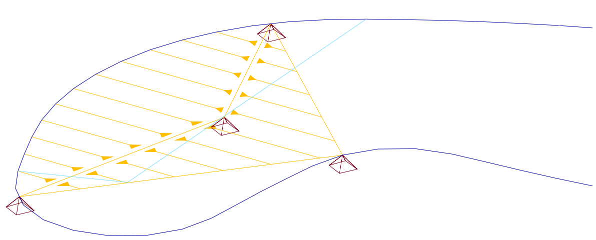


Figure 19c: Cantilevers over girders

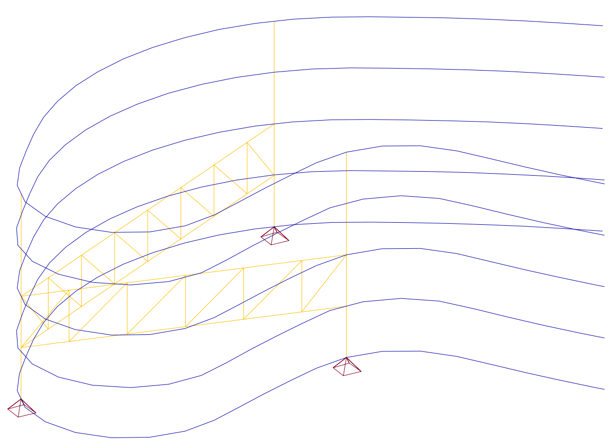


Figure 19d: Level 600 truss

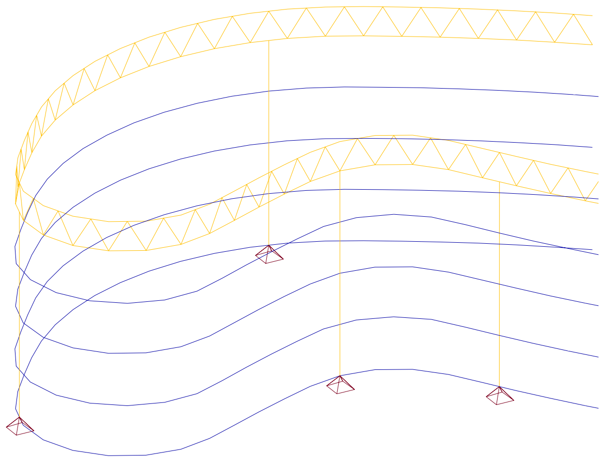


Figure 19e: Perimeter truss

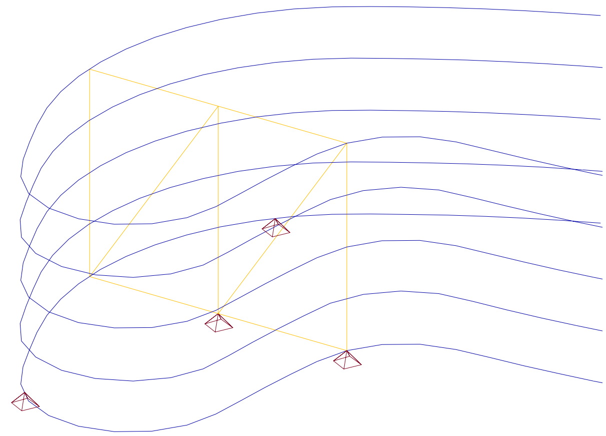


Figure 19f: Reverse truss

A pro-con comparison was made between all of the alternative gravity systems. Each option was evaluated for advantages and disadvantages based on the goals and considerations outlined previously. They were then subjectively ranked from 1 to 6. The results of the study are below in Table 9.

Option	Advantages	Disadvantages	Rating
Interior Hat Truss	Hidden, flexible, can be applied over whole building	Small cantilevers remain, construction sequence will be an issue, truss will add depth to total height, some openings may need to be adjusted, tensile columns	2
Cantilevers Over Columns	Invisible structure, no height increases	Backpinning will be a major issue, no columns can be put through auditorium	6
Cantilevers Over Girders	Hidden, flexible, no height increases	Floor layout will have to be changed drastically, downward slant through auditorium will be extremely hard to negotiate, open space prevents girder from reaching columns	5
Level 600 Truss	Truss can be deep and efficient through mechanical room	Truss will interfere with some mechanical equipment, layout of some public space will have to be replanned, combination of tensile and compression columns	4
Perimeter Truss	Out of the way of the rest of the building, very efficient, can be applied over whole building	Height increase, construction sequence will be an issue, tensile columns	1
Reverse Truss	Provides both gravity and lateral stiffness, fairly efficient, no height increase	Not flexible, diagonals will interfere with spaces and atrium layout will have to change	3

Table 9: Gravity system comparison

The perimeter truss option seemed to be the least disruptive to the floor layout and open spaces of the Athletic Center, unlike the majority of the other options. However, it still had several issues which needed to be investigated and resolved.

Next, ideas for the lateral system were evaluated. There were fewer options available, but the three main types of systems were evaluated, braced frames, moment frames, and shear walls. A pro-con comparison was also done for the lateral systems, summarized in Table 10 below. Braced frames were chosen as the most viable lateral option, due to their relatively easy incorporation into the existing floor/column scheme, and their ability to be placed at several locations throughout the building

Option	Advantages	Disadvantages	Rating
Braced Frames	Braced frames from Level 100-500 are already in place, no impact on floor-to-floor height, less labor than rigid frame	Reduces usable interior space, placement will be a slight issue	1
Moment Frames	Maintains interior spaces, potentially less steel weight	Predominant grid system is not available to develop sufficient frame action, potentially deeper beams	3
Shear Walls	No impact on floor-to-floor height	Heavier loads on foundation, reduces usable interior space, placement will be an issue, introduces concrete construction on site	2

Table 10: Lateral system comparison

Schematic Design

The systems chosen during the conceptual phase were developed further. Several issues were resolved to further refine the design. These issues were:

1) Floor beam sweep
The original design called for horizontal members of the diagrid to be slightly curved. Perpendicular floor members framing into the curve cause torsion, which is transferred as moment at the supporting column connections (Figure 20). This moment was undesirable; however, the 9 foot spans of the original design were short enough to consider torsion negligible. In order to open up the façade and eliminate some of the columns, it was necessary to work with longer spans. These spans would cause an unacceptable amount of torsion on 18’ or 27’ beams. Therefore, the beams were designed to connect straight between the columns, eliminating the effects of torsion.

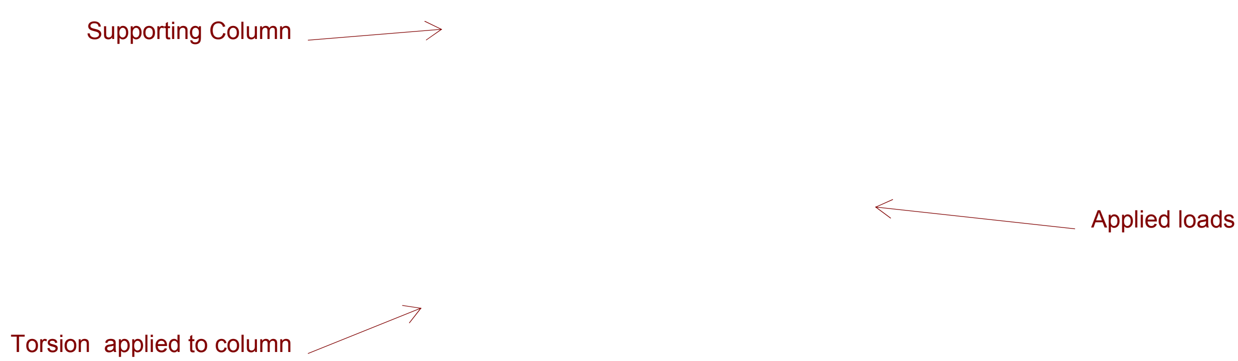


Figure 20: Curved beam torsion

2) Column spacing
The decision to design each floor beam as a straight member brings back consideration of how well the building follows the smooth perimeter outline. Unlike the diagrid geometry alternatives discussed in Solution Area II, the perimeter truss will actually allow column spacing to vary along the perimeter. Naturally, spacing will be 9' in sections of high curvature and 27' in section of low curvature. The column layout is shown below in Figure 21, with small pink dots representing columns in tension and large red dots representing columns in compression.

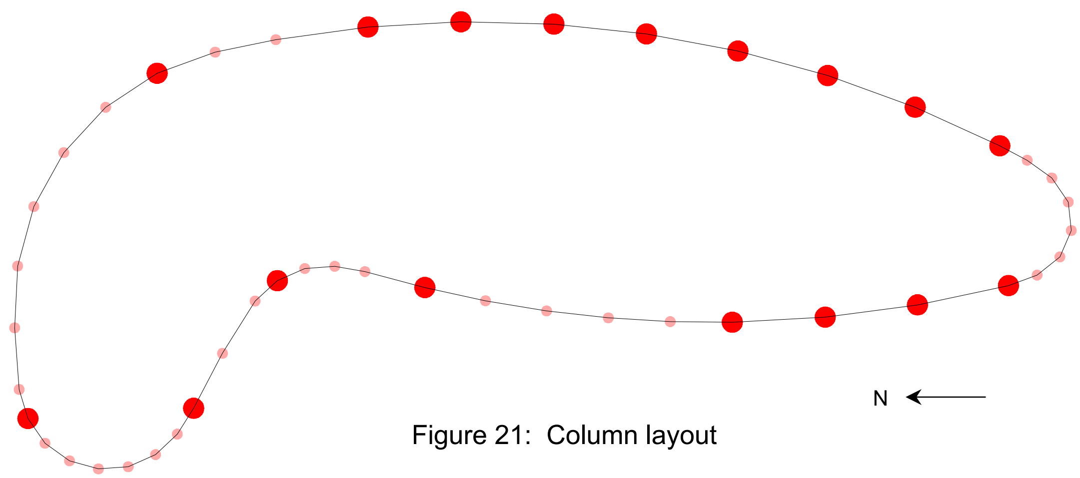


Figure 21: Column layout

3) Pinned vs. fixed connections
Because load is now being carried primarily by the perimeter truss and braced frames, minimizing additional moments on secondary members would reduce sizes while maintaining adequate strength. Therefore, pinned connections (shown in Figure 22 as red circles) were used at all floor beam connections and at the tops of columns, both in tension and compression. Rigid connections are maintained for column continuity and the perimeter truss.

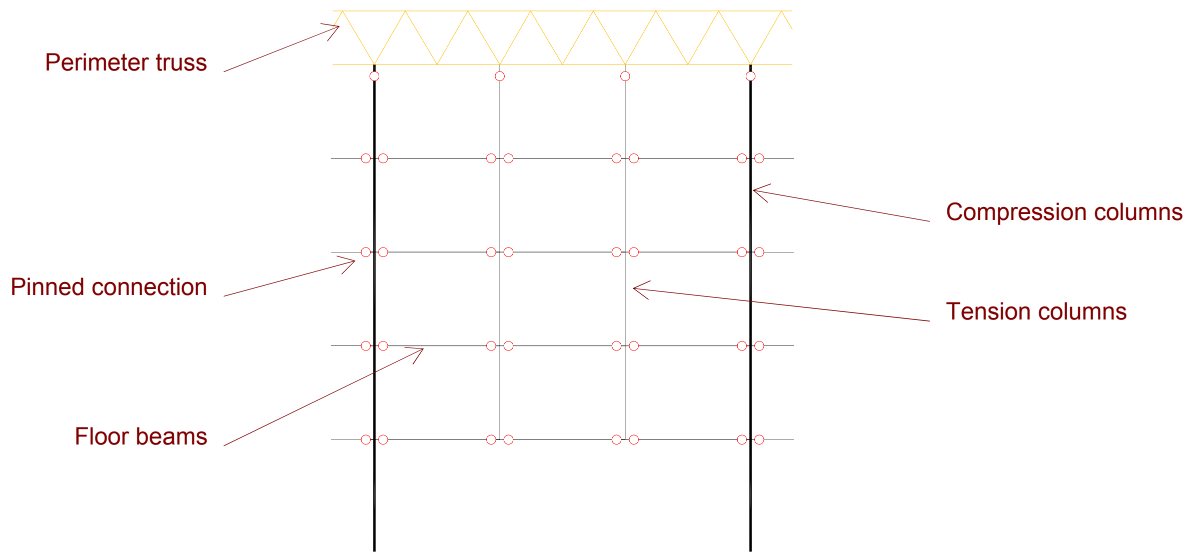


Figure 22: Pinned connection schematic

4) Column deformation compatibility
The differences in load deformation between columns in tension and compression (Figure 23) could have substantial drawbacks to the curtain wall structure. A solution to this situation would be to carefully sequence the construction of the curtain wall. A detailed evaluation of column deformation compatibility will be addressed later in the Construction Study section.

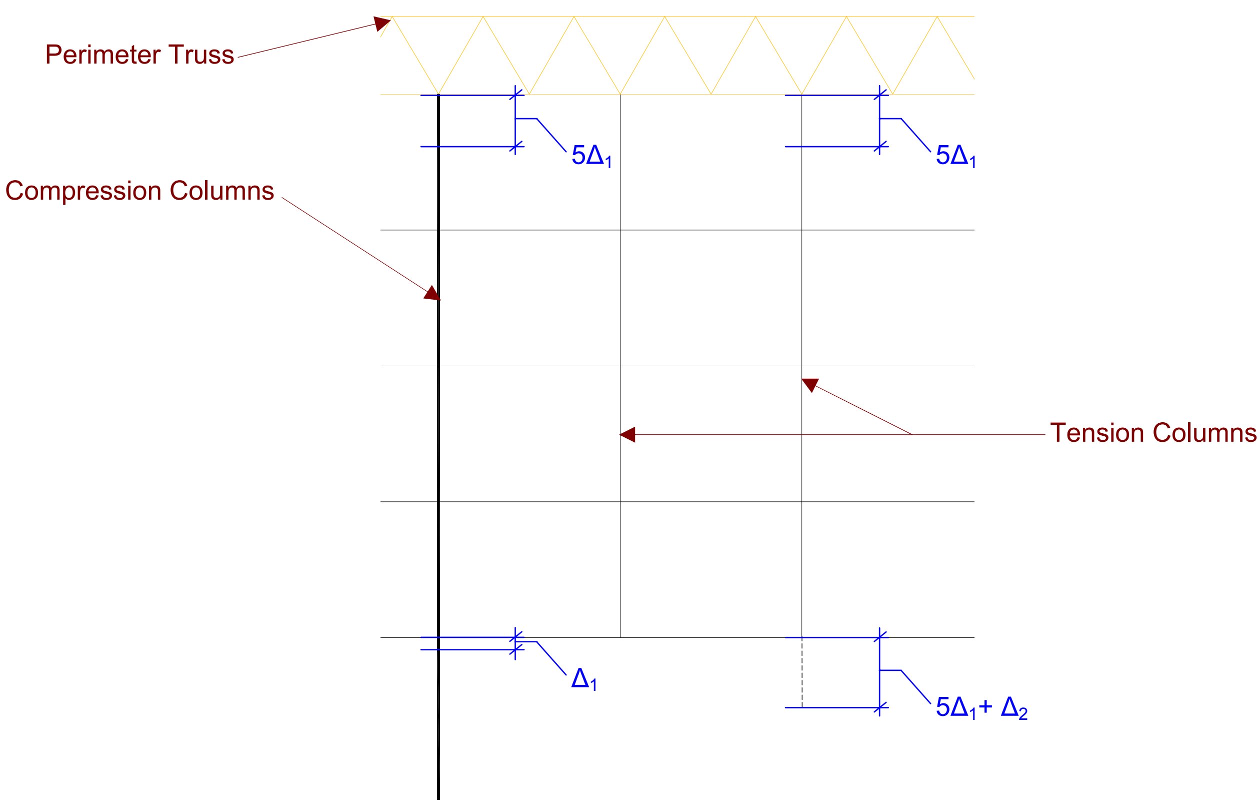


Figure 23: Column deformation

5) Fire Resistance of perimeter truss.
Because the Athletic Center contains A-3, B, and M occupancy types, it is categorized by Table 503 of the Ohio Basic Building Code as a Type 1B construction class. For structural frame elements the fire-resistance rating requirement is 2 hours. This can be obtained by using a spray-applied fire resistive material. The thickness of this fireproofing in the original diagrid system is 2", therefore the same minimum thickness is specified for the new perimeter truss.

6) Thermal movement and stresses
Though the original diagrid design was certainly expressed, the steel structure was insulated behind 3 inches of expanded foam insulation, protecting it from temperature extremes. If left unprotected, the perimeter truss would encounter considerable thermal variation due to sol-air effects and night sky radiation. In order to mitigate detrimental thermal movement, it was decided to insulate the perimeter truss using 3-4 inch thick rigid insulation. The architectural desire to hide the structure will conceal the insulated truss from public view. See Figure 24.

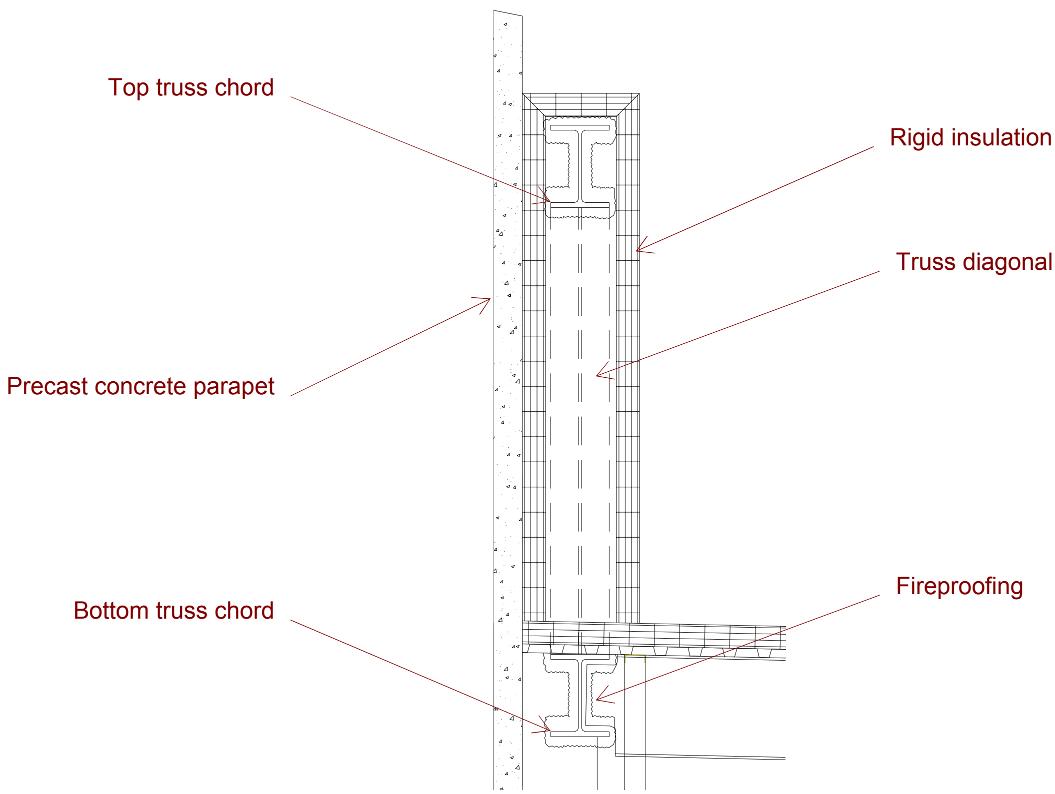


Figure 24: Perimeter truss insulation

7) Truss height
Bay width was set at 9 feet to be consistent with the column layout and spacing. Three options for height were conceived (Figure 25). The first, 4'-6" high, produced 45˚ diagonals. The second, 7'-8" high, created an equilateral triangle pattern. The third, 9'-0" high, matched the width. After consideration of all three, the second option was chosen for its sufficient depth and reasonable member lengths.

