AE Senior Thesis 2004

University of Cincinnati Athletic Center

Structural Redesign of a Perimeter Diagrid Lateral System

Brian Genduso

Structural Option

Topic Outline

1) Building Introduction
2) Structural System Description
3) Problem Statement
4) Design Philosophy
5) Redesign Approach
6) Structural Redesign
7) Daylighting Study
8) Construction Study
9) Recommendation

Building Introduction

General Information

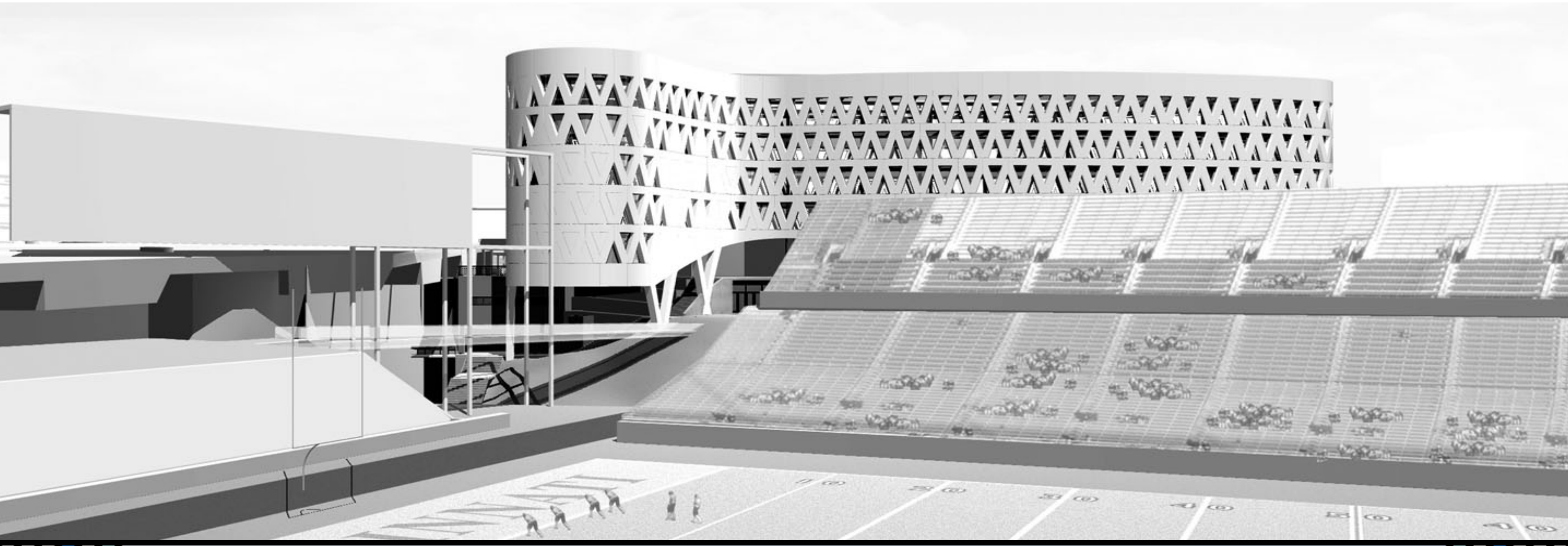
Multi-use

8 stories - 220,000 ft^2

$50.7 million

Design Architect – Bernard Tschumi Architects

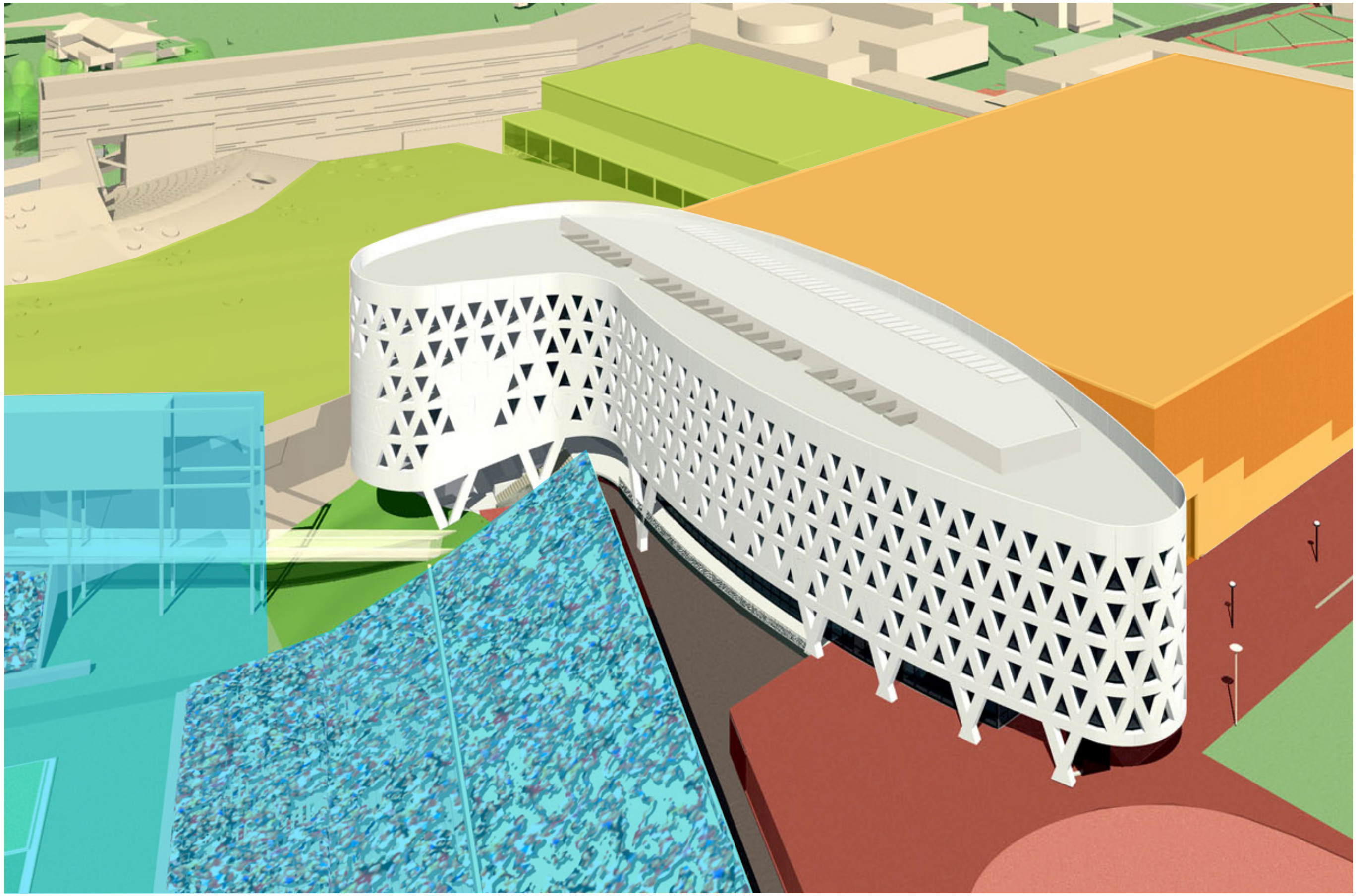
Design Engineer – Arup, New York