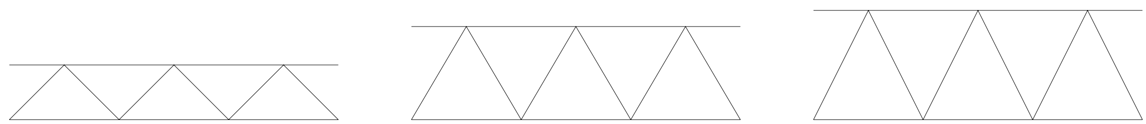


Figure 25: Truss height options

8) Truss lateral bracing
Because the truss acts as a deep beam, its chords undergo considerable compressive forces in some sections. They must be braced to prevent buckling failure. The bottom chord is automatically braced by the roof structure at Level 900. The top chord, however, was designed with angled wide flange braces oriented perpendicular to the perimeter to resist lateral truss movement. Figure 26 illustrates this bracing scheme.

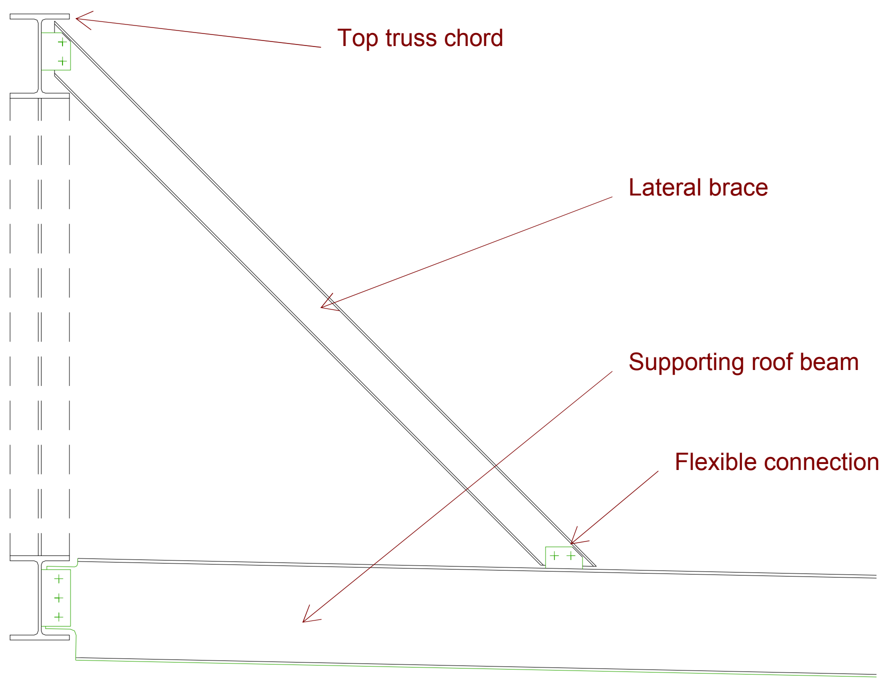


Figure 26: Truss lateral bracing

9) Corrosion
The addition of lateral truss bracing brought up the issue of weather protection for exposed steel. Though the truss will be covered with insulation and a water resistant membrane, the brace pieces are left exposed. Encasing them in a protective would likely be expensive and prone to damage, therefore the braces and their connections will have a corrosion-resistant paint applied after installation.

10) Braced frame placement

The original braced frames, labeled BF1 and BF4, extended from the foundation slab up to Level 500 and were oriented in the East-West direction only (Figure 27a). Their purpose was to transfer East-West lateral loads from the bottom of the diagrid to the foundation walls, while the V columns picked up the North-South load. The new braced frames, designed to carry all lateral load from the roof (Level 900) to the foundation, had to penetrate into previously unobstructed interior space. To minimize the impact of the new braced frames, upper level framing in the East-West direction was continued on top of existing framing. Additionally, BF4 was relocated from grid line D to grid line C, in order to take advantage of existing mechanical chases on Levels 500-800. Finally, new North-South braced frames were added above the elevator shaft on grid line 1 and along the central West stairwell on grid line 2 (Figure 27b).

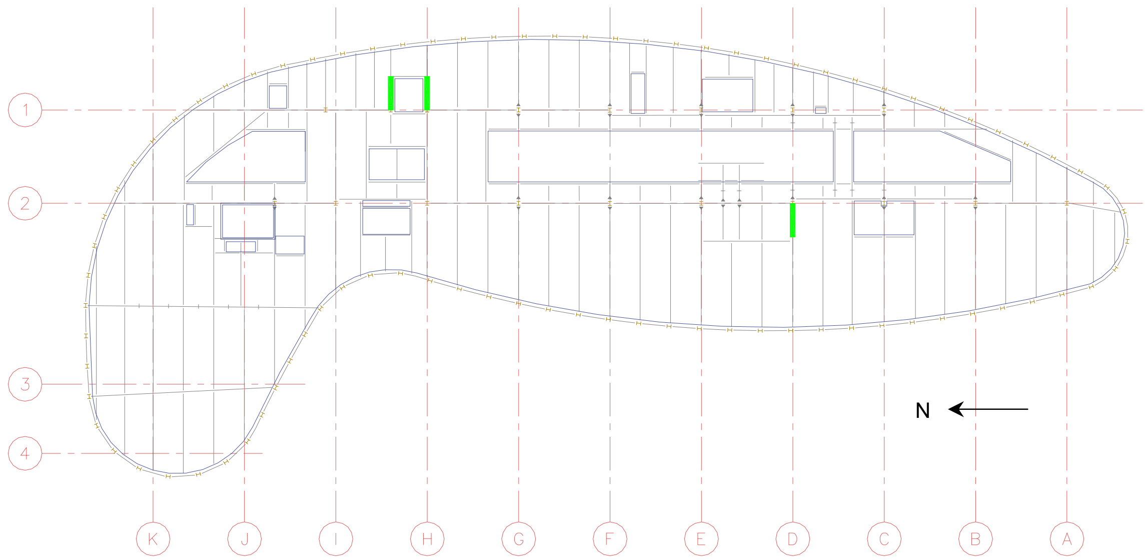


Figure 27a: Original braced frame positions

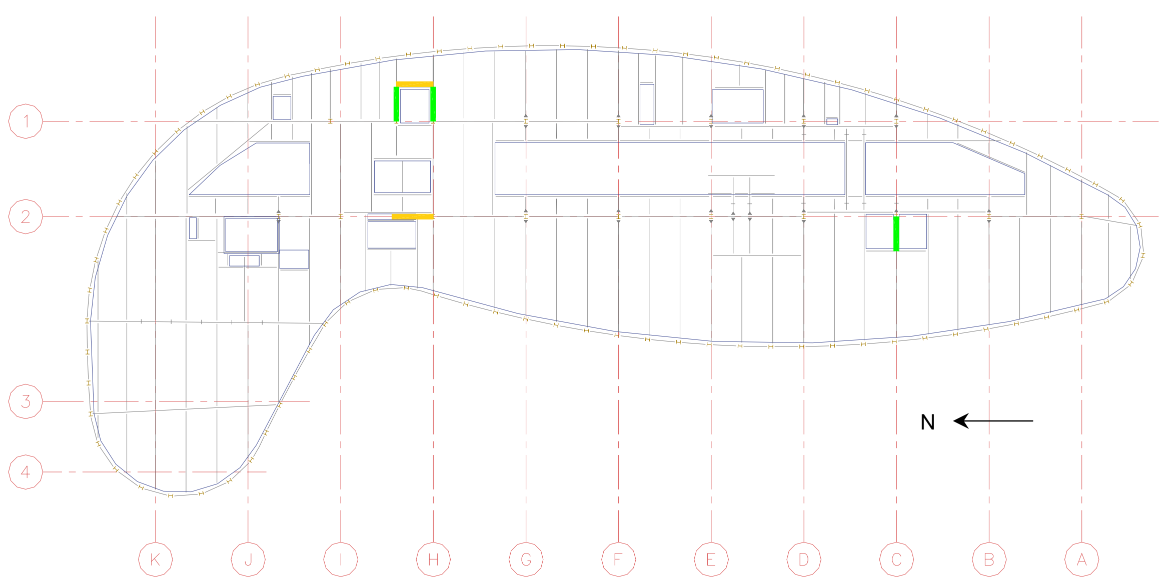


Figure 27b: New braced frame positions

Though these new frames were positioned to be nearly invisible to the interior space layout, they still impacted lower levels of the Athletic Center. It was necessary to assess the layout of the affected spaces. Of primary concern was the new N-S frame above the central West stairwell. The southern column was already there in the original design. The northern column was offset 8'-0" from this grid (Figure 28a). Diagonal members between these columns upset the mechanical ducts adjacent to the stairwell on Levels 400-800. This was resolved by moving the ducts just past the northern column (Figure 28b). At Level 300, the new column and bracing do not interfere with any other structure or equipment; however the frame will need to be covered up for aesthetic reasons. A false wall between the doors accomplishes this (Figures 29a and 29b). At Level 200, the brace cuts right into circulation space. A wall was designed around the brace, which protects the structure while providing storage space for the adjacent Football Meeting Room (Figures 30a and 30b). Level 100 contains a recycling area, which has been moved to another location. In the process more closet space was created for the nearby room (Figures 31a and 31b).

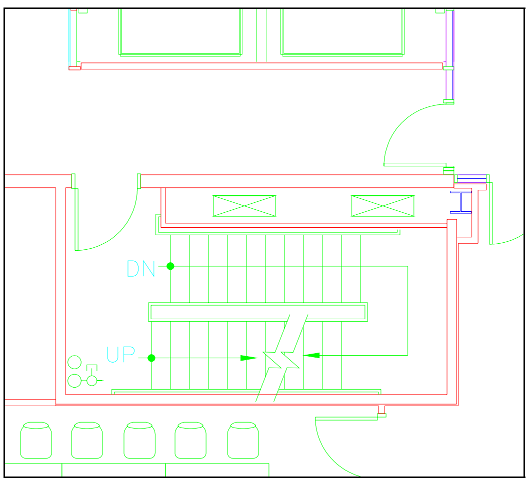


Figure 28a: Level 500 original layout

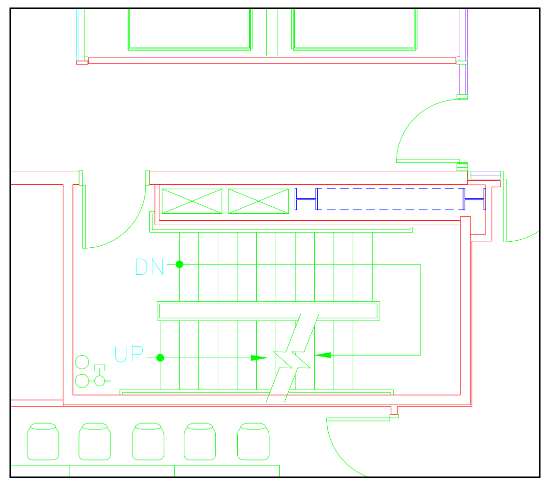


Figure 28b: Level 500 modified layout

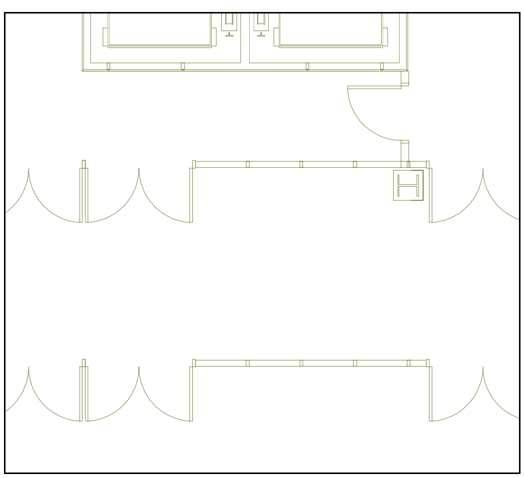


Figure 29a: Level 300 original layout

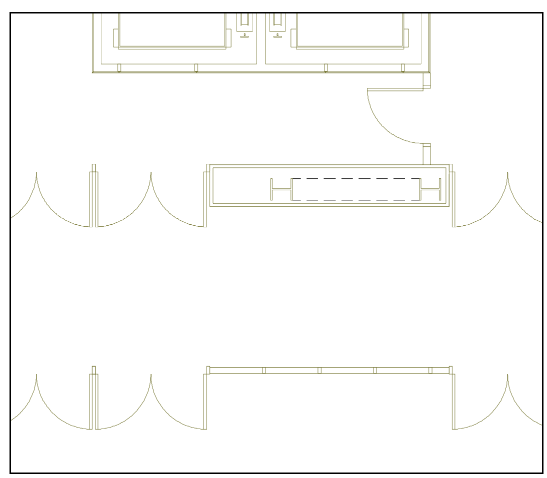


Figure 29b: Level 300 modified layout

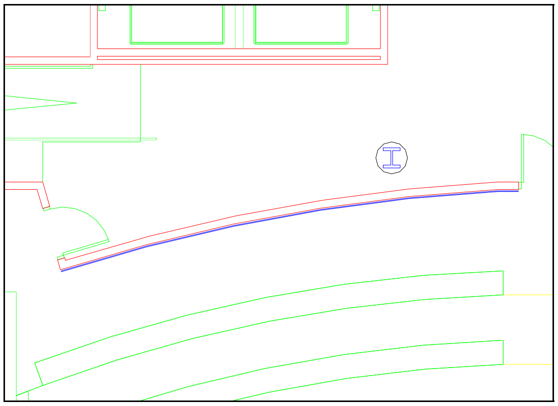


Figure 30a: Level 200 original layout

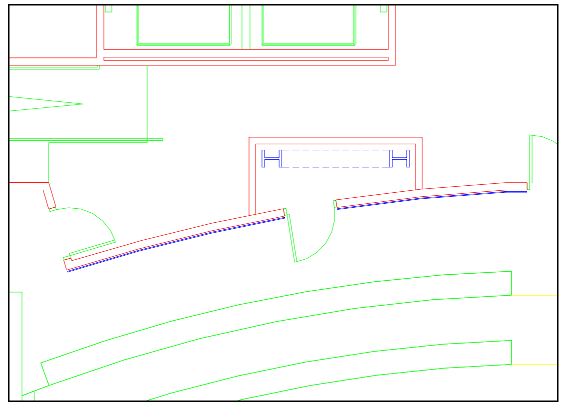


Figure 30b: Level 200 modified layout

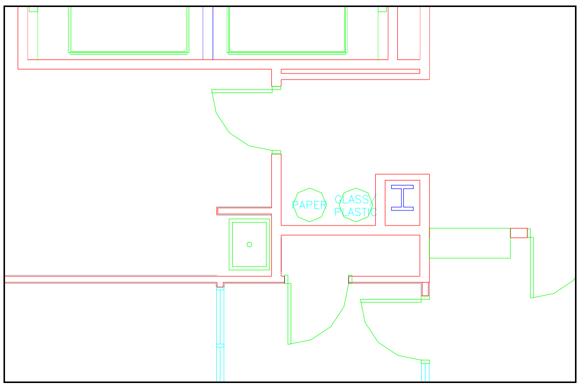


Figure 31a: Level 100 original layout

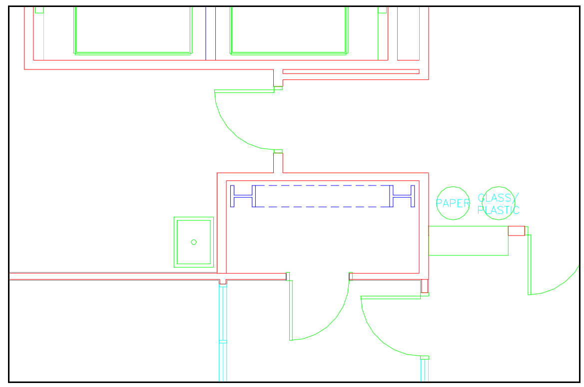


Figure 31b: Level 100 modified layout

Design Development

Once the main Schematic Design issues had been worked out, an actual structural analysis of the perimeter truss system could be performed to find member sizes, long span deflections, and story drifts. Though the building could have been simplified to undertake hand calculations, it was concluded that a more accurate 3-dimensional computer model was the best method of analysis. The Athletic Center was modeled in ETABS, a non-linear, finite element pre and post-processing software package written specifically for structural analysis of buildings.

The model skeleton including the perimeter truss, its columns, cross beams, and the braced frames was first constructed in AutoCAD. It was imported into ETABS as a fully rigid structure. Pinned members were released according to schematic design consideration #3 and base supports were added. Rigid diaphragms were assigned to Levels 500-800 to simulate the composite beam/composite deck action. Lateral bracing for the truss, as specified in schematic consideration #7, was modeled as supports released tangentially and vertically. Loads were added to model dead, live, and wind cases. Load calculations are found in Appendix C.1. Initial member sizes were created based on educated assumptions. Figure 32 is a three-dimensional view of the model.

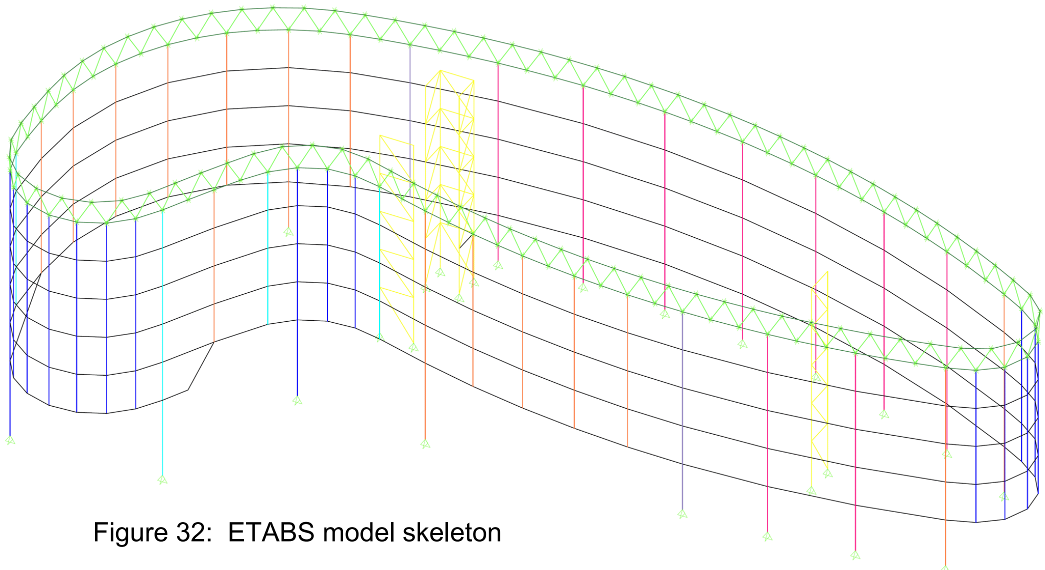


Figure 32: ETABS model skeleton

Once an analysis was performed, force output from ETABS was separated into five member categories: truss horizontals, truss diagonals, truss columns, braced frame diagonals, and braced frame columns. This output was used to find acceptable member sizes for both the perimeter truss system and braced frames with the help of a spreadsheet which applies the proper interaction equation. An example of this spreadsheet can be found in Appendix C.2. The process then became iterative. The new member sizes were inputted into the model, an analysis was performed, the results were compiled, members were resized based on strength or serviceability, and the cycle began again until all criteria were met. Rather than detailing each step of the process, a summary of the iterations, or trials, is provided in Tables 11a and 11b.

Trial #	Perimeter Truss System
1	Initial conditions. Truss sizes all W18x86. Column and BF sizes all W14x53.
2	Resized members for strength based on Trial 1
3	Strength criteria not met for some members. Resized based on Trial 2
4	Strength criteria met. Deflections are horrible. Main column deflections are as much as 2.24" vertically at top of column. Displacement at midpoint of 107' span is nearly 6.62" when allowable is 3.57". Unacceptable. Resized truss and column members.
5	Deflections still bad. Resized columns and increased long span truss sections based on virtual work diagrams.
6	Deflections still unacceptable. Increased truss horizontal "flanges" just over the main compression columns in areas of high negative moment.
7	Realized that factored loads were being used for deflection results. Scaled back gravity loads to represent service load levels.
8	Acceptable deflections from Trial #7. Not necessary.

Table 11a: Perimeter truss system trials

Trial #	Braced Frames
1	Initial conditions. Member sizes estimated from existing braced frames.
2	Strength criteria met. Story and overall drifts are unacceptable. Resized diagonals.

3	Story and overall drifts still bad. Increased Level 400 and 500 members based on virtual work diagrams.
4	Not much better. Realized that factored loads were used rather than service loads. Scaled back load cases.
5	Acceptable drifts. Decreased some overdesigned members because of the service load mistake.
6	Acceptable drifts from Trial #5. Not necessary.

Table 11b: Braced frame trials

The above tables make reference to “virtual work diagrams.” These diagrams were displayed in ETABS to show the relative virtual work that each member contributed. The diagrams, an example of which is shown in Figures 33a and 33b, helped identify general areas where increasing member size would be most beneficial to limiting deflections or drifts.

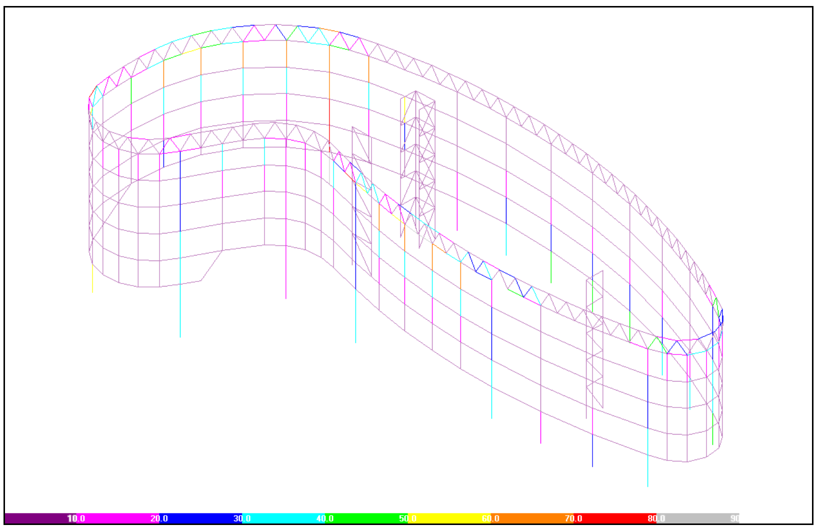


Figure 33a: Perimeter truss virtual work

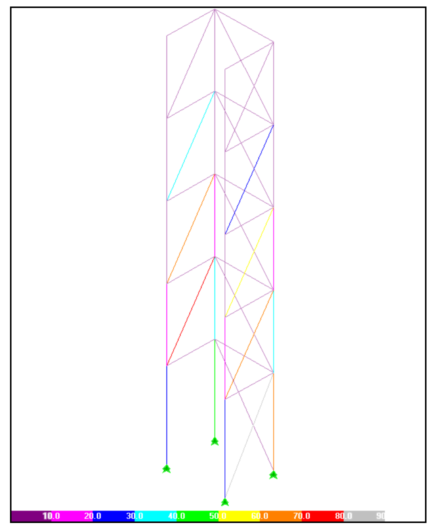


Figure 33b: Braced frame virtual work

To check deflection and drift outputs against allowable values stipulated by the building code, a series of spreadsheet calculations were employed. One set of spreadsheets analyzed gravity deflections of the long spans around the perimeter (Appendix C.3), while one analyzed diaphragm story drift at each level (Appendix C.4). Summaries of these spreadsheets are shown in Tables 12 through 14.

	Midspan Deflection (inches)						
Trial #	**41' span**	**90' span**	**43' span**	**45' span**	**48' span**	**107' span**	**63' span**
4	-1.74	-3.39	-0.64	-0.89	-1.11	-4.52	-1.26
5	-1.58	-2.83	-0.70	-0.89	-1.11	-3.73	-1.21
6	-1.24	-2.37	-0.72	-0.89	-1.08	-3.41	-1.18
7	-1.00	-1.91	-0.58	-0.72	-0.87	-2.75	-0.95
Allowable	-1.37	-3.00	-1.43	-1.50	-1.60	-3.57	-2.10

Key - Failed | Questionable | Acceptable

Allowable Deflection

L/350 = Span*12/350

Allowable Drift

Total: H/400 =

Table 12: Allowable long span gravity deflection comparison

East-West Direction

	Story Drift (inches)					
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Acceptable
Level 900	0.65	0.61	0.54	0.42	0.42	0.46
Level 800	0.60	0.57	0.52	0.38	0.38	0.46
Level 700	0.60	0.56	0.50	0.34	0.34	0.46
Level 600	0.54	0.49	0.42	0.26	0.26	0.46
Level 500	0.38	0.35	0.29	0.18	0.17	0.55
Total Drift	2.78	2.58	2.27	1.57	1.58	2.09

Table 13: Allowable East-West drift comparison

North-South Direction

	Story Drift (inches)					
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Acceptable
Level 900	0.47	0.44	0.40	0.29	0.32	0.46
Level 800	0.39	0.35	0.32	0.25	0.28	0.46
Level 700	0.41	0.37	0.34	0.23	0.26	0.46
Level 600	0.41	0.35	0.30	0.18	0.22	0.46
Level 500	0.22	0.19	0.15	0.09	0.12	0.55
Total Drift	1.90	1.70	1.50	1.04	1.20	2.09

Table 14: Allowable North-South drift comparison

Table 12 shows that midspan gravity deflections for Trial 7 satisfy all allowable deflection limits and are therefore acceptable. Tables 13 and 14 indicate that Trial 5 satisfies the allowable total and story drifts in both the North-South and East-West directions, though story drift for Levels 800 and 900 are close to the allowable limit.

Construction Documents
Final checks were made for foundation overturning and unbalanced wind load torsion.

- Foundation overturning

Using unfactored wind loads from Appendix C.1 and total dead weights from Appendix C.5, overturning and resisting moments were calculated. Overturning was checked in the East-West direction only under the assumption it is the critical case. Summaries of the overturning and resisting moment calculations are given in Tables 15 and 16, respectively.

Level	Windward Pres. plf	Leeward Pres. plf	Trib width ft	Height ft	Moment ft-kips
900	217	132	300	70	7330
800	191	123	300	56.5	5316

700	178	123	300	43	3881
600	162	123	300	29.5	2521
500	158	143	300	16	1444
Sums					20493

Table 15: Overturning moment calculations

Level	Superimposed kips	Superstructure kips	Total kips	2/3 Total kips	Base Dist ft	Moment ft-kips
900	1973	542	2515	1677	40	67075
800	2084	291	2375	1583	40	63336
700	2100	291	2390	1594	40	63742
600	2361	291	2652	1768	40	70725
500	2209	286	2495	1663	40	66525
Sums			12428	8285		331404

Table 16: Resisting moment calculations

Even with the conservative assumption to use two-thirds dead load, the total resistive moment was much higher than the overturning wind moment. Therefore overturning is not an issue. This makes sense because the relatively low building height does not provide enough overturning moment to overcome the wide base of the perimeter frame.

- Torsion

As required by the Ohio Basic Building Code, a wind loading eccentricity of 5% was set up in the ETABS model to account for unbalanced loading conditions. The resulting displacement outputs were analyzed to find the maximum points of drift for each level under East-West and North-South wind loads. As shown in Tables 17 and 18 below, both the East-West and North-South conditions are satisfactory, though Levels 800 and 900 are very close to the allowable story drift.

East-West Wind

Level	Point	UX	Delta X	Allow.
900	70	1.822	0.458	0.46
800	70	1.3638	0.457	0.46
700	70	0.9067	0.402	0.46
600	70	0.5051	0.299	0.46
500	70	0.2057	0.206	0.55
		Total =	1.822	2.09

Table 17: Maximum East-West story drifts with torsion

North-South Wind

Level	Point	UY	Delta Y	Allow.
900	64	1.7259	0.396	0.46
800	64	1.3303	0.406	0.46
700	64	0.924	0.366	0.46
600	64	0.558	0.297	0.46
500	64	0.2607	0.261	0.55
		Total =	1.726	2.09

Table 18: Maximum North-South story drifts with torsion

With the checks completed, perimeter truss and braced frame member sizes were finalized. These sizes are found in Appendix C.6.

Results

Once the models were completed and checked, calculations were performed to size members, estimate weights, and compare systems. A steel take-off of the perimeter truss and braced frame system was carried out, followed by a steel take-off for the original diagrid system.

Before every trial, a spreadsheet recorded the sizes and lengths of each member in the perimeter truss and braced frame system. An example of this spreadsheet is found in Appendix C.7. In all trials, member sizes were repeated as much as possible to promote economy in fabrication. This data was then used to estimate the weight of steel being used per iteration. Tables 19 and 20 summarize the weights for the perimeter truss and the braced frames.

	Weight (tons)						
Member Group	**Trial #1**	**Trial #2**	**Trial #3**	**Trial #4**	**Trial #5**	**Trial #6**	**Trial #7**
Truss Horizontals	39.1	47.6	57.2	59.9	79.9	85.2	85.2
Truss Diagonals	28.8	33.4	38.2	49.8	49.8	54.5	54.5
Truss Columns	75.2	69.5	69.5	80.3	80.3	83.9	83.9
Sum =	143.0	150.6	164.9	189.9	209.9	223.7	223.7

Table 19: Perimeter truss weight summary

	Weight (tons)				
Member Group	**Trial #1**	**Trial #2**	**Trial #3**	**Trial #4**	**Trial #5**
Above Grade Braces	8.1	10.6	11.6	13.0	12.1
Above Grade Columns	87.1	87.1	92.6	63.5	59.4
Below Grade Braces*	4.1	5.3	5.8	6.5	6.1
Below Grade Columns*	43.5	43.5	46.3	31.8	29.7
Sum =	142.8	146.4	156.3	114.7	107.3

*Assumed at 50% of above grade sum

Table 20: Braced frame weight summary

In the sizing and weight tables above, perimeter floor beams were not included. This is because they were modeled in ETABS in a rigid diaphragm and without any loadings. The sizes for each typical span length were determined using basic bending analysis. The analysis itself was considerably conservative due to assumptions regarding perimeter load distribution, so the total weight is larger than what is required. Calculations are found in Appendix C.8. A summary of the weight calculations is found below in Table 21.

Length ft	Pieces per floor	Total Length ft	Weight lb/ft	Total weight tons
9	19	171	26	2.2
18	16	288	55	7.9
27	11	297	106	15.7
Per floor		756		25.9
			x4 Floors	103.5

Table 21: Perimeter floor beam weight summary

The total weight of the perimeter truss system was then found from the sum of the truss, column, brace, and beam components (Table 22).

Perimeter Truss	Tons
Truss Horizontals	85.2
Truss Diagonals	54.5
Columns	83.9
Filler Beams	103.5
Bracing	107.3
Total Weight =	434.4

Table 22: Perimeter truss system total weight

Steel take-offs for the original system were also carried out. Full calculations can be found in Appendix C.9. Total weights are given in Table 23.

Original System	Tons
Diagrid	407.0
V columns	46.9
Bracing	62.3
Total Weight =	516.2

Table 23: Original system total weight

Discussion

Unlike Solution Areas I and II, which utilized numerical criteria to evaluate and compare between alternatives, Solution Area III is most effectively evaluated through qualitative assessments of the perimeter truss and braced frame system. These assessments are based upon the primary goals and considerations outlined in the beginning of this section.

- Change the façade's architectural look and feel.
  The removal of the diagrid structure drastically opened up the perimeter to allow unlimited possibilities for treatment of the façade. The ability to have complete

control of curtain wall window quantity and placement presents the architect with more design freedom.

- Keep the shape of the building intact.
  Though bay spacings now vary from 9' to 27', layout of these spacings was carefully chosen to minimize visual impact to the perimeter. Interruptions to the smooth perimeter will be imperceptible to Athletic Center occupants and passersby.

- Reduce structure weight and complexity.
  The total structural steel weight of the perimeter truss system is over 15% less that the original system. This reduction of steel tonnage saves material costs, as well as having an impact on the foundation system. In addition, the complexity of the structure is greatly reduced. Simple shear connections are now used for every connection except the perimeter truss. Typical fabrication and erection costs account for much of the total structure cost in a steel building, and therefore reduction in the connection complexity can save a considerable amount of shop and labor costs.

- Provide as much glazing opportunity as possible.
  Whereas the original diagrid system utilized a mere 20% of the usable viewing level for windows, the elimination of tightly spaced diagonal columns now permits nearly 100% usage. This provides more impressive views of the football stadium and surrounding landscape.

- Minimize impact to the interior layout.
  Though efforts were made to prevent structural members from taking up interior space, this was not possible. The addition of braced frames to replace the diagrid lateral system requires placement of extra structure in spaces such as corridors, locker rooms, and mechanical chases. The frames must be hidden in existing walls or covered up. This is a definite drawback to the perimeter truss system; however, with careful space planning from the initial design stages it is possible to reasonably minimize structural impact.

- Maintain floor height.
  Floor-to-floor height was not affected at all by the perimeter truss design. The height of the parapet was increased by 2'-6" due to the position of the truss chords, but this increase is relatively insignificant.

- Placement of columns.
  The continuity of the perimeter truss allowed flexible positioning of supporting columns. Therefore, compression columns were able to be placed in the exact same locations as for the original diagrid system. This eliminated any need for lower level room redesign and did not compromise existing spaces from adjacent facilities.

- Penetration of open spaces.
  By placing the main gravity force resisting structure around the perimeter, interior column and floor beam layouts were maintained, and no additional members were

necessary to tie structural elements together. Penetration of open spaces was not an issue, with the exception of the vertical mechanical shaft affected by the new North-South braced frame.

- Floor system impact.
  Because it was possible to frame floor beams between perimeter columns, interior beams were not affected by the new system. Floor framing remains as originally designed.

- Foundation impact.
  The reduction of perimeter loads around the building due to lower structural system weight allows perimeter column footings to be slightly smaller than originally designed. However, the new addition of braced frames will require new piers as well, which could increase foundation costs.

Daylighting Study

Theory

The tightly spaced structural members of the original diagrid inhibit potential panoramic views and limit natural sunlight into exterior spaces. However, the development of the perimeter truss system in Solution Area III opens up the façade in dramatic fashion. This new structural concept provides an opportunity to apply a multitude of curtain wall materials and patterns. With the perimeter truss, windows can be placed in virtually any quantity or arrangement. The freedom to specify how much glazing goes where is sufficient reason to incorporate daylighting. The Athletic Center's original design incorporates daylighting to provide natural light to interior spaces through the use of atrium skylights. Unfortunately, the remainder of the building, primarily perimeter space, was not designed with daylighting concepts in mind.

Why should daylighting be considered for these spaces? There are a number of potential benefits of properly daylighted buildings:

- Increased worker productivity. Pleasant, comfortable daylighted spaces may increase occupant and owner satisfaction and may decrease absenteeism (O'Connor, 1-1).
- Lower operating costs. In general, daylight has a higher light-to-heat ratio. As a result, reduced artificial lighting means reduced space cooling loads, which can save considerable money, especially during peak energy hours.
- Environmentally sound. Daylighted buildings reduce energy consumption and environmental pollution. In some cases they can help obtain LEED certification, giving the building owner certain tax breaks.
- Increased heat gain in winter. This decreases the required heating load and can save mechanical equipment operation costs.

There are also a number of challenges to daylighting the Athletic Center:

- Discipline coordination. Daylighting is highly integrated with other systems and requires much coordination between different disciplines. Ideally, it should have been incorporated into the building program during initial design.
- Increased building glare. Glare occurs when an object is much brighter than the surrounding visual field. It is most frequently experienced by direct sun exposure on the east or west of a building.
- Thermal discomfort. Temperature imbalance from direct ray exposure is irritating to occupants.
- Building orientation and location. This is critical to an early daylighting design. Unfortunately, the Athletic Center's footprint is considered set and cannot be moved or rotated. Neighboring buildings must be taken into account.
- Summer heat gain. Potential unnecessary heat gain will increase cooling loads and energy costs.

The purpose of this study was to design a daylighting system for the perimeter spaces of the Athletic Center and to evaluate its advantages and disadvantages. It was a qualitative study, not a more accurate (and time-consuming) detailed numerical analysis. Simple diagrams and calculations help present the information.

Solution

To begin the study, a determination of which spaces have potential to be daylighted was necessary. A typical floor layout (Figure 34) shows that the daylighted spaces served by atrium skylights (light green) are located on the interior of the building only. Private offices on the western face (orange) are well-suited for daylighting. The large public area at the northwest corner had potential as well, however it faces three directions at once and would be very difficult to properly light and control. All white areas are either back of house spaces, or they face the Shoemaker Arena and would not receive enough light. Therefore, daylighting design focused on the West offices only.