Building Introduction

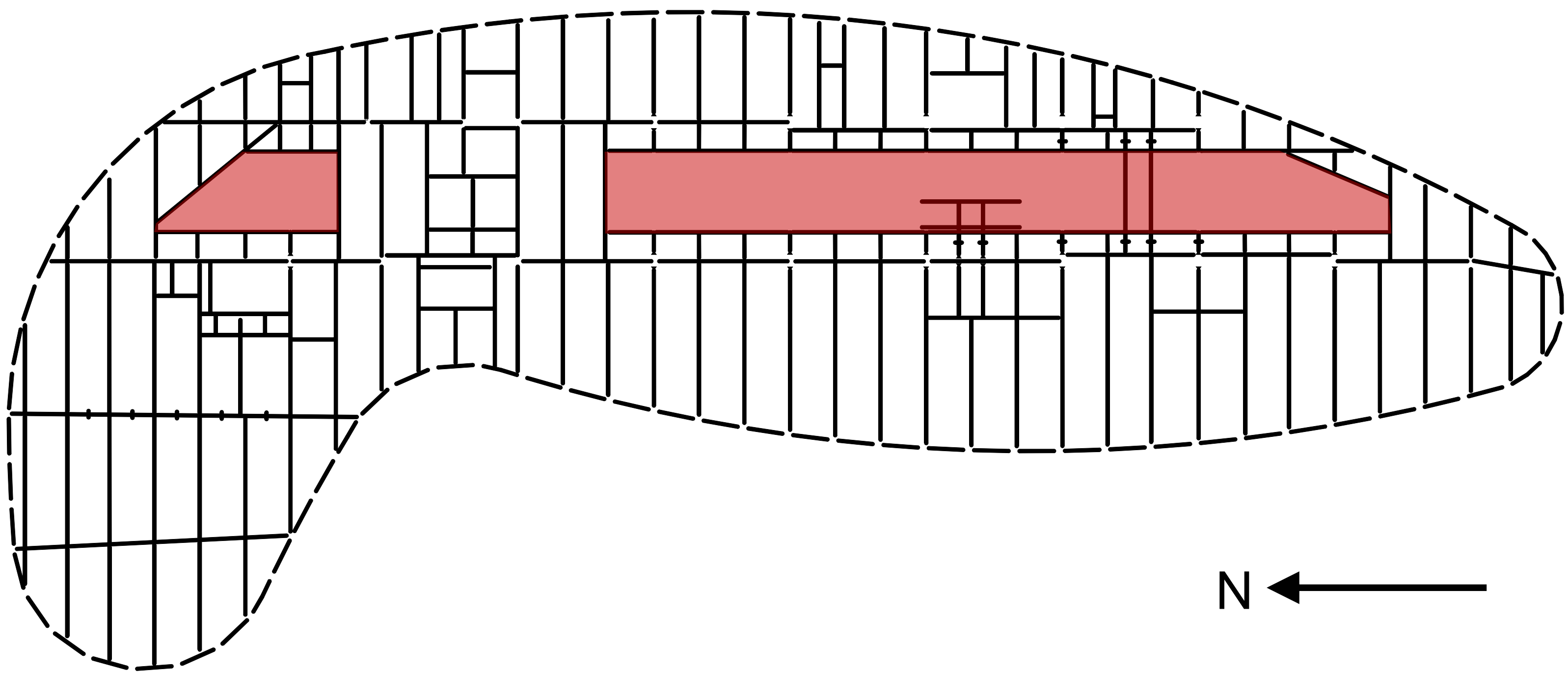
Site

University of Cincinnati "Varsity Village" – Cincinnati, Ohio



Architectural Layout

- Curved perimeter
- 5-story atrium
- Partially above existing facilities



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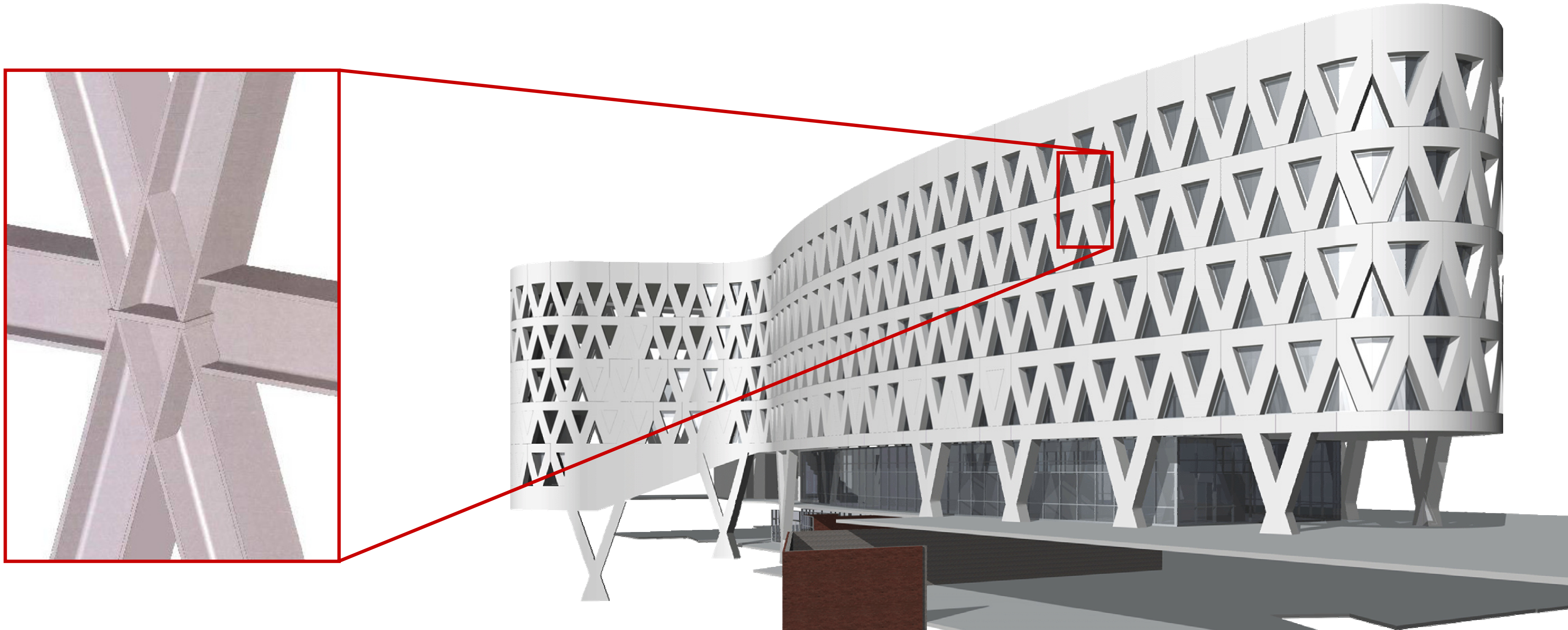
Structural System Description

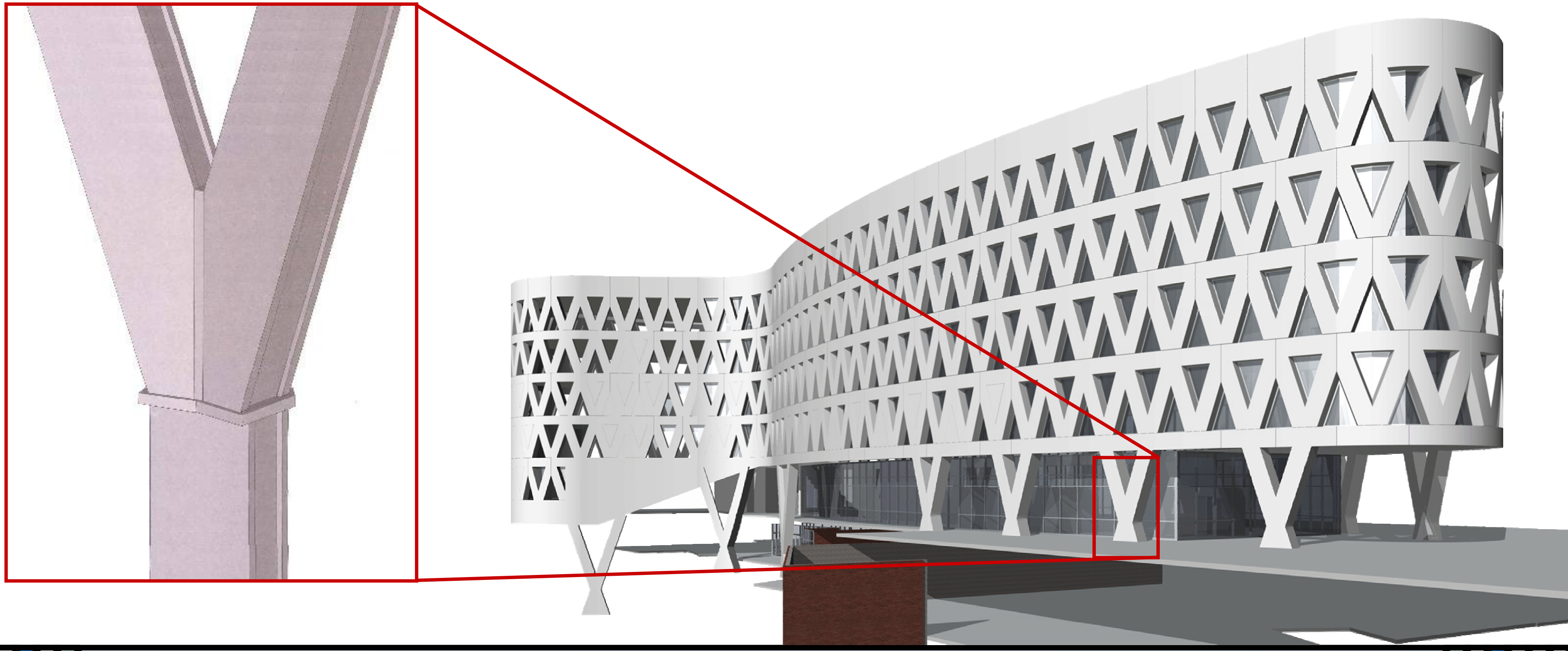
Diagrid

- Triangulated “deep beam” frame
- Functions as both gravity and lateral system
- Constructed from steel wide flange shapes
- Welded or bolted for full rigidity
- Fully insulated and clad in precast concrete



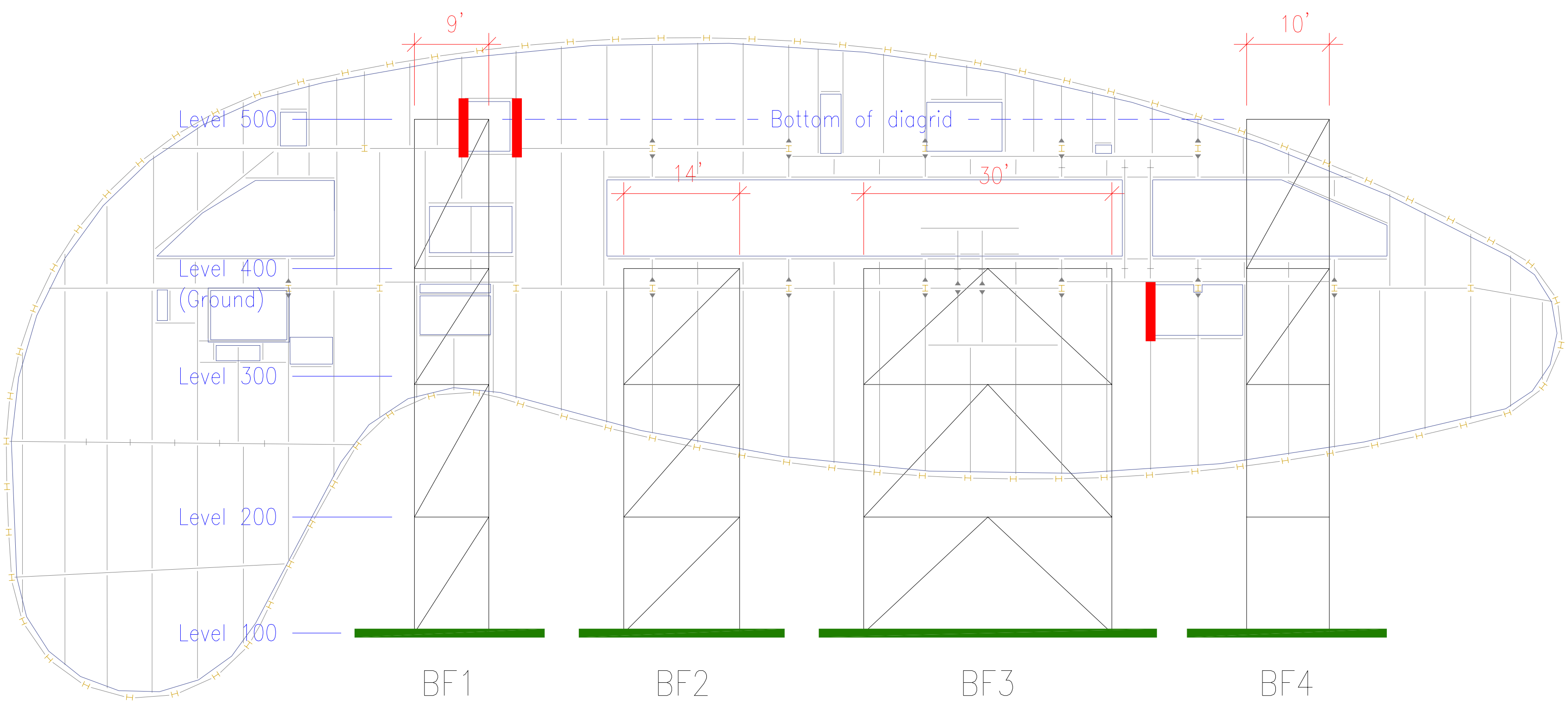
V Columns

- Fabricated from heavy wide-flanges or built-up boxes
- Rigidly connect to the diagrid and substructure
- Help transfer lateral load, primarily in North-South direction



Braced Frames

- Four types
- Help carry lateral load from bottom of diagrid to foundation
- East-West direction only



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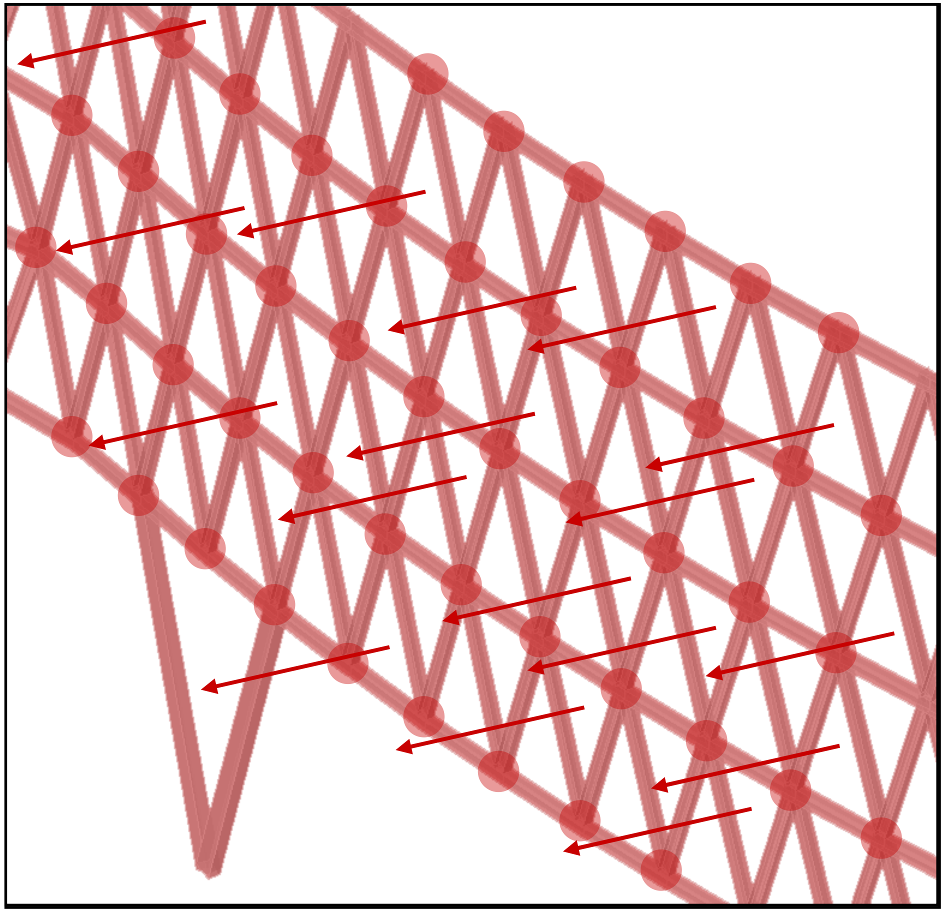
Problem Statement

Three main concerns

- Heavy diagrid
- Connection intensive
- Limited views



Problem Statement

Goals

Address the three main concerns

1) Reduce structure weight
2) Reduce connection complexity
3) Maximize viewable window space

Additionally

- Increase overall structural efficiency
- Decrease overall building cost
- Ensure construction feasibility
- Minimize interior impact
- Maintain building shape
- Maintain floor height

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Design Philosophy

Become an "architect-engineer"

- Aesthetic quality
- Practical application

Unique yet sensible

- Alter the look and feel
- Maintain shape, height, space layout

Innovative architecture demands innovative engineering solutions!