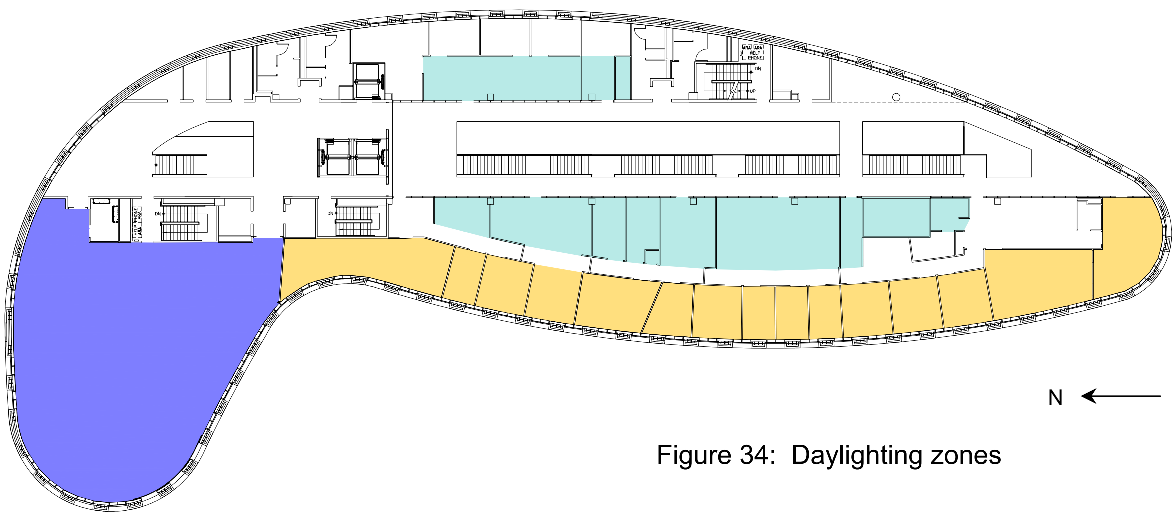


Figure 34: Daylighting zones

The next step in the study was to make building envelope decisions for five major design considerations:

1) Window quantity
   To determine a reasonable quantity of glazing for daylighting use, a Net Area Glazing Calculator was used (O'Connor, 3-7). The calculated value was then multiplied by 1.25 to take into account any framing or mullions. Input assumptions were made to model a representative West office with average reflectance and double pane low-E green tinted glass. The output for the calculations is below in Table 24.

Window Area Calculations	
Average Daylight Factor	3
Room Width (ft)	13
Room Depth (ft)	14
Room Height (ft)	9
Total Area of Interior Surfaces (ft^2)	850
Area-Weighted Average Reflectance	0.5
Visible Transmittance	0.63
Vertical Angle of Sky (degrees)	90
Required Net Glazing (ft^2)	45
Required Gross Glazing (ft^2)	56

Table 24: Window area calculator output

2) Window geometry

The calculated gross glazing area was then divided by the room width and an interference factor of 0.9 to account for columns and other obstructions to the glazing. The resulting required height was 4.8 feet, a reasonable number for an average window. The height was rounded up to 5'-0" for convenience. Useable levels of daylight can be provided to a room depth approximately two times the head height of the window (Mistrick, 2). The West offices are 16' deep from the façade face; therefore window heads were located 8' from the floor. This placed the sill of the window 3' from the floor, a level which permits the occupant to look comfortably out their window. As a result, windows were designed to be continuous along the perimeter, broken only by columns. The continuity also provides a more uniform distribution of light within the space. Finally, the windows were recessed a distance of 1'-4" from the façade face. This "deep façade" approach creates a buffer zone which filters glare and blocks high sun angles. Figure 35 is a section through the typical office showing room dimensions and two key solar angles.

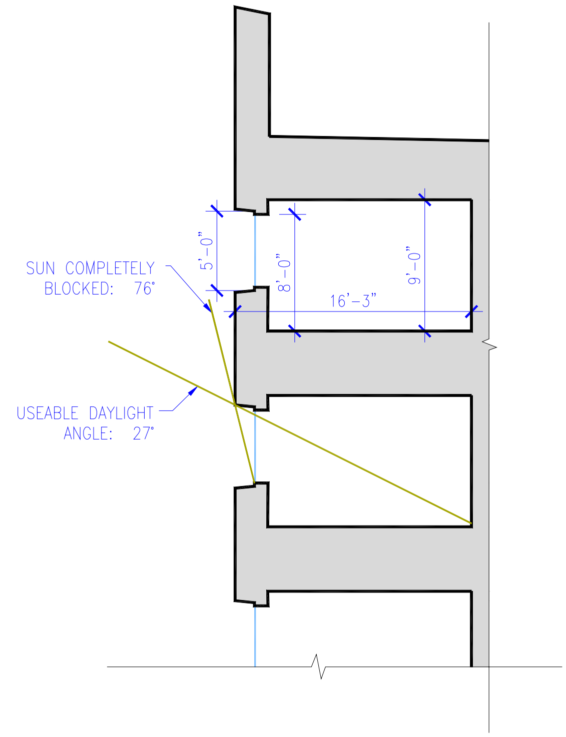


Figure 35: Typical office section

3) Glazing material

As specified in the window quantity calculations, a double pane low-E green tinted glass was selected as the glazing material. This glass works well with the geometric properties of the façade, and has a visible transmittance of about 0.63. The low emissivity also helps control winter heat loss.

4) Window covering

Because much of the building faces North, East, or West directions, the use of vertical blinds is employed. These blinds have an advantage over horizontal blinds by blocking low angle sunlight arriving from high azimuths. No outer window shading is used, as it would disturb the architectural intent of the perimeter.

5) Façade material

The curved shape of the Athletic Center creates potential for reflective glare from one perimeter section to another. Therefore, the building envelope surface material was designed with low specularity. Precast concrete was originally utilized to clad the diagrid members, and was found to be an excellent low specularity material. A roughened precast finish is specified for all spandrel beams and column claddings.

Also important to daylighting performance is the room design. Two factors were considered:

1) Control systems

Because the spaces designed for daylighting are primarily private offices, automatic controls such as photosensors were not employed. However, stepped manual control has been provided. This allows the private office or support room occupant to adjust lighting levels to suit their taste, and does not limit them to an on/off switched situation. It is also considerably less expensive than a dimmed ballast system. Operation cost reduction from the ability to step luminaire levels was not quantified for this study, but there will likely be some energy savings.

2) Interior finishes

Room surface characteristics have substantial effects on the distribution and performance of daylighted space. High reflectance and low specularity are beneficial. Therefore, offices are finished with light colors on the walls and ceilings, and other prominent objects such as the vertical blinds are matte.

Once basic design considerations were settled, curtain wall details could be worked out. The wall system was chosen to be similar to the diagrid cladding in the original design. A precast concrete spandrel beam is placed over the floor structure. It is secured to the perimeter floor beams and filled in with expanding foam insulation. Interior wall structure is built up against the precast concrete and the double pane window is set on an aluminum window frame. Sections of the curtain wall system are detailed below in Figures 36a and 36b.

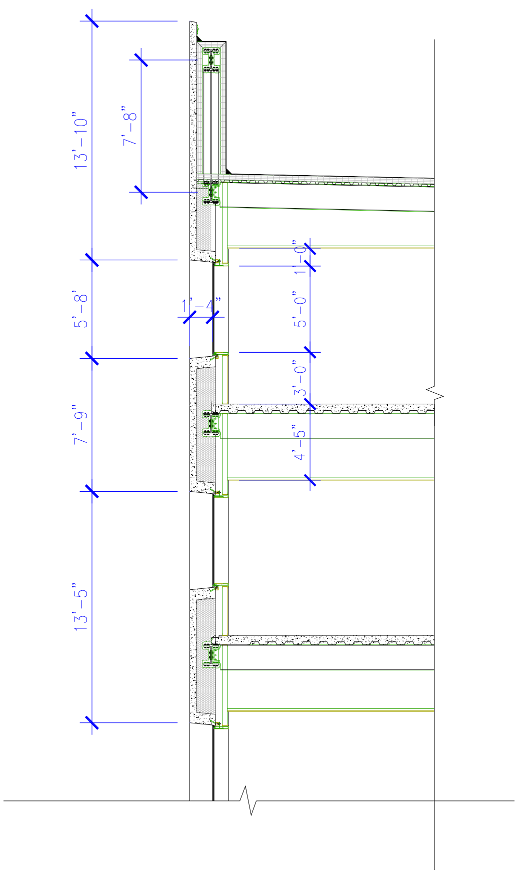


Figure 36a: Curtain wall section

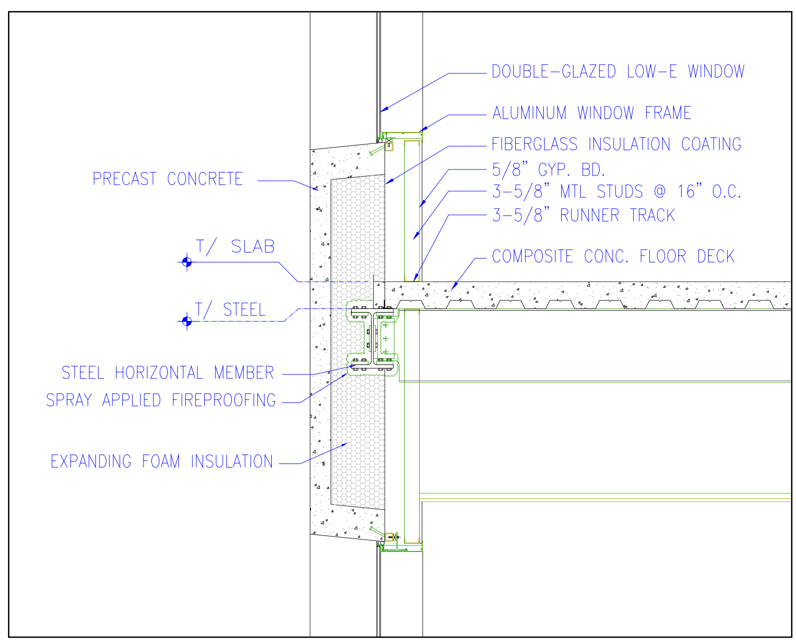


Figure 36b: Spandrel beam detail

Because the exterior wall was changed in the redesign of the structural system and subsequent curtain wall design, a review of code provisions must be considered. Table 705.3 of the Ohio Basic Building Code specifies maximum unprotected or protected window areas for certain fire separation distances. Table 25 below is an abbreviated version of the code table.

	Fire Separation Distance (feet)			
Classification	**0-3**	**>3-5**	**>5-10**	**>10-15**
Unprotected	N.P.	N.P.	10%	15%
Protected	N.P.	15%	25%	45%

Table 25: OBBC Table 705.3 (abbreviated)

The code also states that buildings with an automatic sprinkler system throughout are permitted to use the protected values for unprotected windows. Because the Athletic Center is fully-sprinkled, its unprotected exterior window area may be as much as its protected area. The curtain wall design detailed above has a window area of roughly 35%. All windows have been designed unprotected, so for separation distances less than 10 feet the configuration will not work. The Athletic Center is in close proximity to the Shoemaker Center, about 10'-6" at its nearest point. This translates into a fire separation distance of 5'-3". Therefore, the windows closest to the Shoemaker Center do not meet code provisions and must be changed (Figure 37). Rather than redesigning the entire window system, the section of wall which is 20' or less from the Shoemaker Center was modified by simply introducing non-structural precast cladding panels similar to the column covers at regular intervals along the perimeter. This effectively reduces the window area to less than the 25% maximum allowed by code.

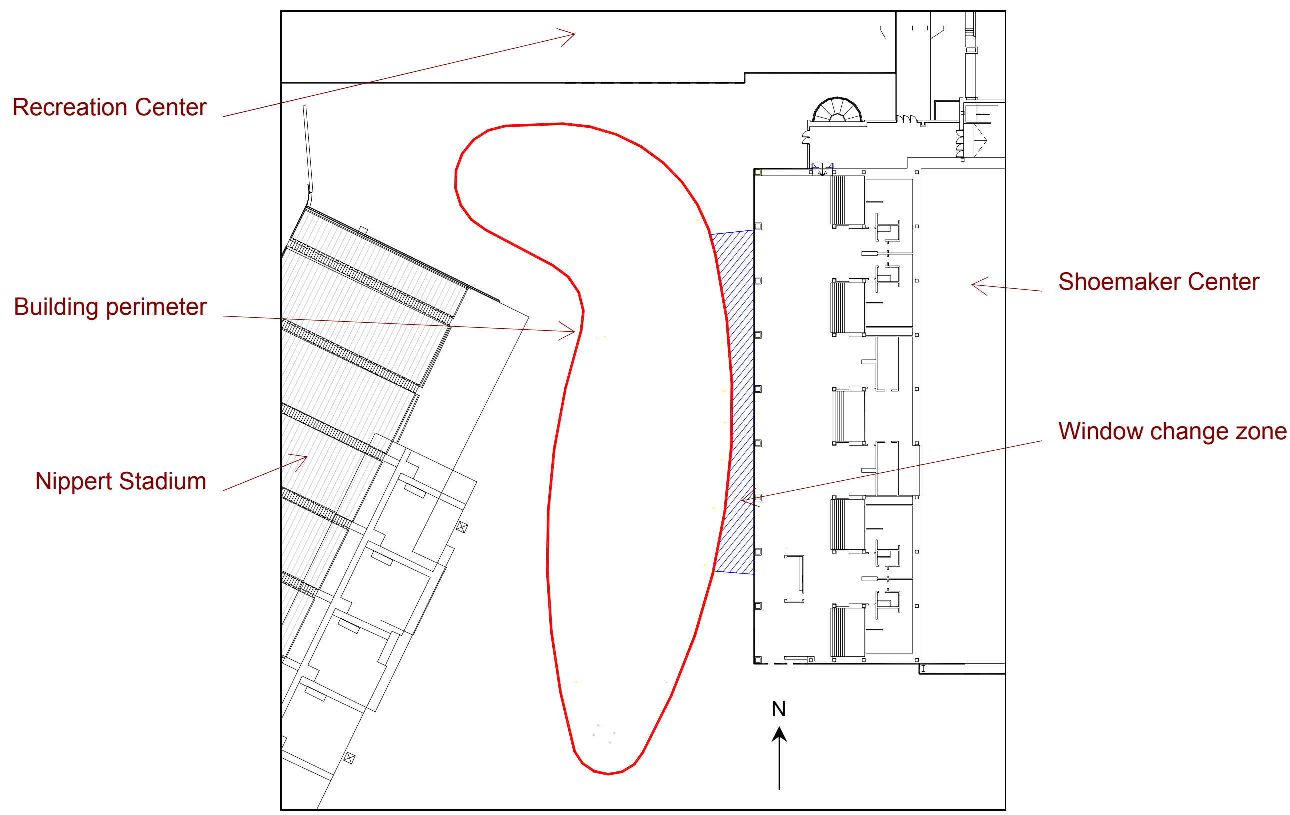


Figure 37: Window change zone

Conclusions

The opportunity to incorporate perimeter daylighting into the Athletic Center was made relatively easy by the structural redesign of Solution Area III. However, the number of spaces which could utilize daylighting was limited. A daylighting program for private offices on the West side of the building was made, taking geometry and material considerations into account. A chart is provided below to summarize the advantages and disadvantages of the perimeter daylighting system relative to the original diagrid system (Table 26).

Issue	Result	Reason
Worker productivity	Advantage	Increased daylight makes offices more comfortable and satisfying
Operating costs	Either	Daylighted offices will benefit from reduced artificial costs; however the other spaces could experience increased mechanical conditioning loads from the additional window area.
Initial cost	Advantage	No additional controls or special equipment is needed for the proposed design. Also, the continuous façade design decreases construction costs due to simple, repetitive pieces.
Environmental Impact	Either	Energy consumption could go either way, base on the same reasoning as for operating costs
Design coordination	Disadvantage	More coordination is needed between disciplines, as well as during the initial design stages.
Glare	Disadvantage	Larger windows placed at the normal viewing height create more opportunity for glare, especially on West side. Vertical blinds help control direct sunlight.
Thermal discomfort	Disadvantage	Increased windows lead to radiation discomfort, especially during winter months. Direct sunlight may be an issue.
Heat gain	Either	Heat gain during winter months is desirable, but during summer months it is a problem.
Views	Advantage	Large, continuous windows at eye level open up views of the Athletic Center surroundings.

Table 26: Daylighting advantages and disadvantages

Given the considerations above, it is safe to conclude that perimeter daylighting for the Athletic Center is certainly possible, but not necessarily feasible. The inherent constraints on building shape and orientation severely decrease the effectiveness of any perimeter daylighting system. Implementation of daylighting for the private office spaces on the west side of the building is a tossup, depending largely on the design intent of the architect and preferences of the building owner.

Construction Study

Theory

Significant changes were made to the Athletic Center in the Structural Redesign and Daylighting Study sections of this report. Not only do they have considerable effects on the design of the structural system and building façade, but they affect the construction methods and management approaches as well. Two construction management issues were discovered during the redesign of the perimeter diagrid lateral system. They are:

1) Truss loading sequence
   The new perimeter truss design incorporates both tension and compression columns as a means of carrying gravity loads. The deformations between adjacent tension and compression columns are incompatible, and large vertical displacement differences occur. This incompatibility presents curtain wall installation problems. A sequencing study was performed to resolve this issue.

2) Site layout
   In the original diagrid design, large sections of the diagrid were meant to be prefabricated and delivered to site for erection directly from the truck. With the new precast curtain wall design, additional space must be provided for panel layout. A site layout plan was developed to better manage the tight site constraints.

The goal of this construction study was to consider these issues and to make informed, logical decisions on each one to better manage the construction of the Athletic Center. Doing this not only strengthened the planning aspects of construction, but justified the changes to the structural and architectural systems as well.

Solution

Truss loading sequence

In order to fully address the issue of column deformation compatibility, it is necessary to understand the reasons why such a problem occurs. A clear visualization of the load path and deformations is important. Load is carried from the tension columns in the spans up to the perimeter truss. The truss carries the load horizontally to the larger compression columns, where it is all brought down to the foundation. As for deformations, consider the diagram in Figure 38. Suppose the bottom of the compression column deflects Δ_1. Disregarding load from the floors acting directly on the column itself, the top of the compression column will deflect approximately $5\Delta_1$. Disregarding truss sag as well, the top of the tension column will be the same, $5\Delta_1$. Finally, the bottom of the tension column will deflect an additional Δ_2, for a total of $5\Delta_1+\Delta_2$. This is many times larger than the bottom of the compression column. Consider the heavily loaded column in the northeast corner of the building. Its deflection at Level 500 is 0.088”, while its deflection at Level 900 is 0.650”. This is a 740% increase. The tension column next to it deflects 1.676” at Level 500. This means there is a 1.588” difference between the adjacent columns at Level 500 over a distance of 27’. Such a difference causes problems of alignment and joint stability between precast panel and window sections.

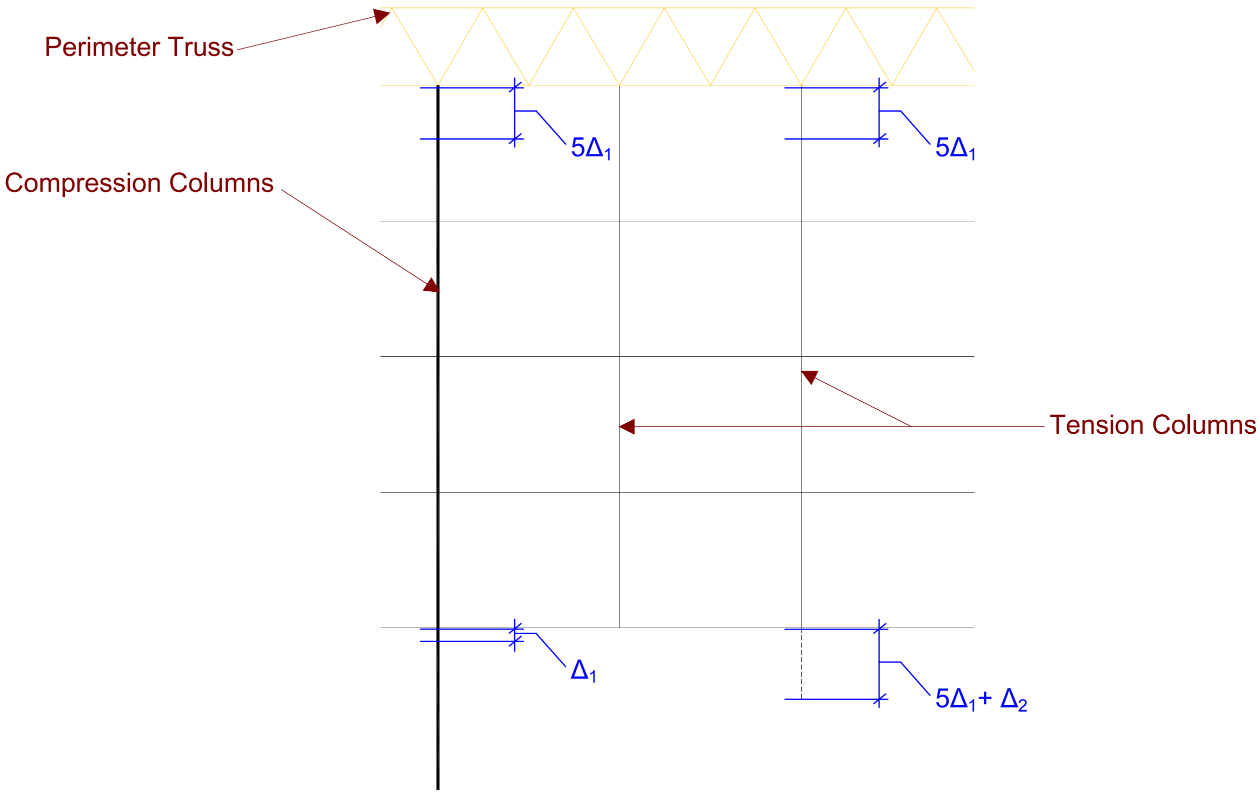


Figure 38: Column deformation incompatibility

There are three ways this issue can be resolved:

- Change the section sizes of the columns to limit the deformations or make them more compatible with each other. This is a not a very economical choice at all and should be disregarded except in extreme circumstances.

- Tension column lengths can be designed initially shorter than required to account for deflection. This is analogous to cambering a beam before loading. Unfortunately, this method causes concrete slab pouring problems. The lower slabs will continue to deflect as upper levels are loaded.

- Construction sequence can be controlled so that deflection change is minimized. Consider two options, installing the curtain wall from the bottom up and from the top down. The relative deflections were found for each level as the structure was loaded in either direction. The results are shown below in Tables 27a and 27b.

	Levels loaded				Total	Total after installation
Level	500	500-600	500-700	500-800		
800	1Δ	1Δ	1Δ	1Δ	4Δ	0
700	2Δ	2Δ	2Δ	1Δ	7Δ	1Δ
600	3Δ	3Δ	2Δ	1Δ	9Δ	3Δ
500	4Δ	3Δ	2Δ	1Δ	10Δ	6Δ

Table 27a: Bottom up sequence

	Levels loaded				Total	Total after installation
Level	500	500-600	500-700	500-800		
800	1Δ	1Δ	1Δ	1Δ	4Δ	3Δ
700	1Δ	2Δ	2Δ	2Δ	7Δ	4Δ
600	1Δ	2Δ	3Δ	3Δ	9Δ	3Δ
500	1Δ	2Δ	3Δ	4Δ	10Δ	0

Table 27b: Top down sequence

The bottom up sequence results in a maximum relative deflection of 6Δ after installation. The top down sequence produces the same overall deflections; however its maximum relative deflection after installation is only 4Δ. Therefore, it is advantageous to install the curtain wall from the top down. In a traditional building this is an unusual situation, however it is not only possible but logical to perform such a construction sequence.

Site layout

The use of precast concrete panels requires more careful planning of site layout. Because the panels are not lifted directly from the truck, they take up space on a limited job site. Figure 39 shows the general layout of the site plan.

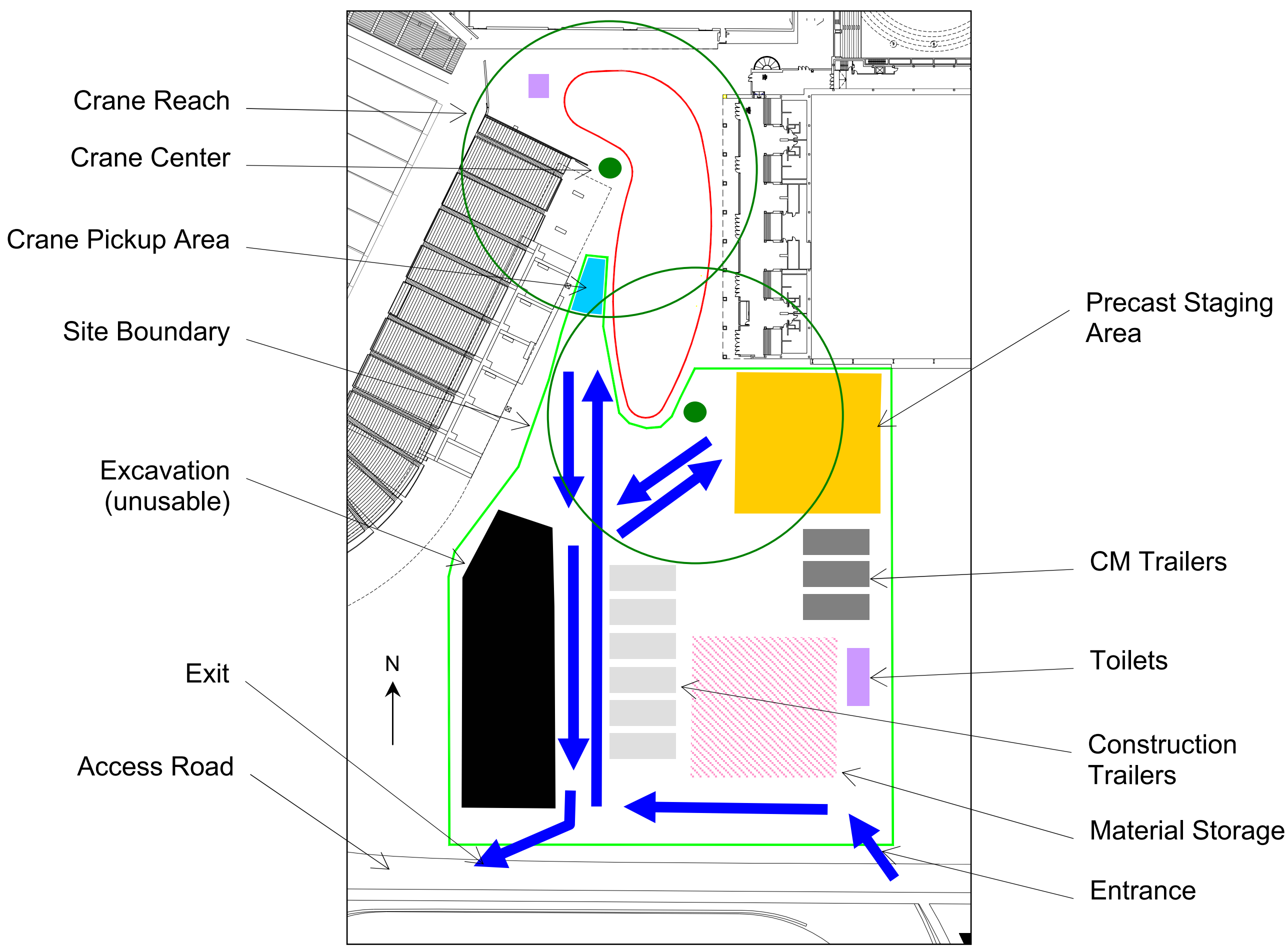


Figure 39: General site layout

The Athletic Center is outlined in red while the usable construction boundary is in green. An entrance and an exit at opposite sides of the site allow better traffic flow. Two cranes must be used in order to reach the entire building perimeter. The precast staging is tucked in the Northeast corner of the site. Toilets are located on both sides of the site.

In addition to the layout of the site, several other site planning issues are to be considered:

1) Site area lighting and street lighting shall be maintained throughout construction.
2) Power distribution shall be maintained throughout construction.
3) Fire department services and access shall be provided.
4) Surface storm drainage and sewer systems shall be provided.
5) Fall protection for all pedestrian areas adjacent to excavation shall be provided.
6) Pedestrian access through or around site shall be maintained.
7) Provide warning signage throughout site.
8) Do not interrupt nearby vehicular passageways.

Conclusions

It is clear from the problems considered above that modifying the structure and/or architecture of the Athletic Center impacts the planning and methodology of certain construction management procedures. Though the two considerations of truss loading sequence and site planning were not in-depth, they presented quick and simple solutions to the issues resulting from the structural redesign.

Final Recommendation

The perimeter diagrid structural system of the University of Cincinnati Athletic Center was redesigned using three distinct approaches; changing its material, modifying its geometry, and removing it altogether. Changing the material did not produce any additional benefits over the original steel wide flange system. Modifying the geometry made the system more structurally efficient, but other factors decreased its effectiveness. However, removing the diagrid and replacing it with a perimeter truss and braced frame system led to significant advantages, both structurally and architecturally.

The proposed perimeter truss satisfies the three main issues presented in the problem statement.

1) Structurally, it is more efficient than the diagrid, reducing steel weight and material costs.
2) Its connections are fewer and less complex than the diagrid, reducing labor costs and erection time.
3) It opens up the façade to support a curtain wall and glazing system, creating more desirable views of the surrounding landscape.

Because these three issues were fully resolved and because daylighting and construction management studies worked out additional details of façade design and erection, the perimeter truss and braced frame system performs as well or better than the diagrid system for most considerations. Not only does it satisfy the design parameters of the Athletic Center, it also an innovative structural solution which makes a unique architectural statement. The perimeter truss and braced frame system is recommended as a sound engineering alternative to the original perimeter diagrid lateral design.

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Picture credits

Figures 1, 2, 4	Glaserworks
Figure 3	Bernard Tschumi Architects
Figures 7, 9	Arup
Figure 11	Office for Metropolitan Architecture

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Appendix A

Solution Area I

A.1 – Diagrid material comparison chart

A.1 - Diagrid material comparison chart

Material Comparison Chart

Material	Mat. Cost	Availability	Lead time	Erect. time	Flexibility	Durability	Weight	Labor Cost	Fire Resist.	Size
Wide Flanges	75	100	75	100	80	90	100	100	70	95
Rectangular HSS	75	95	75	100	80	90	90	100	70	95
Round HSS	75	95	75	100	80	90	90	100	70	100
Glulam Timber	40	80	75	100	50	40	60	90	80	50
Precast	60	100	90	75	100	100	30	75	100	70
Cast-in-place	100	100	100	60	100	100	30	60	100	70
	1.0	0.5	0.6	0.8	0.7	0.8	1.0	1.0	0.9	0.9

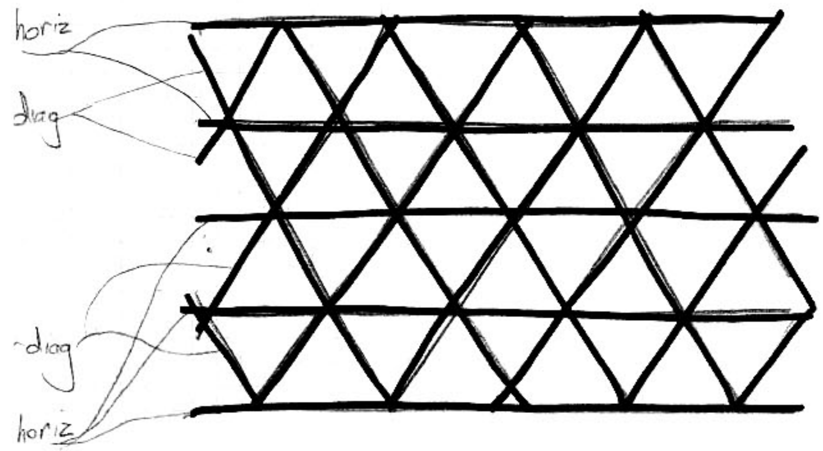
Material	Score	Rank
Wide Flanges	88.6	1
Rectangular HSS	87.1	3
Round HSS	87.6	2
Glulam Timber	65.7	6
Precast	77.1	5
Cast-in-place	79.4	4

Appendix B

Solution Area II

B.1 – Geometric configuration sketches
B.2 – Diagrid efficiency tabulation example
B.3 – Diagrid efficiency weight summary

ORIGINAL ELEVATION



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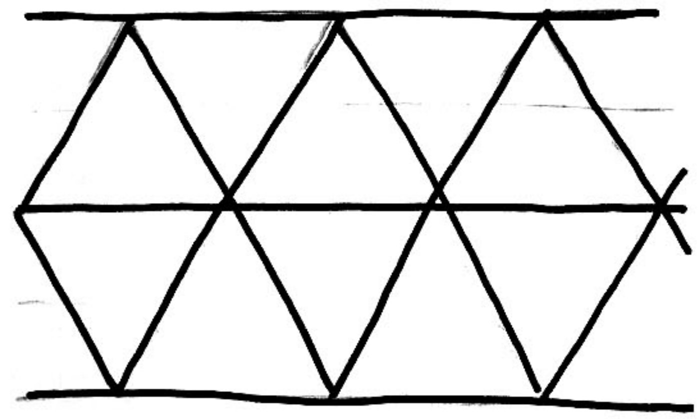

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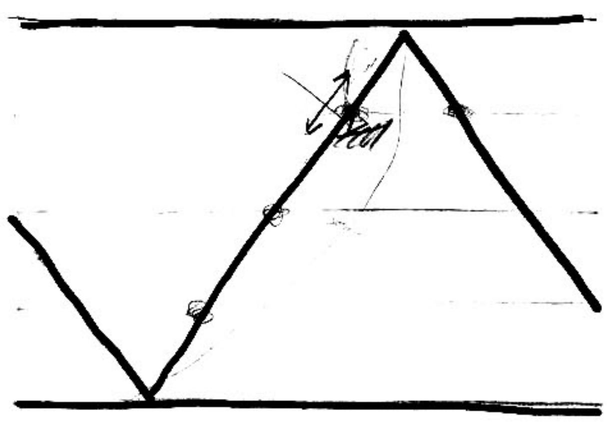

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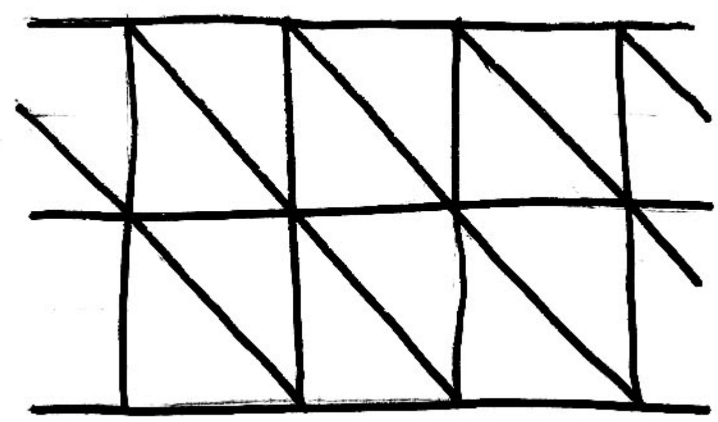

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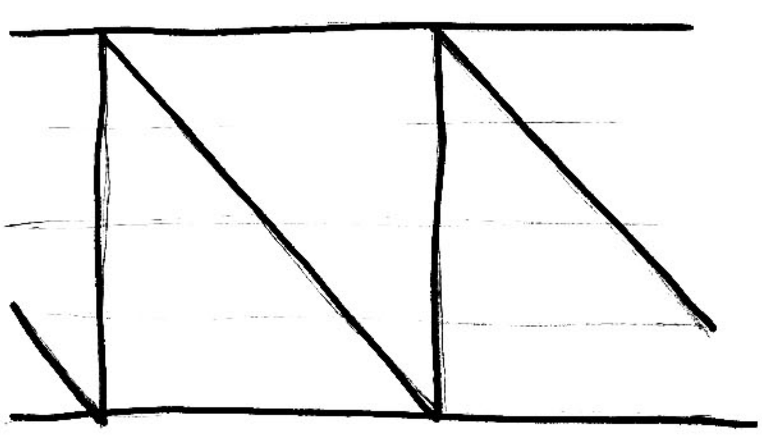

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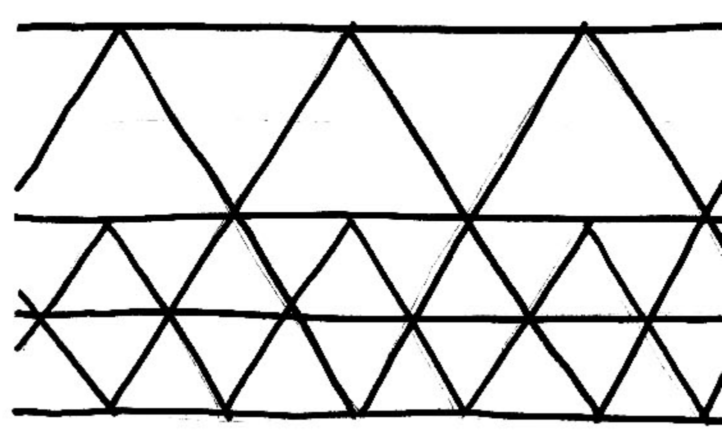

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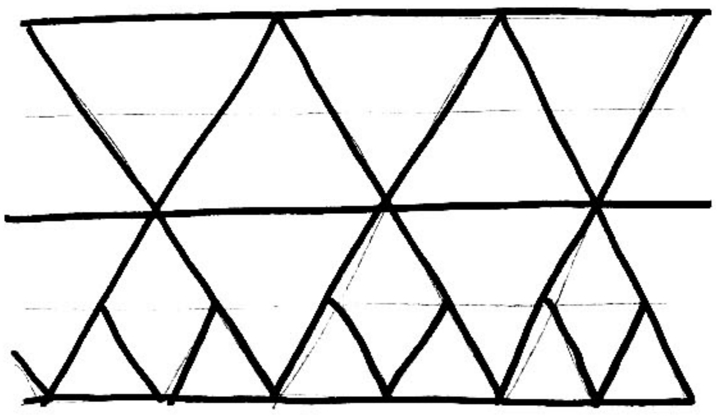

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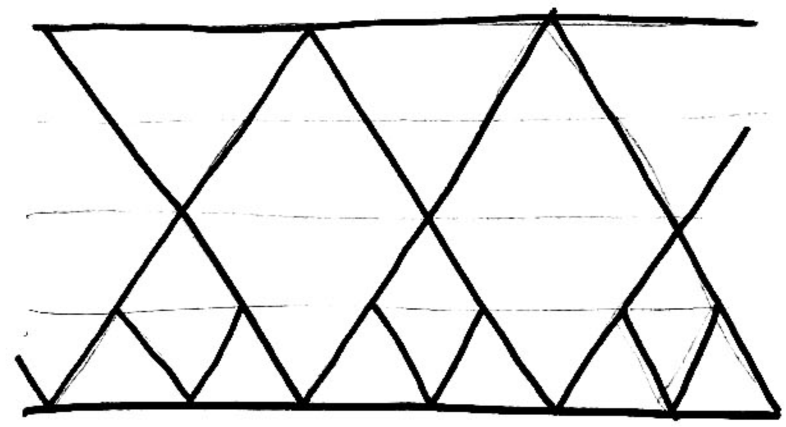