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Redesign Approach

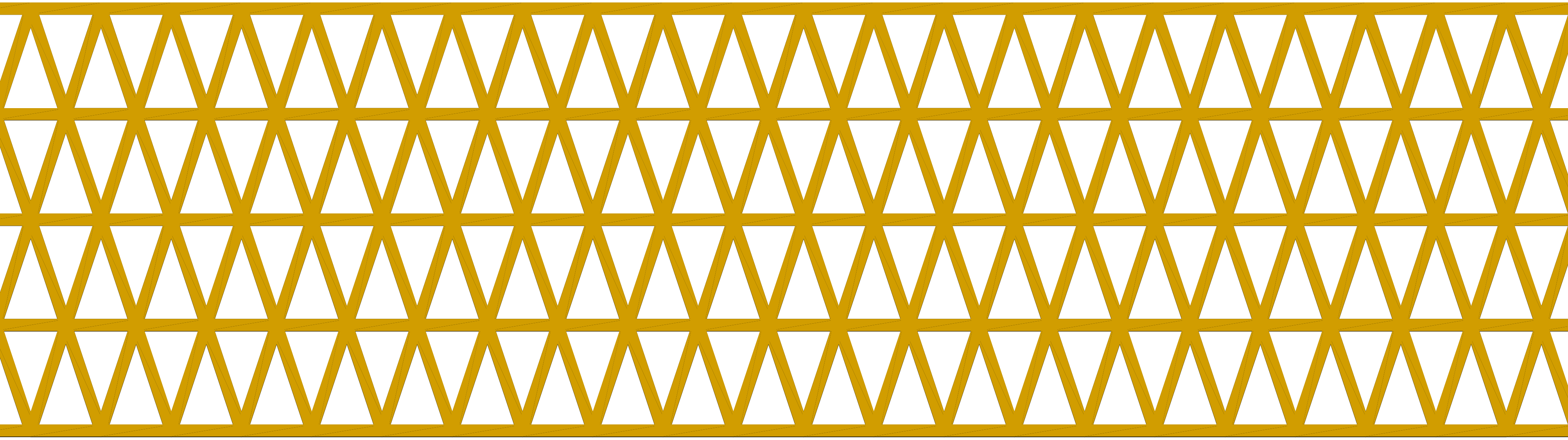
Solution Area Concept

Solution Area I - Changing the material

Solution Area II – Modifying the geometry

Solution Area III – Removing it altogether

Progressively disruptive!



Redesign Approach

Breadth Areas

Daylighting Study

- Façade will change
- Attempt to integrate daylighting into new exterior
- Qualitative assessment

Construction Study

- Erection sequence
- Material layout planning

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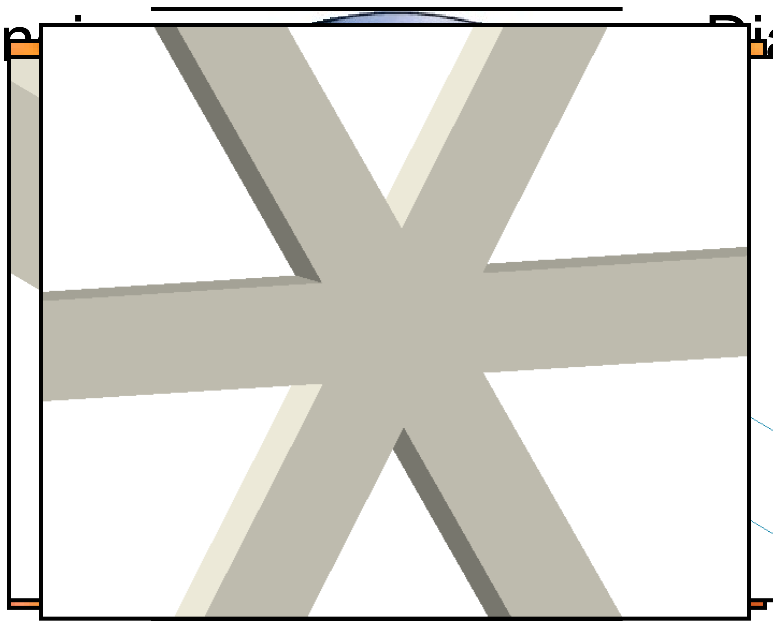
5 different materials

- Steel wide flange
- Round/rectangular HSS
- Glulam timber
- Precast concrete
- Cast-in-place concrete

Solution Area I

Chan… …iagrid



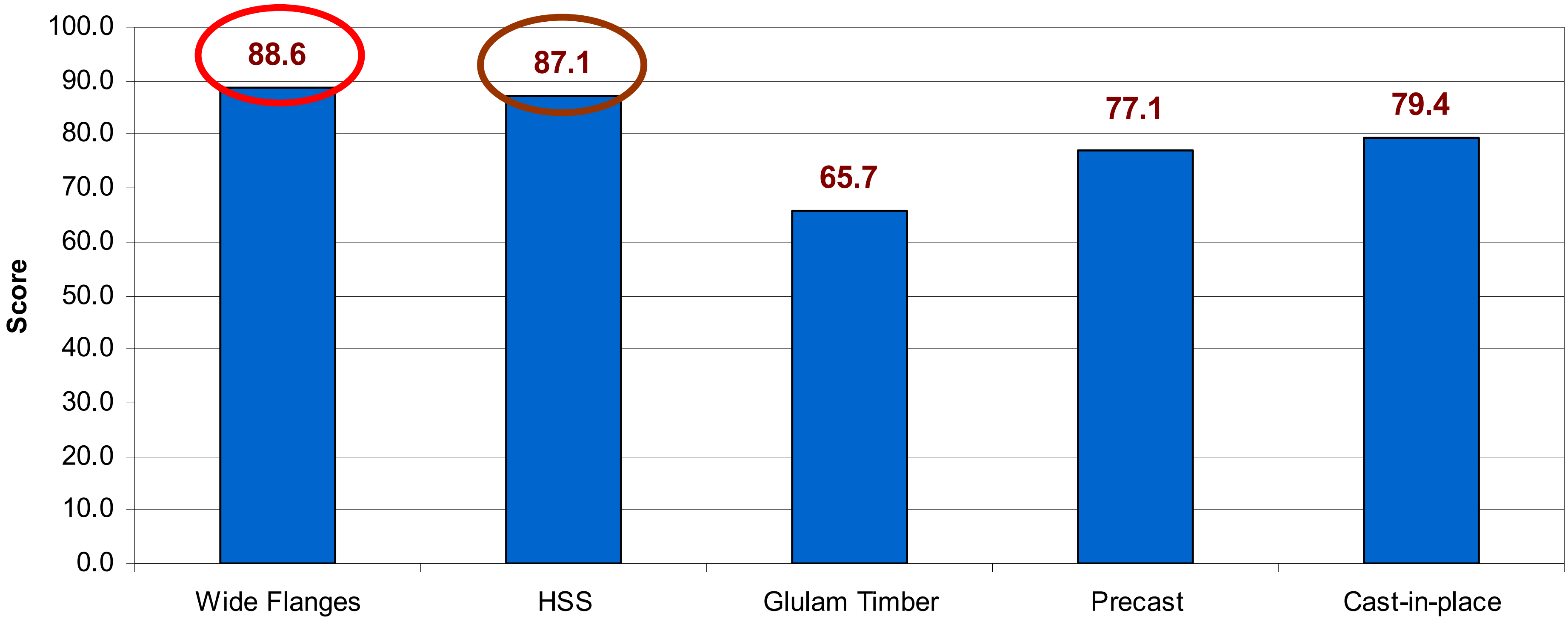
Tabular Results

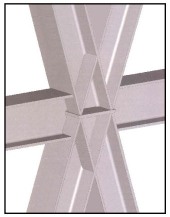
Material	Mat. Cost	Availability	Lead time	Erect. time	Flexibility
Wide Flanges	75	100	75	100	80
Rectangular HSS	75	95	75	100	80
Round HSS	75	95	75	100	80
Glulam Timber	40	80	75	100	50
Precast	60	100	90	75	100
Cast-in-place	100	100	100	60	100
	1.0	0.5	0.6	0.8	0.7