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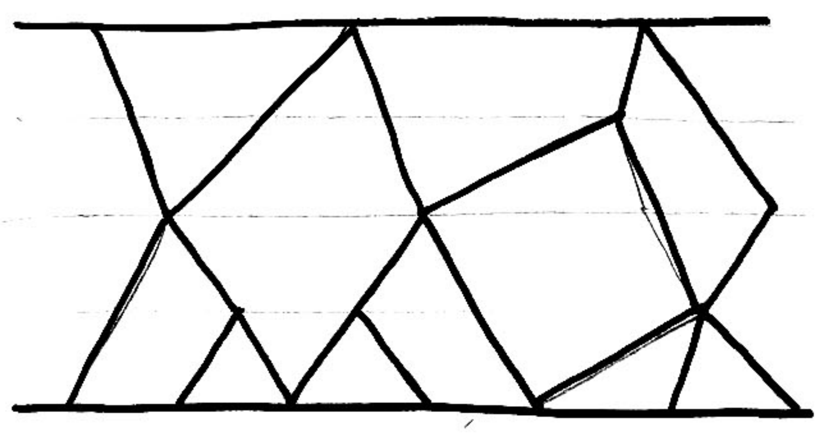

Diagrid Efficiency Tabulation

Beam	Load Case	Length (in)	Max Comp Stress (ksi)	Max Tens Stress (ksi)	Max Stress (ksi)
158	1:UNIT	170.763	0.56		0.56
156	1:UNIT	170.763	0.07	-0.321	0.321
154	1:UNIT	170.763		-0.365	0.365
153	1:UNIT	170.763	0.538		0.538
120	1:UNIT	170.763	0.462		0.462
119	1:UNIT	170.763	0.018	-0.317	0.317
117	1:UNIT	170.763	0.136	-0.314	0.314
115	1:UNIT	170.763	0.554		0.554
114	1:UNIT	170.763		-0.91	0.91
112	1:UNIT	170.763	1.071		1.071
110	1:UNIT	170.763	1.146		1.146
109	1:UNIT	170.763		-0.888	0.888
100	1:UNIT	170.763		-0.561	0.561
99	1:UNIT	170.763	0.752		0.752
97	1:UNIT	170.763	0.766		0.766
95	1:UNIT	170.763		-0.623	0.623
94	1:UNIT	170.763	0.23	-0.141	0.23
92	1:UNIT	170.763	0.399		0.399
90	1:UNIT	170.763	0.363	-0.052	0.363
89	1:UNIT	170.763	0.169	-0.201	0.201
80	1:UNIT	170.763	0.567		0.567
79	1:UNIT	170.763	0.004	-0.373	0.373
77	1:UNIT	170.763	0.065	-0.312	0.312
75	1:UNIT	170.763	0.563		0.563
74	1:UNIT	170.763		-0.51	0.51
72	1:UNIT	170.763	0.734		0.734
70	1:UNIT	170.763	0.773		0.773
69	1:UNIT	170.763		-0.549	0.549
64	1:UNIT	170.763	0.677		0.677
62	1:UNIT	170.763	0.011	-0.519	0.519
60	1:UNIT	170.763		-0.518	0.518
59	1:UNIT	170.763	0.805		0.805
50	1:UNIT	170.763	0.912		0.912
49	1:UNIT	170.763		-0.702	0.702
47	1:UNIT	170.763		-0.692	0.692
45	1:UNIT	170.763	0.889		0.889
44	1:UNIT	170.763	0.214	-0.141	0.214
42	1:UNIT	170.763	0.401		0.401
40	1:UNIT	170.763	0.346	-0.019	0.346
39	1:UNIT	170.763	0.153	-0.201	0.201
34	1:UNIT	170.763	0.203	-0.211	0.211
32	1:UNIT	170.763	0.438		0.438
30	1:UNIT	170.763	0.389		0.389
29	1:UNIT	170.763	0.109	-0.238	0.238
20	1:UNIT	170.763	0.249	-0.091	0.249
19	1:UNIT	170.763	0.234	-0.099	0.234
17	1:UNIT	170.763	0.341	-0.084	0.341
15	1:UNIT	170.763	0.331	-0.051	0.331
14	1:UNIT	170.763	0.306	-0.094	0.306
12	1:UNIT	170.763	0.321	-0.079	0.321
10	1:UNIT	170.763	0.4	-0.279	0.4
9	1:UNIT	170.763	0.246	-0.155	0.246

Sum	26.30
Count	52
Avg.	0.5058
Max.	1.146

Diagrid Efficiency Study Summary

Case 5a

	Count	Avg. Stress (ksi)	Max. Stress (ksi)	Efficiency (%)	Length (in)	Weight
Upper Diagonals	52	0.4081	0.838	48.7	170.8	7443
Lower Diagonals	104	0.3109	1.357	22.9	170.8	24105
Upper Horizontals	26	0.5543	0.941	58.9	108	2642
Lower Horizontals	79	0.2834	0.78	36.3	108	6655
	261			35.7		40845

Case 5b

	Count	Avg. Stress (ksi)	Max. Stress (ksi)	Efficiency (%)	Length (in)	Weight
Upper Diagonals	52	0.4585	1.063	43.1	170.8	9441
Lower Diagonals	52	0.6862	2.359	29.1	170.8	20952
Filler Diagonals	26	0.2841	1.24	22.9	170.8	5507
Upper Horizontals	26	0.6320	1.134	55.7	108	3184
Lower Horizontals	52	0.5705	1.073	53.2	108	6026
	208			41.2		45110

Case 5c

	Count	Avg. Stress (ksi)	Max. Stress (ksi)	Efficiency (%)	Length (in)	Weight
Upper Diagonals	52	0.6895	1.803	38.2	170.8	16014
Lower Diagonals	52	0.8421	3.616	23.3	170.8	32116
Filler Diagonals	26	0.3950	2.157	18.3	170.8	9579
Upper Horizontals	26	0.8380	1.753	47.8	108	4922
Lower Horizontals	26	0.8967	1.918	46.8	108	5386
	182			33.7		68016

Case 6

	Count	Avg. Stress (ksi)	Max. Stress (ksi)	Efficiency (%)	Length (in)	Weight
Upper Diagonals	72	0.1632	0.636	25.7	170.8	7821
Lower Diagonals	64	0.2741	1.193	23.0	170.8	13041
Left Sloped Braces	6	0.1545	0.258	59.9	229.1	355
Right Low Sloped Braces	8	0.1855	0.308	60.2	411.3	1013
Right Big Sloped Braces	16	0.2969	0.463	64.1	229.1	1697
Upper Horizontals	53	0.2053	0.626	32.8	108	3583
Lower Horizontals	79	0.1944	0.664	29.3	108	5665
	298			31.0		33176

Diagrid Efficiency Study Summary

Case 0

	Count	Avg. Stress (ksi)	Max. Stress (ksi)	Efficiency (%)	Length (in)	Weight
Upper Diagonals	104	0.1653	0.589	28.1	170.8	10463
Lower Diagonals	104	0.2759	1.288	21.4	170.8	22879
Upper Horizontals	53	0.1957	0.572	34.2	108	3274
Lower Horizontals	79	0.2231	0.651	34.3	108	5554
	340			28.4		42170

Case 1

	Count	Avg. Stress (ksi)	Max. Stress (ksi)	Efficiency (%)	Length (in)	Weight
Upper Diagonals	52	0.5058	1.146	44.1	170.8	10178
Lower Diagonals	52	0.6804	1.805	37.7	170.8	16031
Upper Horizontals	26	0.6638	1.173	56.6	108	3294
Lower Horizontals	52	0.5910	1.191	49.6	108	6689
	182			45.6		36192

Case 2

	Count	Avg. Stress (ksi)	Max. Stress (ksi)	Efficiency (%)	Length (in)	Weight
Diagonals	52	2.1767	4.087	53.3	170.8	36299
Upper Horizontals	26	1.7067	2.656	64.3	108	7458
Lower Horizontals	26	1.6685	2.81	59.4	108	7890
	104			57.5		51648

Case 3

	Count	Avg. Stress (ksi)	Max. Stress (ksi)	Efficiency (%)	Length (in)	Weight
Upper Diagonals	26	0.6047	1.093	55.3	194.7	5533
Lower Diagonals	26	0.7029	1.381	50.9	194.7	6991
Upper Verticals	26	0.3539	0.972	36.4	162	4094
Lower Verticals	26	0.5974	1.717	34.8	162	7232
Upper Horizontals	26	0.5526	0.989	55.9	108	2777
Lower Horizontals	52	0.5630	1.209	46.6	108	6790
	182			46.6		33417

Case 4

	Count	Avg. Stress (ksi)	Max. Stress (ksi)	Efficiency (%)	Length (in)	Weight
Diagonals	28	3.5198	4.948	71.1	194.5	26947
Verticals	32	1.3162	2.512	52.4	162	13022
Upper Horizontals	28	1.9587	4.347	45.1	108	13145
Lower Horizontals	28	2.0084	4.206	47.8	108	12719
	116			54.0		65833

Appendix C

Solution Area III

C.1 – Load calculations
C.2 – Member sizing example
C.3 – Long span gravity displacement example
C.4 – Diaphragm drifts
C.5 – Total dead weight calculations
C.6 – Final member sizes
C.7 – Recorded trial size example
C.8 – Floor beam sizing calculations
C.9 – Original system takeoff

Load Calculations - Based on a 15' Tributary width

Trib width (ft) 9

	Area ft^2	Roof Dead psf	Area ft^2	Office Dead psf	Length ft	Enclosure Dead plf*	Total Dead kip	Difference*
Level 900	135	95	0	96	0	405	12.8	12.8
Level 800	135	95	135	96	9	405	29.4	16.6
Level 700	135	95	270	96	18	405	46.0	16.6
Level 600	135	95	405	96	27	405	62.6	16.6
Level 500	135	95	540	96	36	405	79.2	16.6

* 30psf*13.5

	Area ft^2	Snow psf	Total Snow kip	Difference*
Level 900	135	30	4.1	4.1
Level 800	135	30	4.1	0.0
Level 700	135	30	4.1	0.0
Level 600	135	30	4.1	0.0
Level 500	135	30	4.1	0.0

Area ft^2	Office Live psf	Kll	LLR	Reduced LL psf	Total Live kip	Difference*	CASE 2 1.2D+1.6L+.5S	Deflection Service Loads
0	50	4	1	50.0	0.0	0.0	17.4	16.9
135	50	4	0.895	44.8	6.0	6.0	29.6	22.6
270	50	4	0.706	35.3	9.5	3.5	25.5	20.1
405	50	4	0.623	31.1	12.6	3.1	24.8	19.7
540	50	4	0.573	28.6	15.5	2.9	24.5	19.5

*These are the loads applied to each diagrid level in STAAD or ETABS

0.92

Trib width (ft) 13.5

	Area ft^2	Roof Dead psf	Area ft^2	Office Dead psf	Length ft	Enclosure Dead plf*	Total Dead kip	Difference*
Level 900	202.5	95	0	96	0	405	19.2	19.2
Level 800	202.5	95	202.5	96	13.5	405	44.1	24.9
Level 700	202.5	95	405	96	27	405	69.1	24.9
Level 600	202.5	95	607.5	96	40.5	405	94.0	24.9
Level 500	202.5	95	810	96	54	405	118.9	24.9

* 30psf*13.5

	Area ft^2	Snow psf	Total Snow kip	Difference*
Level 900	202.5	30	6.1	6.1
Level 800	202.5	30	6.1	0.0
Level 700	202.5	30	6.1	0.0
Level 600	202.5	30	6.1	0.0
Level 500	202.5	30	6.1	0.0

Area ft^2	Office Live psf	Kll	LLR	Reduced LL psf	Total Live kip	Difference*	CASE 2 1.2D+1.6L+.5S	Deflection Service Loads
0	50	4	1	50.0	0.0	0.0	26.1	25.3
202.5	50	4	0.777	38.9	7.9	7.9	42.5	32.8
405	50	4	0.623	31.1	12.6	4.7	37.5	29.6
607.5	50	4	0.554	27.7	16.8	4.2	36.7	29.1
810	50	4	0.514	25.7	20.8	4.0	36.2	28.9

*These are the loads applied to each diagrid level in STAAD or ETABS

0.93

Trib width (ft) 18

	Area ft^2	Roof Dead psf	Area ft^2	Office Dead psf	Length ft	Enclosure Dead plf*	Total Dead kip	Difference*
Level 900	270	95	0	96	0	405	25.7	25.7
Level 800	270	95	270	96	18	405	58.9	33.2
Level 700	270	95	540	96	36	405	92.1	33.2
Level 600	270	95	810	96	54	405	125.3	33.2
Level 500	270	95	1080	96	72	405	158.5	33.2

* 30psf*13.5

	Area ft^2	Snow psf	Total Snow kip	Difference*
Level 900	270	30	8.1	8.1
Level 800	270	30	8.1	0.0
Level 700	270	30	8.1	0.0
Level 600	270	30	8.1	0.0
Level 500	270	30	8.1	0.0

Area ft^2	Office Live psf	Kll	LLR	Reduced LL psf	Total Live kip	Difference*	CASE 2 1.2D+1.6L+.5S	Deflection Service Loads
0	50	4	1	50.0	0.0	0.0	34.8	33.8
270	50	4	0.706	35.3	9.5	9.5	55.1	42.7
540	50	4	0.573	28.6	15.5	5.9	49.3	39.1
810	50	4	0.514	25.7	20.8	5.3	48.4	38.5
1080	50	4	0.478	23.9	25.8	5.0	47.9	38.2

*These are the loads applied to each diagrid level in STAAD or ETABS

0.93

Trib width (ft) 22.5

	Area ft^2	Roof Dead psf	Area ft^2	Office Dead psf	Length ft	Enclosure Dead plf*	Total Dead kip	Difference*
Level 900	337.5	95	0	96	0	405	32.1	32.1
Level 800	337.5	95	337.5	96	22.5	405	73.6	41.5
Level 700	337.5	95	675	96	45	405	115.1	41.5
Level 600	337.5	95	1013	96	67.5	405	156.6	41.5
Level 500	337.5	95	1350	96	90	405	198.1	41.5

* 30psf*13.5

	Area ft^2	Snow psf	Total Snow kip	Difference*
Level 900	337.5	30	10.1	10.1
Level 800	337.5	30	10.1	0.0
Level 700	337.5	30	10.1	0.0
Level 600	337.5	30	10.1	0.0
Level 500	337.5	30	10.1	0.0

Area ft^2	Office Live psf	Kll	LLR	Reduced LL psf	Total Live kip	Difference*	CASE 2 1.2D+1.6L+.5S	Deflection Service Loads
0	50	4	1	50.0	0.0	0.0	43.5	42.2
337.5	50	4	0.658	32.9	11.1	11.1	67.6	52.6
675	50	4	0.539	26.9	18.2	7.1	61.1	48.6
1013	50	4	0.486	24.3	24.6	6.4	60.1	47.9
1350	50	4	0.454	22.7	30.7	6.1	59.5	47.6

*These are the loads applied to each diagrid level in STAAD or ETABS

0.94

Trib width (ft) 27

	Area ft^2	Roof Dead psf	Area ft^2	Office Dead psf	Length ft	Enclosure Dead plf*	Total Dead kip	Difference*
Level 900	405	95	0	96	0	405	38.5	38.5
Level 800	405	95	405	96	27	405	88.3	49.8
Level 700	405	95	810	96	54	405	138.1	49.8
Level 600	405	95	1215	96	81	405	187.9	49.8
Level 500	405	95	1620	96	108	405	237.7	49.8

* 30psf*13.5

	Area ft^2	Snow psf	Total Snow kip	Difference*
Level 900	405	30	12.2	12.2
Level 800	405	30	12.2	0.0
Level 700	405	30	12.2	0.0
Level 600	405	30	12.2	0.0
Level 500	405	30	12.2	0.0

Area ft^2	Office Live psf	Kll	LLR	Reduced LL psf	Total Live kip	Difference*	CASE 2 1.2D+1.6L+.5S	Deflection Service Loads
0	50	4	1	50.0	0.0	0.0	52.2	50.6
405	50	4	0.623	31.1	12.6	12.6	80.0	62.4
810	50	4	0.514	25.7	20.8	8.2	72.9	58.0
1215	50	4	0.465	23.3	28.3	7.5	71.7	57.3
1620	50	4	0.436	21.8	35.3	7.1	71.1	56.9

*These are the loads applied to each diagrid level in STAAD or ETABS

0.94

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N-S Direction

Coefficients	
Windward	16.3
Leeward	-3.7

Height (ft)	Kz	Windward (psf)	Leeward (psf)	Total MWFRS (psf)
0-15	0.57	9.3	-3.7	13.0
15-20	0.62	10.1	-3.7	13.8
20-25	0.66	10.8	-3.7	14.5
25-30	0.70	11.4	-3.7	15.1
30-40	0.76	12.4	-3.7	16.1
40-50	0.81	13.2	-3.7	16.9
50-60	0.85	13.9	-3.7	17.6
60-70	0.89	14.5	-3.7	18.2
70-80	0.93	15.2	-3.7	18.9

E-W Direction

Coefficients	
Windward	16.3
Leeward	-9.1

Height (ft)	Kz	Windward (psf)	Leeward (psf)	Total MWFRS (psf)
0-15	0.57	9.3	-9.1	18.4
15-20	0.62	10.1	-9.1	19.2
20-25	0.66	10.8	-9.1	19.9
25-30	0.70	11.4	-9.1	20.5
30-40	0.76	12.4	-9.1	21.5
40-50	0.81	13.2	-9.1	22.3
50-60	0.85	13.9	-9.1	23.0
60-70	0.89	14.5	-9.1	23.6
70-80	0.93	15.2	-9.1	24.3

E-W Direction Windward

Building height (ft)	72
Building trib width (ft)	300

Level	Story ht. (ft)	Trib ht. (ft)	Total ht. (ft)	P 1 (psf)	H 1 (ft)	P 2 (psf)	H 2 (ft)	P 3 (psf)	H 3 (ft)	Story Dist. Load (plf)
Roof		14.5		14.5	4.75	15.2	9.75			217
	13.5		65.25							
800		13.5		13.9	8.25	14.5	5.25			191
	13.5		51.75							
700		13.5		12.4	1.75	13.2	10	13.9	1.75	178
	13.5		38.25							
600		13.5		10.8	0.25	11.4	5	12.4	8.25	162
	13.5		24.75							
500		15.75		9.3	6	10.1	5	10.8	4.75	158
	18		9							
400 (ground)		9		9.3	9					N/A