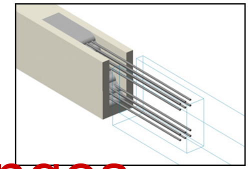
Material	Durability	Weight	Labor Cost	Fire Resist.	Size
Wide Flanges	90	100	100	70	95
Rectangular HSS	90	90	100	70	95
Round HSS	90	90	100	70	100
Glulam Timber	40	60	90	80	50
Precast	100	30	75	100	70
Cast-in-place	100	30	60	100	70
	0.8	1.0	1.0	0.9	0.9

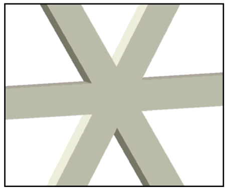
Structural Redesign

Overall Results









Stick with steel wide flanges

Structural Redesign

Two main ways to accomplish this:

1) Open up the grid

2) Adjust configuration

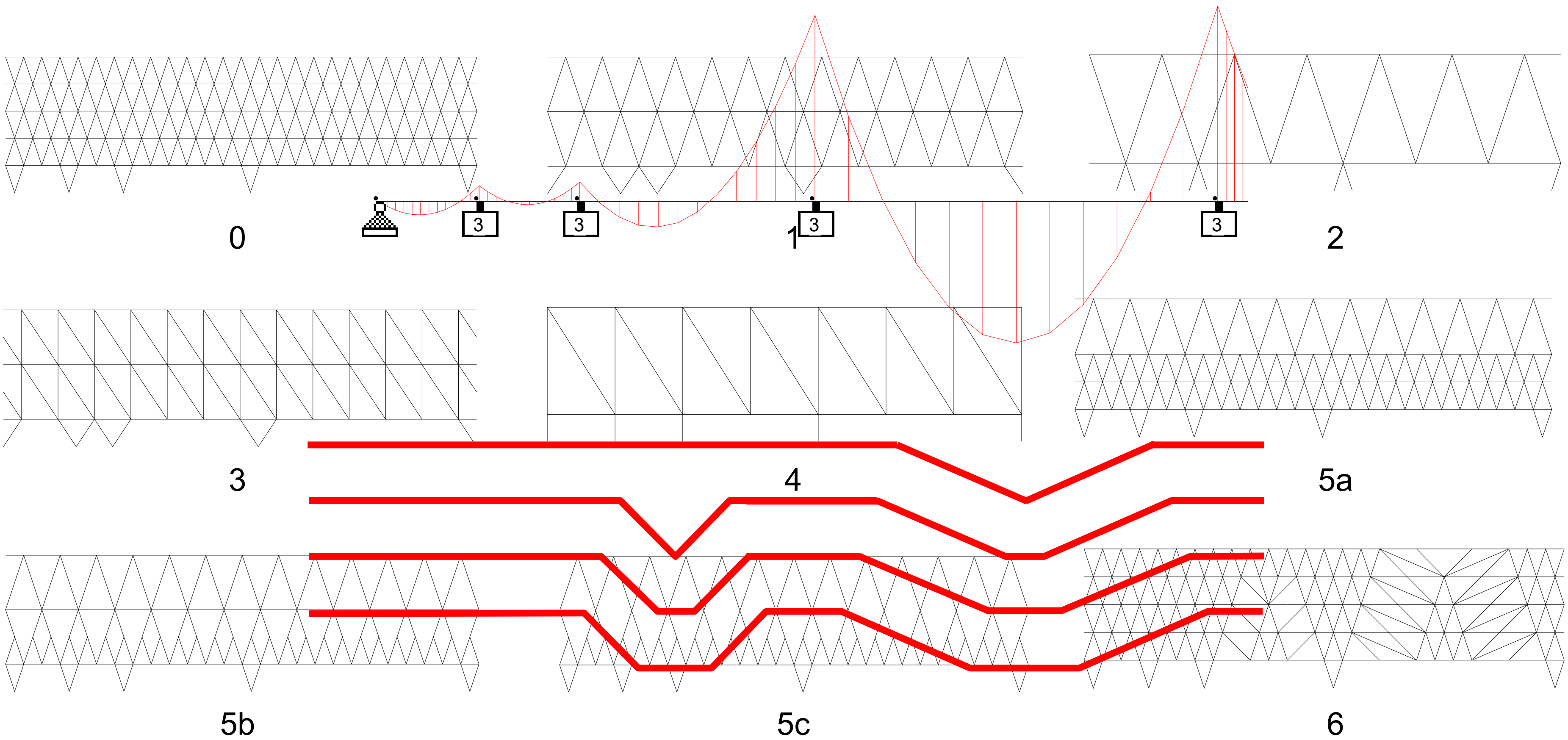
tion Ar

the Diagrid

John Hancock Center

Central China Television Tower

Configurations

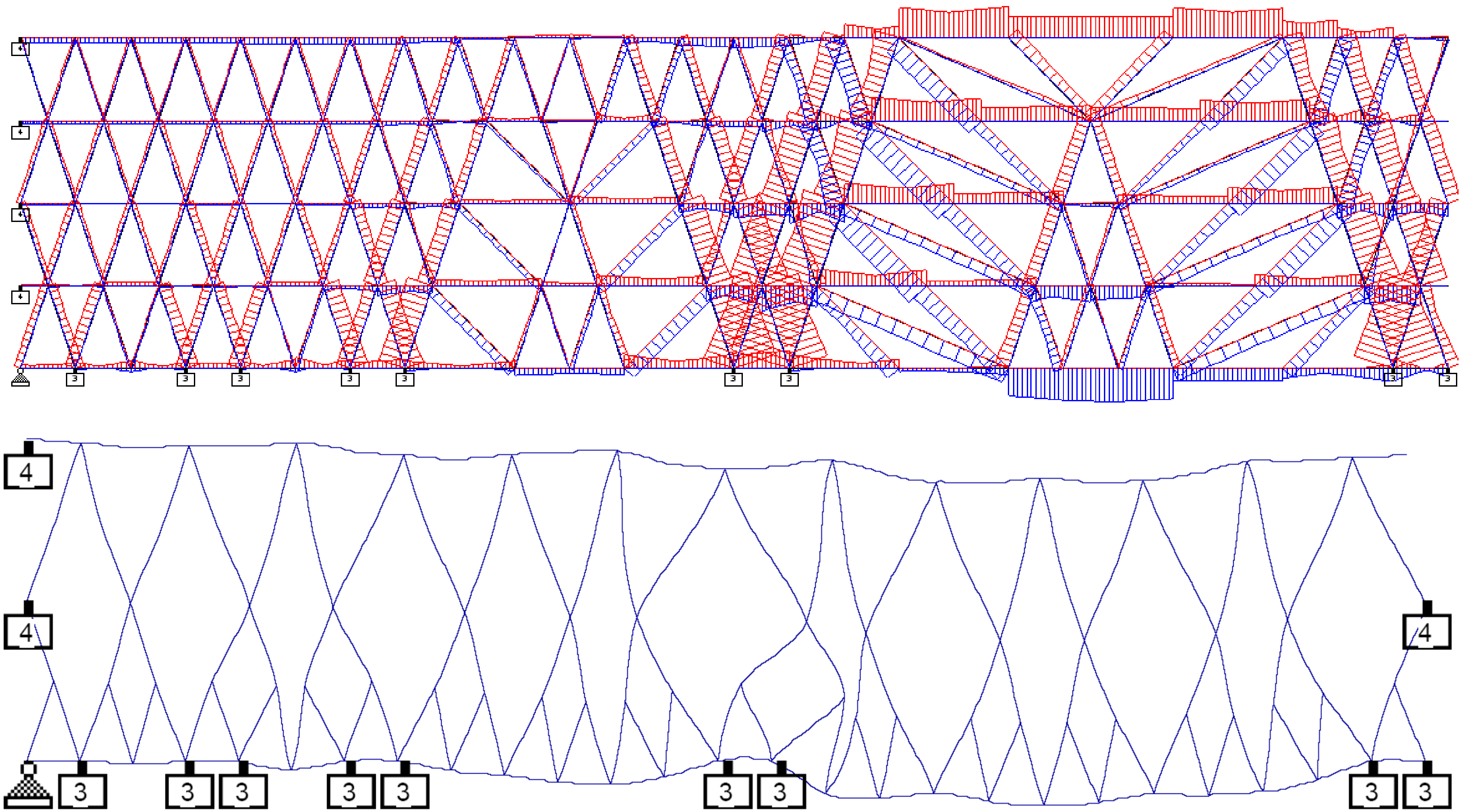


Structural Redesign

Considerations

- Structural Efficiency
- Structural Stability
- Architectural Impact
- Floor Framing Impact
- Material Cost
- Complexity

2D STAAD Model



Structural Redesign

Tabular Results

	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

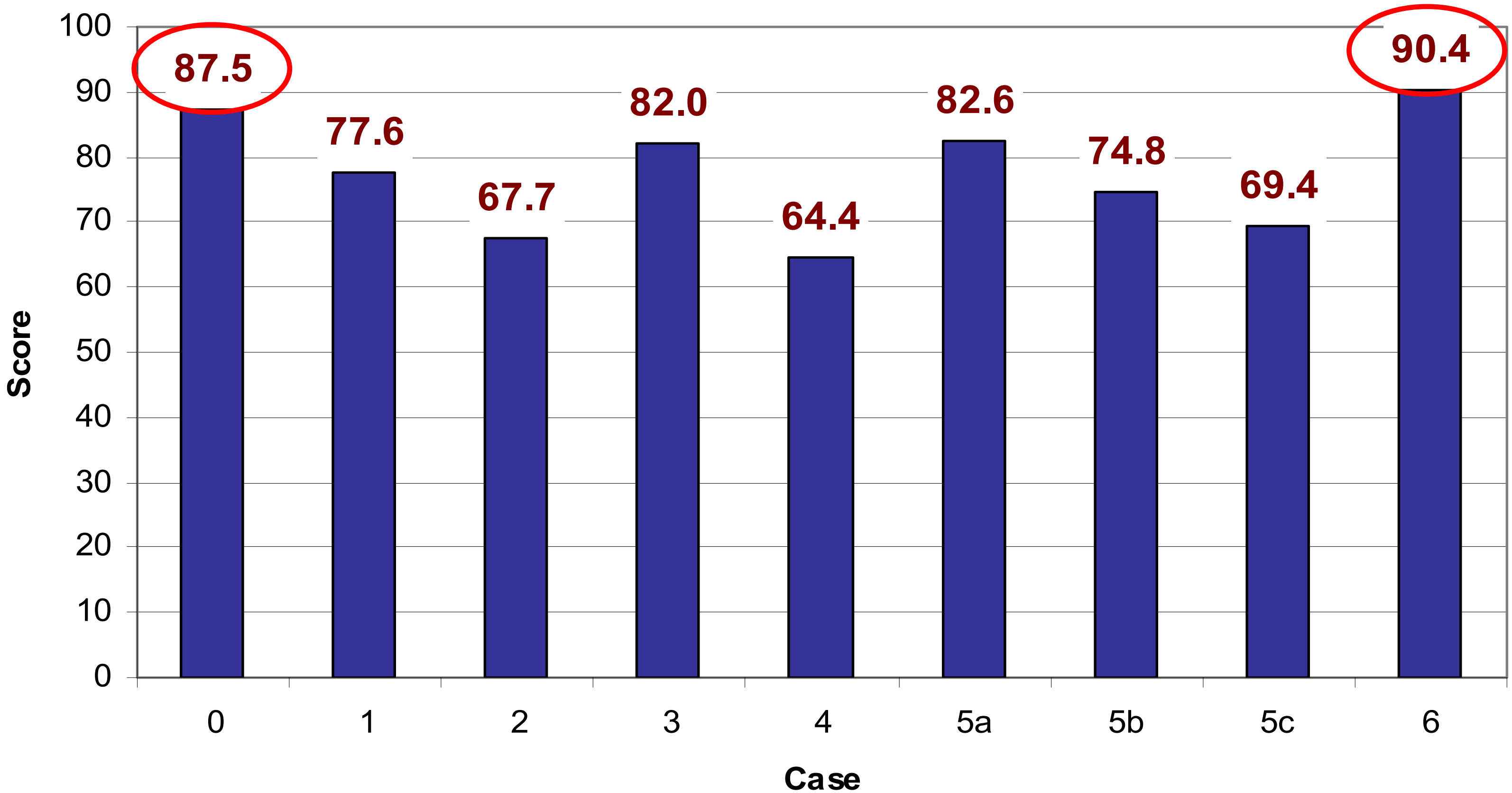
Observations

Varying member length has a substantial impact on structural efficiency.

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

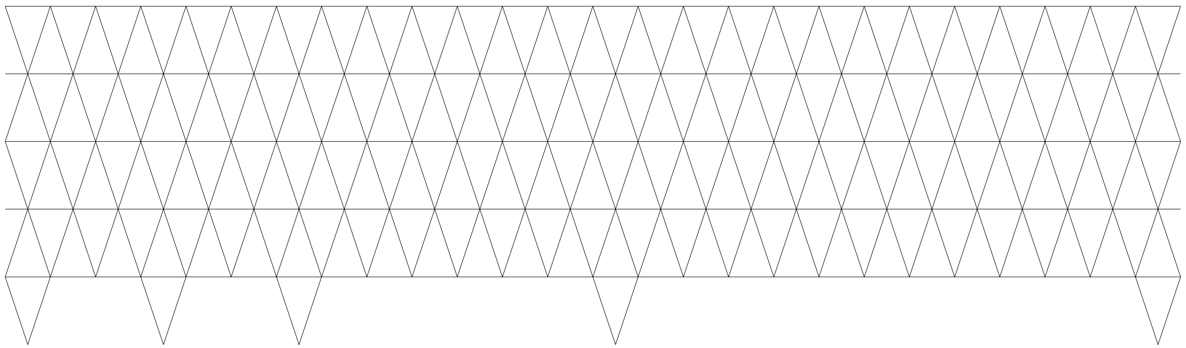
High system redundancy helps control deflection.

Overall Results



Conclusion

Original



Stick with the original diagrid configuration!

A whole new approach

- Diagrid is eliminated
- Move lateral system within the building
- Curtain wall becomes new building enclosure

Solution Area III

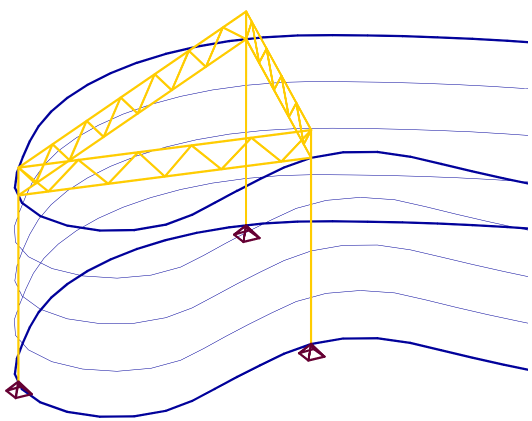
Removing the Diagrid

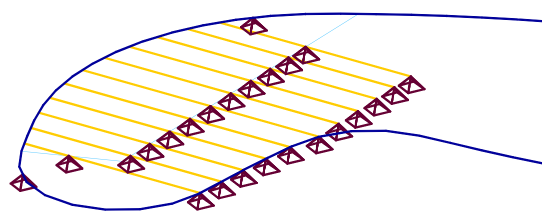
Development phases

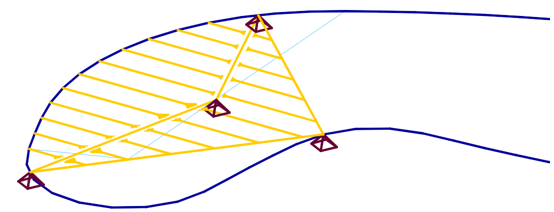
- Conceptual Design
- Schematic Design
- Design Development
- Construction Documents