E-W Direction Leeward

Building height (ft)	72
Building trib width (ft)	300

Level	Story ht. (ft)	Trib ht. (ft)	Total ht. (ft)	P 1 (psf)	H 1 (ft)	P 2 (psf)	H 2 (ft)	P 3 (psf)	H 3 (ft)	Story Dist. Load (plf)
Roof		14.5		9.1	4.75	9.1	9.75			132
	13.5		65.25							
800		13.5		9.1	8.25	9.1	5.25			123
	13.5		51.75							
700		13.5		9.1	1.75	9.1	10	9.1	1.75	123
	13.5		38.25							
600		13.5		9.1	0.25	9.1	5	9.1	8.25	123
	13.5		24.75							
500		15.75		9.1	6	9.1	5	9.1	4.75	143
	18		9							
400 (ground)		9		9.1	9					N/A

N-S Direction Windward

Building height (ft)	72
Building trib width (ft)	300

Level	Story ht. (ft)	Trib ht. (ft)	Total ht. (ft)	P 1 (psf)	H 1 (ft)	P 2 (psf)	H 2 (ft)	P 3 (psf)	H 3 (ft)	Story Dist. Load (plf)
Roof		14.5		14.5	4.75	15.2	9.75			217
	13.5		65.25							
800		13.5		13.9	8.25	14.5	5.25			191
	13.5		51.75							
700		13.5		12.4	1.75	13.2	10	13.9	1.75	178
	13.5		38.25							
600		13.5		10.8	0.25	11.4	5	12.4	8.25	162
	13.5		24.75							
500		15.75		9.3	6	10.1	5	10.8	4.75	158
	18		9							
400 (ground)		9		9.3	9					N/A

N-S Direction Leeward

Building height (ft)	72
Building trib width (ft)	300

Level	Story ht. (ft)	Trib ht. (ft)	Total ht. (ft)	P 1 (psf)	H 1 (ft)	P 2 (psf)	H 2 (ft)	P 3 (psf)	H 3 (ft)	Story Dist. Load (plf)
Roof		14.5		3.7	4.75	3.7	9.75			54
	13.5		65.25							
800		13.5		3.7	8.25	3.7	5.25			50
	13.5		51.75							
700		13.5		3.7	1.75	3.7	10	3.7	1.75	50
	13.5		38.25							
600		13.5		3.7	0.25	3.7	5	3.7	8.25	50
	13.5		24.75							
500		15.75		3.7	6	3.7	5	3.7	4.75	58
	18		9							
400 (ground)		9		3.7	9					N/A

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E-W Direction Windward

Level	Story Dist. Load (plf)
Roof	217
800	191
700	178
600	162
500	158

E-W Direction Leeward

Level	Story Dist. Load (plf)
Roof	132
800	123
700	123
600	123
500	143

N-S Direction Windward

Level	Story Dist. Load (plf)
Roof	217
800	191
700	178
600	162
500	158

N-S Direction Leeward

Level	Story Dist. Load (plf)
Roof	54
800	50
700	50
600	50
500	58

*These are the loads applied to the ETABS model

Truss Horizontal Members

Fy [ksi] = 50

Member Information				Loads				Section Properties			Euler Information						Member Capacity			Utilization Factor		
Story	Name	Location (in)	Section	Load Case	Axial (kip)	Mxx (in-kip)	Myy (in-kip)	Area (in^2)	Zx (in^3)	Zy (in^3)	Kx	Lx (ft)	Ky	Ly (ft)	L_b (ft)	λc	φPn (kip)	φMnx (in-kip)	φMny (in-kip)	H1-1a	H1-1b	Invalid
STORY6	B100	0	W14x159	GRAVITY	97.51	-1492.063	2.448	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.14	
STORY6	B100	108.035	W14x159	GRAVITY	97.51	1052.168	-1.201	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.10	
STORY6	B101	0	W14x159	GRAVITY	540.23	-517.977	3.108	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	0.27	-	
STORY6	B101	107.955	W14x159	GRAVITY	540.23	-1386.536	1.218	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	0.33	-	
STORY6	B102	0	W14x159	GRAVITY	458.81	-1079.229	-0.552	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.18	
STORY6	B102	107.951	W14x159	GRAVITY	458.81	-373.382	-0.372	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.13	
STORY6	B103	0	W14x159	GRAVITY	360.1	-756.323	2.401	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.14	
STORY6	B103	108.057	W14x159	GRAVITY	360.1	-267.343	-1.593	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.10	
STORY6	B104	0	W14x159	GRAVITY	263.63	-558.806	1.209	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.10	
STORY6	B104	108.046	W14x159	GRAVITY	263.63	-195.693	-1.5	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.07	
STORY6	B105	0	W14x159	GRAVITY	210.46	-434.176	1.95	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.08	
STORY6	B105	107.932	W14x159	GRAVITY	210.46	-201.162	-1.933	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.06	
STORY6	B106	0	W14x159	GRAVITY	158.72	-384.376	1.431	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.06	
STORY6	B106	107.976	W14x159	GRAVITY	158.72	-120.472	-1.715	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.04	
STORY6	B107	0	W14x159	GRAVITY	107.68	-272.1	1.165	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.04	
STORY6	B107	108.038	W14x159	GRAVITY	107.68	-86.858	-2.101	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.03	
STORY6	B108	0	W14x159	GRAVITY	82.63	-206.404	1.304	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.03	
STORY6	B108	108.012	W14x159	GRAVITY	82.63	-96.956	-0.356	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.03	
STORY6	B109	0	W14x159	GRAVITY	58.9	-160.97	0.176	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.03	
STORY6	B109	107.972	W14x159	GRAVITY	58.9	-184.701	-2.157	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.03	
STORY6	B110	0	W14x159	GRAVITY	23.56	-683.243	28.268	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.06	
STORY6	B110	108.008	W14x159	GRAVITY	23.56	329.099	-56.553	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.04	
STORY6	B111	0	W14x159	GRAVITY	-331.46	-437.757	-222.843	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	0.4	1881.73	12915.00	6570.00	-	0.16	
STORY6	B111	105.33	W14x159	GRAVITY	-331.46	1050.505	196.149	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	0.4	1881.73	12915.00	6570.00	-	0.20	
STORY6	B112	0	W14x159	GRAVITY	-359.14	81.719	172.794	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	0.4	1881.73	12915.00	6570.00	-	0.13	
STORY6	B112	103.08	W14x159	GRAVITY	-359.14	736.462	-66.339	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	0.4	1881.73	12915.00	6570.00	-	0.16	
STORY6	B113	0	W14x159	GRAVITY	-391.51	298.389	-41.587	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	0.4	1881.73	12915.00	6570.00	0.23	-	
STORY6	B113	103.272	W14x159	GRAVITY	-391.51	559.59	-42.153	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	0.4	1881.73	12915.00	6570.00	0.25	-	
STORY6	B114	0	W14x159	GRAVITY	-412.36	554.627	-68.52	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	0.4	1881.73	12915.00	6570.00	0.27	-	
STORY6	B114	103.262	W14x159	GRAVITY	-412.36	359.417	180.541	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	0.4	1881.73	12915.00	6570.00	0.27	-	
STORY6	B115	0	W14x159	GRAVITY	-438.19	853.398	227.364	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	0.4	1881.73	12915.00	6570.00	0.32	-	
STORY6	B115	104.932	W14x159	GRAVITY	-438.19	146.949	-194.079	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	0.4	1881.73	12915.00	6570.00	0.27	-	
STORY6	B116	0	W14x159	GRAVITY	-149.54	990.423	-144.287	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	0.4	1881.73	12915.00	6570.00	-	0.14	
STORY6	B116	107.893	W14x159	GRAVITY	-149.54	-564.724	1.771	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	0.4	1881.73	12915.00	6570.00	-	0.08	
STORY6	B117	0	W14x159	GRAVITY	200.21	125.552	34.678	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.06	
STORY6	B117	108.032	W14x159	GRAVITY	200.21	-781.009	-2.644	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.10	
STORY6	B118	0	W14x159	GRAVITY	196.48	-372.645	-16.901	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.07	
STORY6	B118	107.922	W14x159	GRAVITY	196.48	-153.837	8.653	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.06	
STORY6	B119	0	W14x159	GRAVITY	181.79	-217.8	0.351	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.06	
STORY6	B119	107.93	W14x159	GRAVITY	181.79	-170.268	3.459	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.05	
STORY6	B120	0	W14x159	GRAVITY	167.11	-238.275	-3.771	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.05	
STORY6	B120	107.91	W14x159	GRAVITY	167.11	-124.361	4.882	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.05	
STORY6	B121	0	W14x159	GRAVITY	131.7	-219.32	-0.999	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.05	
STORY6	B121	107.895	W14x159	GRAVITY	131.7	-42.154	3.058	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.03	
STORY6	B122	0	W14x159	GRAVITY	95.98	-166.271	-0.615	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.03	
STORY6	B122	108.118	W14x159	GRAVITY	95.98	10.675	2.396	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.02	
STORY6	B123	0	W14x159	GRAVITY	61.4	-82.96	0.238	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.02	
STORY6	B123	108.118	W14x159	GRAVITY	61.4	27.23	0.607	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.02	
STORY6	B124	0	W14x159	GRAVITY	49.21	-38.969	0.042	46.7	287.00	146.00	1.00	9.00	1.00	9.00	0.0	-	2335.00	12915.00	6570.00	-	0.01	

Point Displacements

Trial 5

Story	Point	UZ	Story	Point	UZ	Difference				Delta col	Allowable
			STORY5	1	-0.6706						
			STORY5	2	-0.4991						
STORY1	3	-0.1059	STORY5	3	-0.3228	-0.2169					
			STORY5	4	-0.3092						
			STORY5	5	-0.336						
STORY1	6	-0.1485	STORY5	6	-0.3796	-0.2311					
			STORY5	7	-0.3974						
			STORY5	8	-0.4109						
STORY1	9	-0.1579	STORY5	9	-0.4205	-0.2626					
			STORY5	10	-0.425						
			STORY5	11	-0.4265						
STORY1	12	-0.1591	STORY5	12	-0.4258	-0.2667			No Span		
			STORY5	13	-0.4257						
			STORY5	14	-0.4238						
STORY1	15	-0.1576	STORY5	15	-0.4192	-0.2616					
			STORY5	16	-0.4096						
			STORY5	17	-0.3976						
STORY1	18	-0.1494	STORY5	18	-0.3837	-0.2343					
			STORY5	19	-0.3496						
			STORY5	20	-0.3346						
STORY1	21	-0.1422	STORY5	21	-0.3524	-0.2102					
			STORY5	22	-0.3615						
			STORY5	23	-0.4293						
STORY1	24	-0.1558	STORY5	24	-0.5848	-0.429					
STORY1	25	-1.2518	STORY5	25	-1.04	0.2118					
STORY1	26	-1.5888	STORY5	26	-1.377	0.2118					
STORY1	27	-1.732	STORY5	27	-1.5202	0.2118	41' Span			-1.5826	1.37
STORY1	28	-1.6912	STORY5	28	-1.4794	0.2118	63' length				
STORY1	29	-1.4782	STORY5	29	-1.2664	0.2118					
STORY1	30	-1.1614	STORY5	30	-0.9496	0.2118					
STORY1	31	-0.1494	STORY5	31	-0.5568	-0.4074					
			STORY5	32	-0.4219						
			STORY5	33	-0.3464						
STORY1	34	-0.1327	STORY5	34	-0.311	-0.1783					
			STORY5	35	-0.2445				No Span		
			STORY5	36	-0.2077						
STORY1	37	-0.109	STORY5	37	-0.2079	-0.0989					
			STORY5	38	-0.1612						
			STORY5	39	-0.2656						
STORY1	40	-0.146	STORY5	40	-0.5537	-0.4077					
			STORY5	41	-1.1504						
STORY1	42	-2.1795	STORY5	42	-1.7719	0.4076					
			STORY5	43	-2.2359						
STORY1	44	-2.9771	STORY5	44	-2.5695	0.4076	90' Span			-2.8311	3.00
			STORY5	45	-2.6453		90' length				
STORY1	46	-2.9536	STORY5	46	-2.546	0.4076					
			STORY5	47	-2.1987						
STORY1	48	-2.1486	STORY5	48	-1.741	0.4076					
			STORY5	49	-1.1552						
STORY1	50	-0.2286	STORY5	50	-0.633	-0.4044					
			STORY5	51	-0.5472						
STORY1	52	-0.8797	STORY5	52	-0.5696	0.3101		43' Span		-0.6974	1.43
STORY1	53	-0.7835	STORY5	53	-0.5717	0.2118		45' length			
STORY1	54	-0.7557	STORY5	54	-0.5438	0.2119					
STORY1	55	-0.1823	STORY5	55	-0.4983	-0.316					
STORY1	56	-0.9722	STORY5	56	-0.662	0.3102					
			STORY5	57	-0.7586		45' Span				
STORY1	58	-1.0734	STORY5	58	-0.8242	0.2492	45' length			-0.8911	1.50
			STORY5	59	-0.7794						
STORY1	60	-0.3657	STORY5	60	-0.7872	-0.4215					
STORY1	61	-1.2854	STORY5	61	-1.0736	0.2118					
STORY1	62	-1.4664	STORY5	62	-1.2546	0.2118		48' Span			
STORY1	63	-1.4781	STORY5	63	-1.2663	0.2118		63' length		-1.1124	1.60
STORY1	64	-1.4051	STORY5	64	-1.1932	0.2119					
STORY1	65	-1.1698	STORY5	65	-1.0757	0.0941					
STORY1	66	-1.0532	STORY5	66	-0.9592	0.094					
STORY1	67	-0.4129	STORY5	67	-0.9318	-0.5189					
STORY1	68	-1.5504	STORY5	68	-1.4128	0.1376					
			STORY5	69	-1.9515						
STORY1	70	-2.7973	STORY5	70	-2.505	0.2923					
			STORY5	71	-2.9498						
STORY1	72	-3.7562	STORY5	72	-3.2924	0.4638	107' Span				
			STORY5	73	-3.4355		117' length				
STORY1	74	-3.8367	STORY5	74	-3.4291	0.4076				-3.7283	3.57
			STORY5	75	-3.2119						
STORY1	76	-3.2802	STORY5	76	-2.8726	0.4076					
			STORY5	77	-2.3874						
STORY1	78	-2.2881	STORY5	78	-1.8805	0.4076					
			STORY5	79	-1.3111						
STORY1	80	-0.1084	STORY5	80	-0.8015	-0.6931					
			STORY5	81	-0.7342						
STORY1	82	-1.1773	STORY5	82	-0.7697	0.4076					
			STORY5	83	-0.7815			63' Span			
STORY1	84	-1.3143	STORY5	84	-0.8098	0.5045		63' length		-1.2084	2.10

Diaphragm Drift Comparison

			Trial 1			Trial 2			Trial 3			Trial 4			Trial 5			
Story	**Diaphragm**	**Load**	**UX**	**UY**	**delta/flr.**	**UX**	**UY**	**delta/flr.**	**UX**	**UY**	**delta/flr.**	**UX**	**UY**	**delta/flr.**	**UX**	**UY**	**delta/flr.**	**% Accept.**
STORY5	LVL900	EWWIND	3.0069		0.6489	2.74		0.6099	2.3527		0.5385	1.5842		0.418	1.5971		0.4239	0.92
STORY4	LVL800	EWWIND	2.358		0.5994	2.1301		0.5685	1.8142		0.5154	1.1662		0.3817	1.1732		0.384	0.83
STORY3	LVL700	EWWIND	1.7586		0.6021	1.5616		0.5587	1.2988		0.5037	0.7845		0.3365	0.7892		0.3383	0.73
STORY2	LVL600	EWWIND	1.1565		0.5442	1.0029		0.4936	0.7951		0.4212	0.448		0.2625	0.4509		0.2633	0.57
STORY1	LVL500	EWWIND	0.6123		0.3824	0.5093		0.3487	0.3739		0.2939	0.1855		0.1759	0.1876		0.1748	0.38
STORY1	LVL400	EWWIND	0.2299		0.2299	0.1606		0.1606	0.08		0.08	0.0096		0.0096	0.0128		0.0128	0.03
STORY5	LVL900	NSWIND		-2.1664	-0.4676		-1.9125	-0.4427		-1.6367	-0.3977		-1.0877	-0.2851		-1.2899	-0.3225	0.70
STORY4	LVL800	NSWIND		-1.6988	-0.389		-1.4698	-0.3538		-1.239	-0.324		-0.8026	-0.2472		-0.9674	-0.2802	0.61
STORY3	LVL700	NSWIND		-1.3098	-0.414		-1.116	-0.3677		-0.915	-0.3371		-0.5554	-0.2328		-0.6872	-0.2639	0.57
STORY2	LVL600	NSWIND		-0.8958	-0.4066		-0.7483	-0.3507		-0.5779	-0.2953		-0.3226	-0.1848		-0.4233	-0.2191	0.47
STORY1	LVL500	NSWIND		-0.4892	-0.2247		-0.3976	-0.1894		-0.2826	-0.1498		-0.1378	-0.0896		-0.2042	-0.1171	0.25
STORY1	LVL400	NSWIND		-0.2645	-0.2645		-0.2082	-0.2082		-0.1328	-0.1328		-0.0482	-0.0482		-0.0871	-0.0871	0.19
						Percent of Trial 1			**Percent of Trial 1**			**Percent of Trial 1**			**Percent of Trial 1**			
						0.91			0.78			0.53			0.53			
						0.90			0.77			0.49			0.50			
						0.89			0.74			0.45			0.45			
						0.87			0.69			0.39			0.39			
						0.83			0.61			0.30			0.31			
						0.70			0.35			0.04			0.06			
							0.88			0.76			0.50			0.60		
							0.87			0.73			0.47			0.57		
							0.85			0.70			0.42			0.52		
							0.84			0.65			0.36			0.47		
							0.81			0.58			0.28			0.42		
							0.79			0.50			0.18			0.33		

Superimposed Load Types

	Area Occupancy	Floor Finish (psf)	Floor Slab (psf)	Ceiling/Services (psf)	Partitions (psf)	Additional (psf)	Total Dead (psf)	Live Load (psf)	Total Unfactored (psf)
1	High Roof		60	10			70	30	100
2	Office		66	10	20		96	50	146
3	Multi-purpose club		66	10			76	100	176
4	Stair					30	30	100	130
5	Atrium/Corridor	25	66	10			101	100	201
6	Mechanical room		66	10		50	126	125	251
7	Computer lab	25	66	10			101	100	201
8	Fixed seating		110	10		10	130	60	190
9	Stage	25	66	10			101	100	201
10	Lobby/General assembly	25	66	10			101	100	201
11	Locker room	25		10	20		55	100	155
12	Work area	25	65	10	20		120	100	220
13	Showers/Rest room	25	66	10			101	60	161
14	Storage	25	66	10			101	125	226
15	Laundry	25		10			35	150	185
16	Ramp	25	66				91	100	191
17	Elevator machine room		66				66	250	316
18	Meeting room		66	10			76	60	136
19	Treatment area	25	66	10	20		121	100	221
20	Video room	25	66	10	20		121	100	221
21	Hydrotherapy	25	66	10			101	400	501
22	Loading dock	30	66	10			106	100	206
23	Ambulance parking	30	79	10			119	100	219
24	Walkway roof	13	5				18	30	48
25	Theater control room	25	66	10	20		121	100	221
26	Trash compactor		66	10			76	350	426
27	Roof	25	60	10			95	60	155
28	Exterior truck loading	90	79	10			179	100	279
29	Exterior non-truck loading	90	66	10			166	100	266