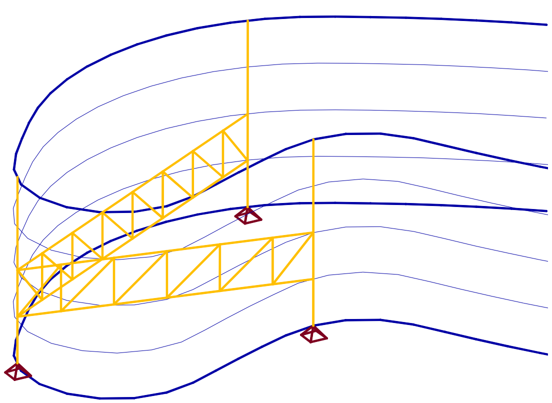
Structural Redesign

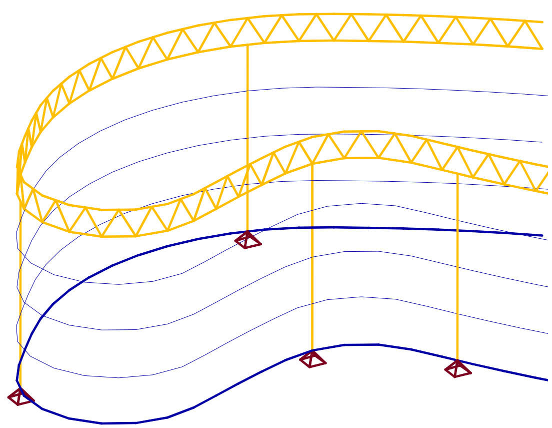
Conceptual Design

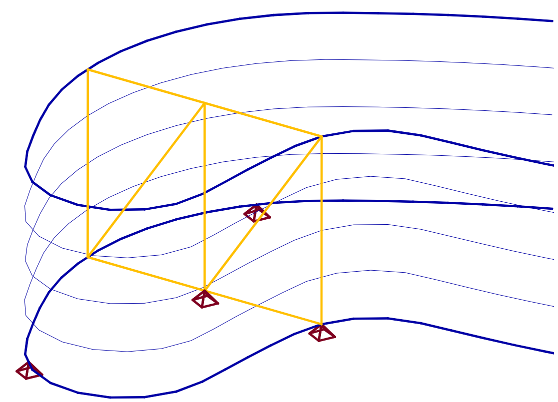

Interior Hat Truss


Cantilevers Over Columns


Cantilevers Over Girders


Level 600 Truss


Perimeter Truss


Reverse Truss

Pro-Con Comparison

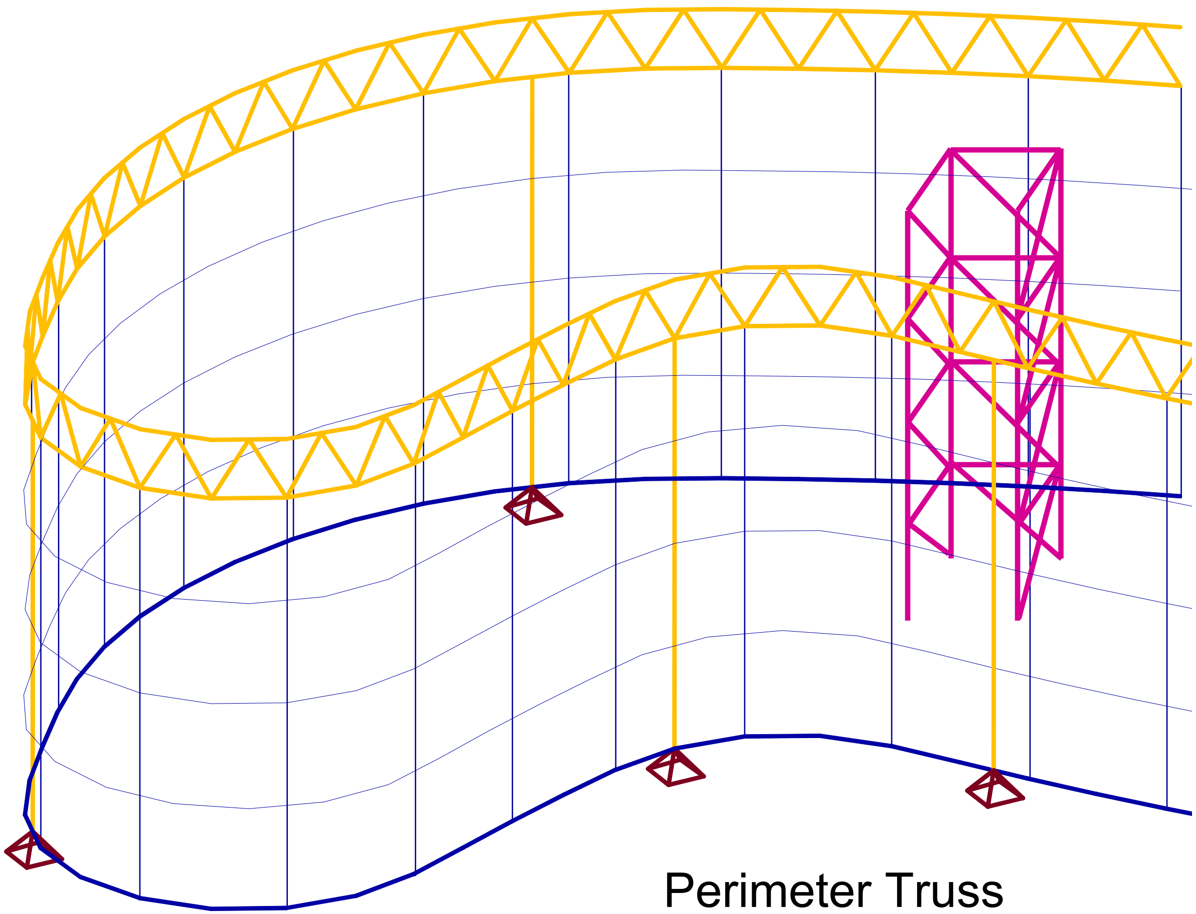
Gravity System

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**

Lateral System

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**