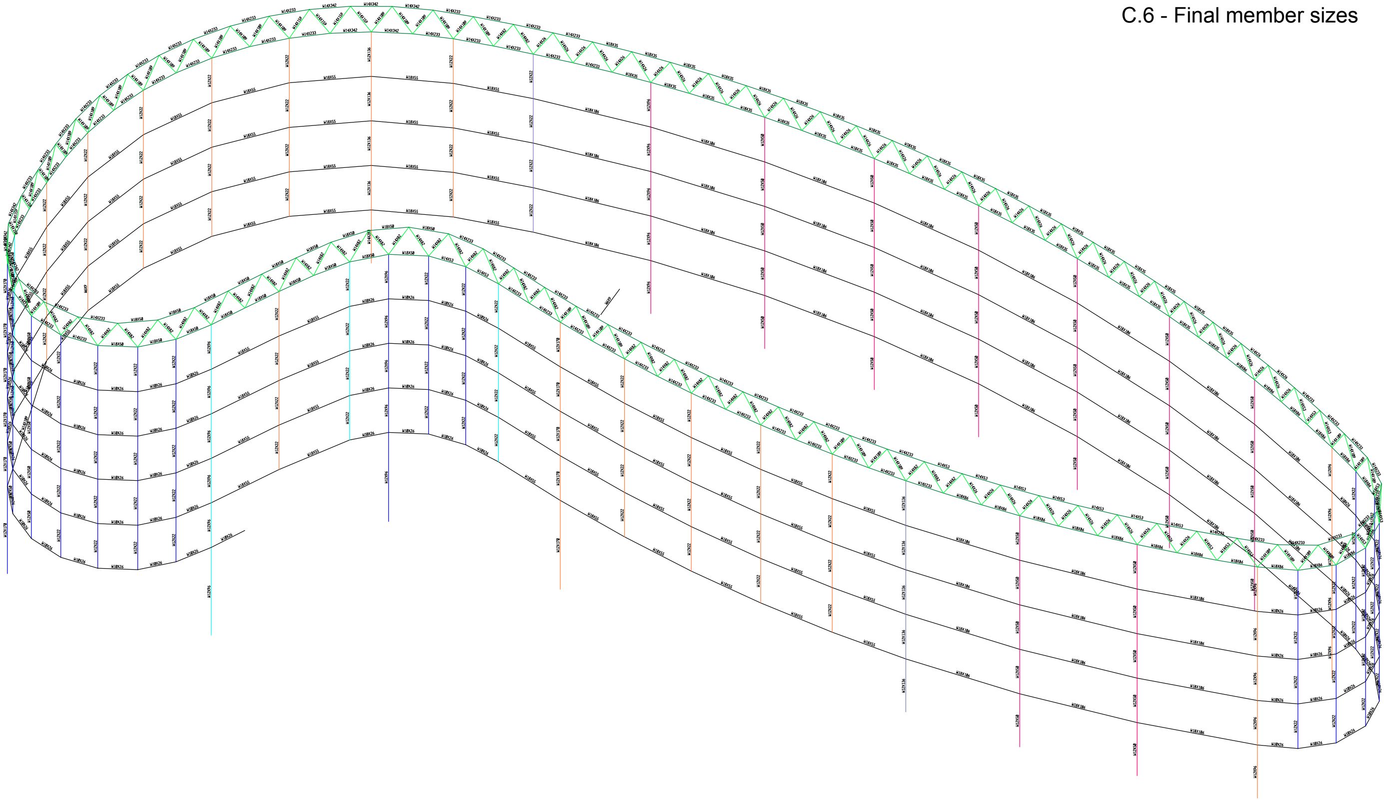
Superimposed Dead Load Calculations

	Level																	
	100		200		300		400		500		600		700		800		Roof	
Type	Area (ft^2)	Total (kip)	Area (ft^2)	Total (kip)	Area (ft^2)	Total (kip)	Area (ft^2)	Total (kip)	Area (ft^2)	Total (kip)	Area (ft^2)	Total (kip)	Area (ft^2)	Total (kip)	Area (ft^2)	Total (kip)	Area (ft^2)	Total (kip)
1																	10382	727
2			2224	214	997	96	3586	344	7583	728	10249	984	9973	957	10038	964		
3													4234	322	4772	363		
4			483	14	669	20	1046	31	1615	48	1428	43	1694	51	1655	50		
5			3750	379	3598	363			6170	623	5887	595	6106	617	6058	612		
6			1558	196	10932	1377					5472	689						
7									2228	225								
8							2307	300	2485	323								
9							803	81					544	55				
10							8907	900										
11	17259	949																
12																		
13							2017	204	1053	106	501	51	969	98	955	96		
14			641	65														
15	4393	154																
16					887	81												
17	358	24																
18			8510	647	548	42												
19			3529	427	1749	212												
20																		
21			943	95														
22					2556	271												
23					1033	123												
24																		
25									1282	155								
26					451	34												
27																	13119	1246
28					5050	904	4723	845										
29							13982	2321										
Sums	22010	1127	21638	2037	28470	3523	37371	5026	22416	2209	23537	2361	23520	2100	23478	2084	23501	1973

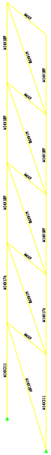
Superstructure Dead Load

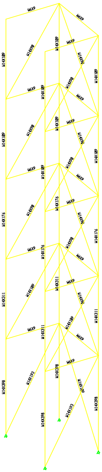
	Floor Framing			Interior Columns					Perimeter Truss System			
Level	Dist. Load (psf)	Area (ft^2)	Weight/floor (kips)	# of cols.	Typ. weight (plf)	Story Ht. (ft)	Wt./floor (kips)	Trib. Wt. (kips)	Truss (kips)	Columns (kips)	Trib. Wt. (kips)	Total
Roof	10	23500	235					6.9	279.4		21.0	542.3
				17	60	13.5	13.8			42		
800	10	23500	235					13.8			42.0	290.8
				17	60	13.5	13.8			42		
700	10	23500	235					13.8			42.0	290.8
				17	60	13.5	13.8			42		
600	10	23500	235					13.8			42.0	290.8
				17	60	13.5	13.8			42		
500	10	23500	235					29.6			21.0	285.6
				21	120	18	45.4					
400	10	37500	375					22.7				397.7

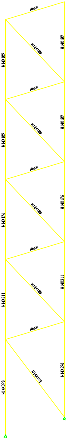
C.6 - Final member sizes



C.6 - Final member sizes







Truss Horizontal Members - Partial Bracing

Actual Applied Sizes - Trial 6

Member Information						
Story	Name	W14x26	W14x53	W14x82	W14x233	W14x342
STORY6	B085		X			
STORY6	B085		X			
STORY6	B086		X			
STORY6	B086		X			
STORY6	B087		X			
STORY6	B087		X			
STORY6	B088				X	
STORY6	B088				X	
STORY6	B089				X	
STORY6	B089				X	
STORY6	B090				X	
STORY6	B090				X	
STORY6	B091				X	
STORY6	B091				X	
STORY6	B092				X	
STORY6	B092				X	
STORY6	B093				X	
STORY6	B093				X	
STORY6	B094				X	
STORY6	B094				X	
STORY6	B095				X	
STORY6	B095				X	
STORY6	B096				X	
STORY6	B096				X	
STORY6	B097				X	
STORY6	B097				X	
STORY6	B098				X	
STORY6	B098				X	
STORY6	B099				X	
STORY6	B099				X	
STORY6	B100				X	
STORY6	B100				X	
STORY6	B101				X	
STORY6	B101				X	
STORY6	B102		X			
STORY6	B102		X			
STORY6	B103		X			
STORY6	B103		X			
STORY6	B104		X			
STORY6	B104		X			
STORY6	B105		X			
STORY6	B105		X			
STORY6	B106		X			
STORY6	B106		X			
STORY6	B107		X			
STORY6	B107		X			
STORY6	B108		X			
STORY6	B108		X			
STORY6	B109				X	
STORY6	B109				X	
STORY6	B110				X	
STORY6	B110				X	
STORY6	B111				X	
STORY6	B111				X	
STORY6	B112				X	
STORY6	B112				X	
STORY6	B113				X	
STORY6	B113				X	
STORY6	B114				X	
STORY6	B114				X	
STORY6	B115				X	
STORY6	B115				X	
STORY6	B116				X	
STORY6	B116				X	
STORY6	B117				X	
STORY6	B117				X	
STORY6	B118				X	
STORY6	B118				X	
STORY6	B119	X				
STORY6	B119	X				
STORY6	B120	X				
STORY6	B120	X				
STORY6	B121	X				
STORY6	B121	X				
STORY6	B122	X				
STORY6	B122	X				
STORY6	B123	X				
STORY6	B123	X				
STORY6	B124	X				
STORY6	B124	X				
STORY6	B125	X				
STORY6	B125	X				
STORY6	B126	X				
STORY6	B126	X				
STORY6	B127	X				
STORY6	B127	X				
STORY6	B128	X				
STORY6	B128	X				
STORY6	B129	X				
STORY6	B129	X				
STORY6	B130	X				
STORY6	B130	X				
STORY6	B131	X				
STORY6	B131	X				
STORY6	B132	X				
STORY6	B132	X				

		W14x26	W14x53	W14x109	W14x233	W14x342
STORY5	B56		X			
STORY5	B56		X			
STORY5	B55		X			
STORY5	B55		X			
STORY5	B54		X			
STORY5	B54		X			
STORY5	B53		X			
STORY5	B53		X			
STORY5	B52		X			
STORY5	B52		X			
STORY5	B51				X	
STORY5	B51				X	
STORY5	B50				X	
STORY5	B50				X	
STORY5	B49				X	
STORY5	B49				X	
STORY5	B48				X	
STORY5	B48				X	
STORY5	B47				X	
STORY5	B47				X	
STORY5	B46				X	
STORY5	B46				X	
STORY5	B45				X	
STORY5	B45				X	
STORY5	B44				X	
STORY5	B44				X	
STORY5	B43				X	
STORY5	B43				X	
STORY5	B42				X	
STORY5	B42				X	
STORY5	B41				X	
STORY5	B41				X	
STORY5	B40				X	
STORY5	B40				X	
STORY5	B39				X	
STORY5	B39				X	
STORY5	B38		X			
STORY5	B38		X			
STORY5	B37		X			
STORY5	B37		X			
STORY5	B36		X			
STORY5	B36		X			
STORY5	B35		X			
STORY5	B35		X			
STORY5	B34		X			
STORY5	B34		X			
STORY5	B33		X			
STORY5	B33		X			
STORY5	B32		X			
STORY5	B32		X			
STORY5	B31		X			
STORY5	B31		X			
STORY5	B30		X			
STORY5	B30		X			
STORY5	B29		X			
STORY5	B29		X			
STORY5	B28		X			
STORY5	B28		X			
STORY5	B27		X			
STORY5	B27		X			
STORY5	B26		X			
STORY5	B26		X			
STORY5	B25		X			
STORY5	B25		X			
STORY5	B24		X			
STORY5	B24		X			
STORY5	B23		X			
STORY5	B23		X			
STORY5	B22		X			
STORY5	B22		X			
STORY5	B21		X			
STORY5	B21		X			
STORY5	B20	X				
STORY5	B20	X				
STORY5	B19	X				
STORY5	B19	X				
STORY5	B18	X				
STORY5	B18	X				
STORY5	B17	X				
STORY5	B17	X				
STORY5	B16	X				
STORY5	B16	X				
STORY5	B15	X				
STORY5	B15	X				
STORY5	B14	X				
STORY5	B14	X				
STORY5	B13	X				
STORY5	B13	X				
STORY5	B12	X				
STORY5	B12	X				
STORY5	B11	X				
STORY5	B11	X				
STORY5	B10	X				
STORY5	B10	X				
STORY5	B09	X				
STORY5	B09	X				

43' Span
45' length

90' Span
90' length

No Span

41' Span
63' length

No Span

C.7 - Recorded trial size example

STORY6	B133	X				
STORY6	B133	X				
STORY6	B134	X				
STORY6	B134	X				
STORY6	B135	X				
STORY6	B135	X				
STORY6	B136	X				
STORY6	B136	X				
STORY6	B137	X				
STORY6	B137	X				
STORY6	B138	X				
STORY6	B138	X				
STORY6	B139	X				
STORY6	B139	X				
STORY6	B140				X	
STORY6	B140				X	
STORY6	B141				X	
STORY6	B141				X	
STORY6	B142				X	
STORY6	B142				X	
STORY6	B143				X	
STORY6	B143				X	
STORY6	B144					X
STORY6	B144					X
STORY6	B145					X
STORY6	B145					X
STORY6	B146					X
STORY6	B146					X
STORY6	B147				X	
STORY6	B147				X	
STORY6	B148				X	
STORY6	B148				X	
STORY6	B149				X	
STORY6	B149				X	
STORY6	B150				X	
STORY6	B150				X	
STORY6	B151				X	
STORY6	B151				X	
STORY6	B152				X	
STORY6	B152				X	
STORY6	B153				X	
STORY6	B153				X	
STORY6	B154				X	
STORY6	B154				X	
STORY6	B155				X	
STORY6	B155				X	
STORY6	B156				X	
STORY6	B156				X	
STORY6	B157					X
STORY6	B157					X
STORY6	B158					X
STORY6	B158					X
STORY6	B159					X
STORY6	B159					X
STORY6	B160				X	
STORY6	B160				X	
STORY6	B161				X	
STORY6	B161				X	
STORY6	B162				X	
STORY6	B162				X	
STORY6	B163		X			
STORY6	B163		X			
STORY6	B164		X			
STORY6	B164		X			
STORY6	B165		X			
STORY6	B165		X			
STORY6	B166		X			
STORY6	B166		X			
STORY6	B167		X			
STORY6	B167		X			
STORY6	B168		X			
STORY6	B168		X			
		42	32	0	82	12
		26	53	82	233	233
		9	9	9	9	9
		9828	15264	0	171954	25164

sum/2 = 111.105 kips
*Divide by 2 since there were two outputs per element

TOTAL = 170.46

STORY5	B08	X				
STORY5	B08	X				
STORY5	B07	X				
STORY5	B07	X				
STORY5	B06	X				
STORY5	B06	X				
STORY5	B05	X				
STORY5	B05	X				
STORY5	B04	X				
STORY5	B04	X				
STORY5	B03	X				
STORY5	B03	X				
STORY5	B02	X				
STORY5	B02	X				
STORY5	B01				X	
STORY5	B01				X	
STORY5	B84				X	
STORY5	B84				X	
STORY5	B83				X	
STORY5	B83				X	
STORY5	B82				X	
STORY5	B82				X	
STORY5	B81				X	
STORY5	B81				X	
STORY5	B80					X
STORY5	B80					X
STORY5	B79					X
STORY5	B79					X
STORY5	B78				X	
STORY5	B78				X	
STORY5	B77				X	
STORY5	B77				X	
STORY5	B76				X	
STORY5	B76				X	
STORY5	B75				X	
STORY5	B75				X	
STORY5	B74				X	
STORY5	B74				X	
STORY5	B73				X	
STORY5	B73				X	
STORY5	B72				X	
STORY5	B72				X	
STORY5	B71				X	
STORY5	B71				X	
STORY5	B70				X	
STORY5	B70				X	
STORY5	B69				X	
STORY5	B69				X	
STORY5	B68				X	
STORY5	B68				X	
STORY5	B67					X
STORY5	B67					X
STORY5	B66					X
STORY5	B66					X
STORY5	B65				X	
STORY5	B65				X	
STORY5	B64				X	
STORY5	B64				X	
STORY5	B63				X	
STORY5	B63				X	
STORY5	B62		X			
STORY5	B62		X			
STORY5	B61		X			
STORY5	B61		X			
STORY5	B60		X			
STORY5	B60		X			
STORY5	B59		X			
STORY5	B59		X			
STORY5	B58		X			
STORY5	B58		X			
STORY5	B57		X			
STORY5	B57		X			
		38	28	0	38	8
		26	53	109	233	233
		9	9	9	9	9
		8892	13356	0	79686	16776

sum/2 = 59.355
*Divide by 2 since there were two outputs per element

63' Span
63' length

107' Span
117' length

48' Span
63' length

45' Span
45' length

C.8 - Floor beam sizing calculations

	Dead Load						
Length ft	Trib ft	Roof Dead psf	Trib ft	Office Dead psf	Height ft	Enclosure Dead plf*	Total Dead kip
9	15	0	15	96	13.5	405	6.91
18	15	0	15	96	13.5	405	6.91
27	15	0	15	96	13.5	405	6.91

* 30psf*13.5'

Live Load					
Area ft^2	Office Live psf	Kll	LLR	Reduced LL psf	Total Live kip
135	50	1	1.000	50.0	0.75
270	50	1	1.000	50.0	0.75
405	50	1	0.995	49.8	0.75

Factored
1.2D+1.6L
9.49
9.49
9.48

Mu	Least Weight*	W18 or smaller*
96	W10x26	W10x26
384	W18x55	W18x55
864	W27x84	W18x106

*using beam design table in AISC manual

Original System Steel Take-off - Diagrid

			Length ft/pc.	Pieces/Level	# of Levels	Total Length ft	Member size	Weight lb/ft	Total Weight tons
Light	Upper	Horizontal	9	37	3	999	W14x53	53	26.5
		Diagonal	14.2	74	2	2102	W12x35	35	36.8
	Lower	Horizontal	9	37	2	666	W14x53	53	17.6
		Diagonal	14.2	74	2	2102	W12x50	50	52.5
Heavy	Upper	Horizontal	9	47	3	1269	W14x82	82	52.0
		Diagonal	14.2	94	2	2670	W12x53	53	70.7
	Lower	Horizontal	9	47	2	846	W14x82	82	34.7
		Diagonal	14.2	94	2	2670	W12x87	87	116.1
V columns	W-shape		16.6	24	1	398	W12x170	170	33.9
	Box		26.6	8	1	213	12.75^2x.75x.75	122.5	13.0

			Sums		
			Horizontals	Diagonals	V columns
Light	Upper	Horizontal	26.5		
		Diagonal		36.8	
	Lower	Horizontal	17.6		
		Diagonal		52.5	
Heavy	Upper	Horizontal	52.0		
		Diagonal		70.7	
	Lower	Horizontal	34.7		
		Diagonal		116.1	
V columns	W-shape				33.9
	Box				13.0
			130.8	**276.2**	**46.9**

Original System Steel Take-off - Below-grade bracing

		Size 1				Size 2				Size 3			
		Size	Weight lb/ft	Length ft	Total tons	Size	Weight lb/ft	Length ft	Total tons	Size	Weight lb/ft	Length ft	Total tons
BF1	**Columns**	W14x311	311	248	38.6								
	Beams	W10x12	12	18	0.1	W14x30	30	54	0.8				
	Diagonals	W14x22	22	36	0.4	W14x90	90	36	1.6				
BF4	**Columns**	W14x311	311	124	19.3								
	Beams	W10x12	12	9	0.1	W27x84	84	9	0.4	W14x30	30	18	0.27
	Diagonals	W14x90	90	18	0.8								
				Subtotals =	59.2				2.8				0.3
				Total =	62.3								