System Selection



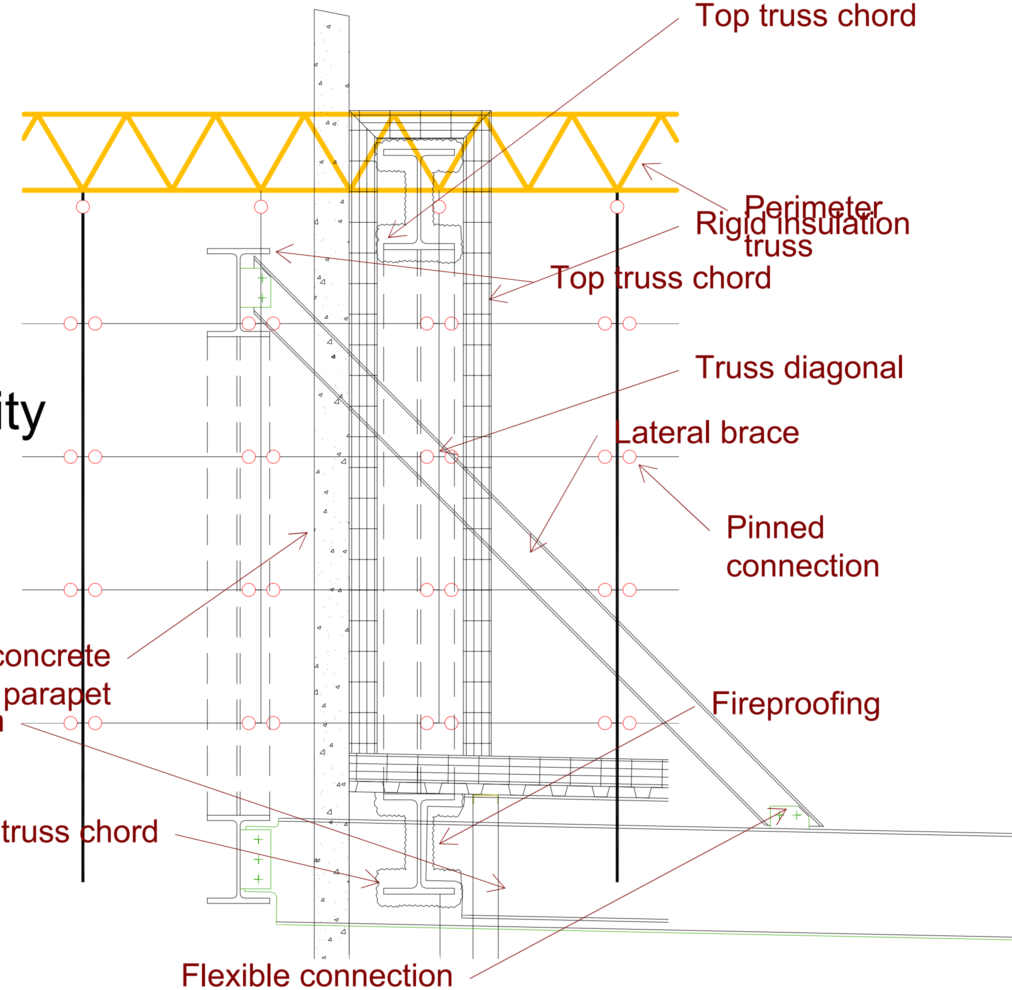
Perimeter Truss
with Braced Frames

Structural Redesign

Schematic Design

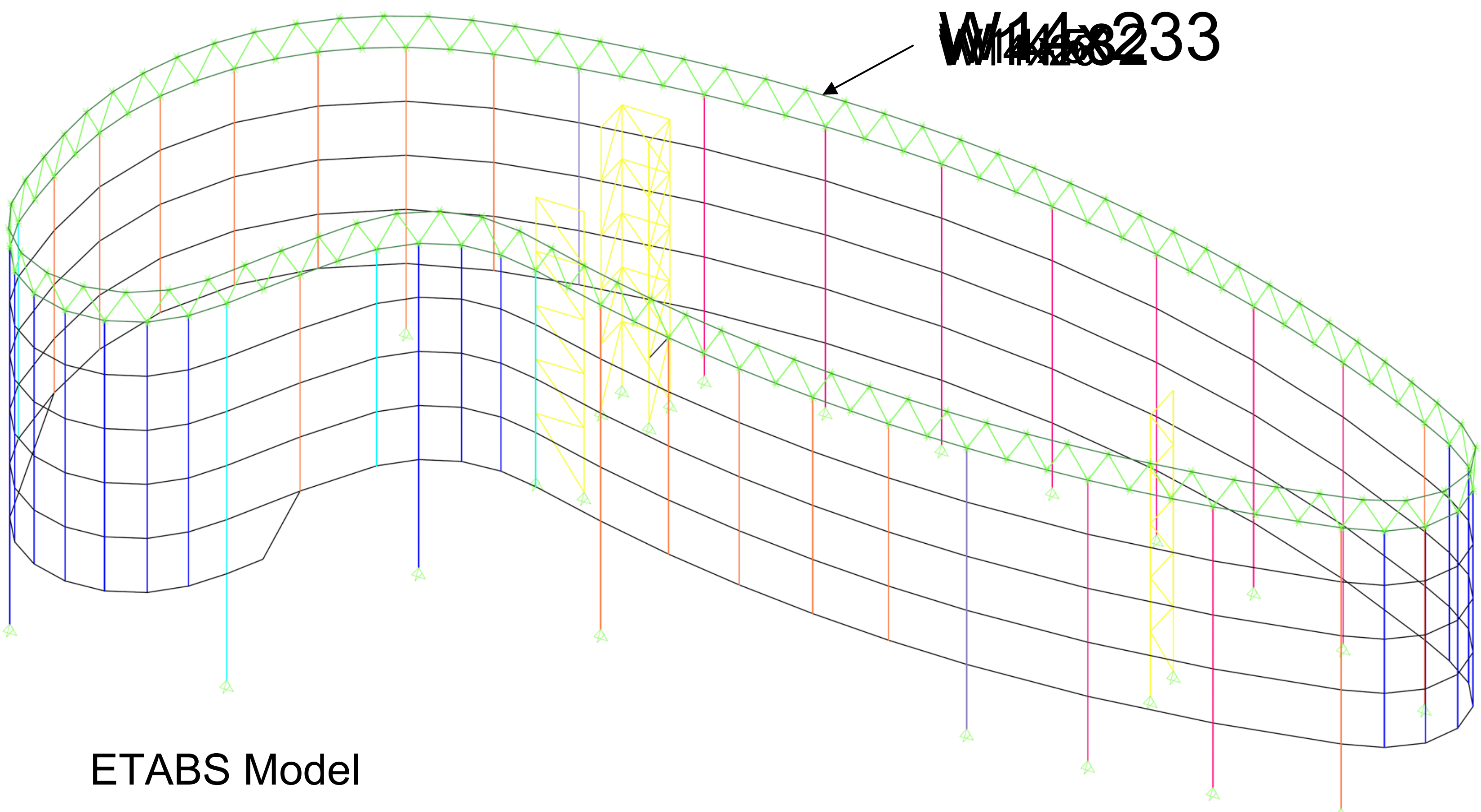
10 Considerations

1) Floor beam sweep
2) Column spacing
3) Pinned vs. fixed connections
4) Column deformation compatibility
5) Fire resistance
6) Thermal movement
7) Truss height
8) Truss lateral bracing
9) Corrosion
10) Braced frame placement



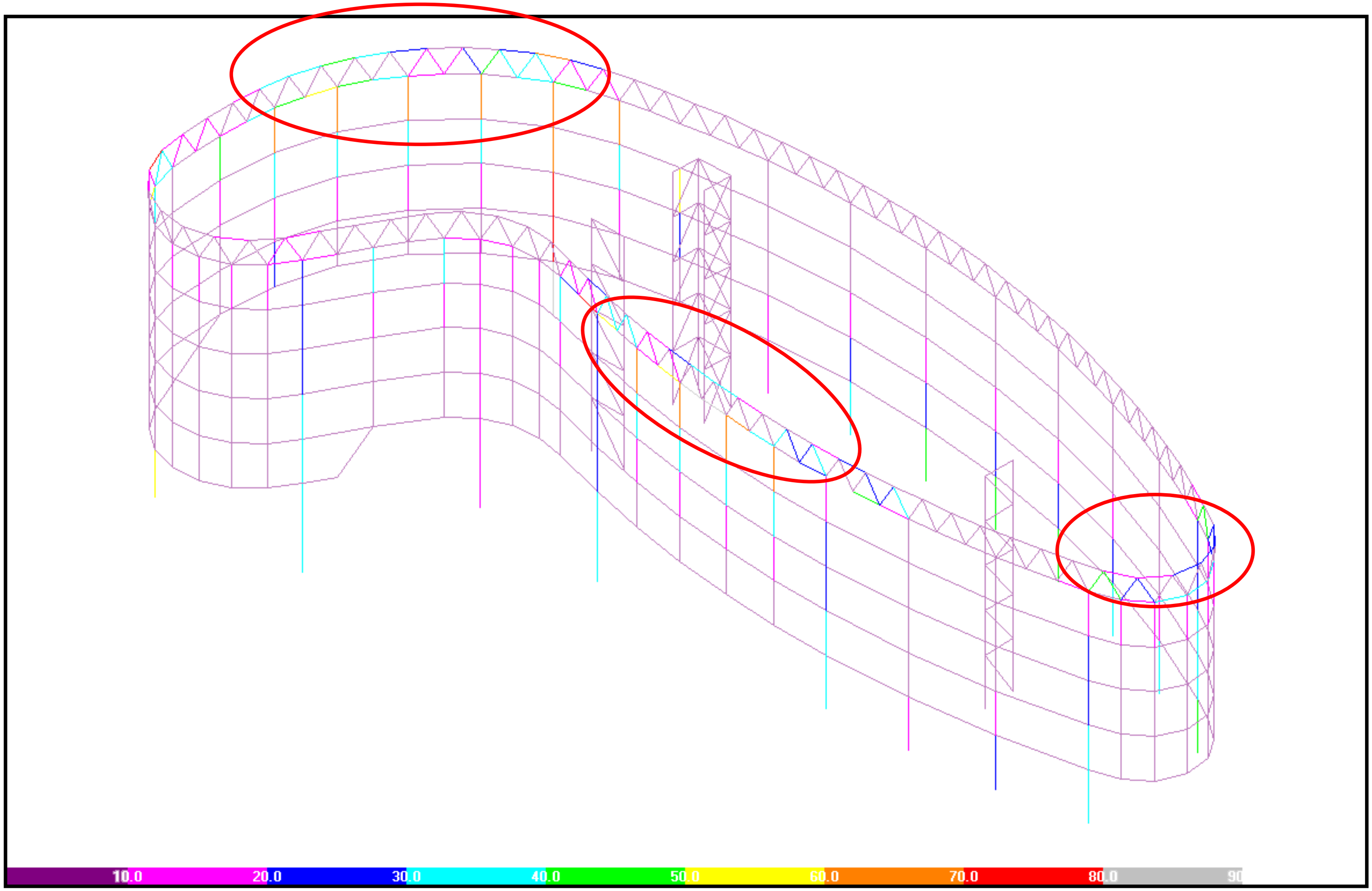
Structural Redesign

Design Development

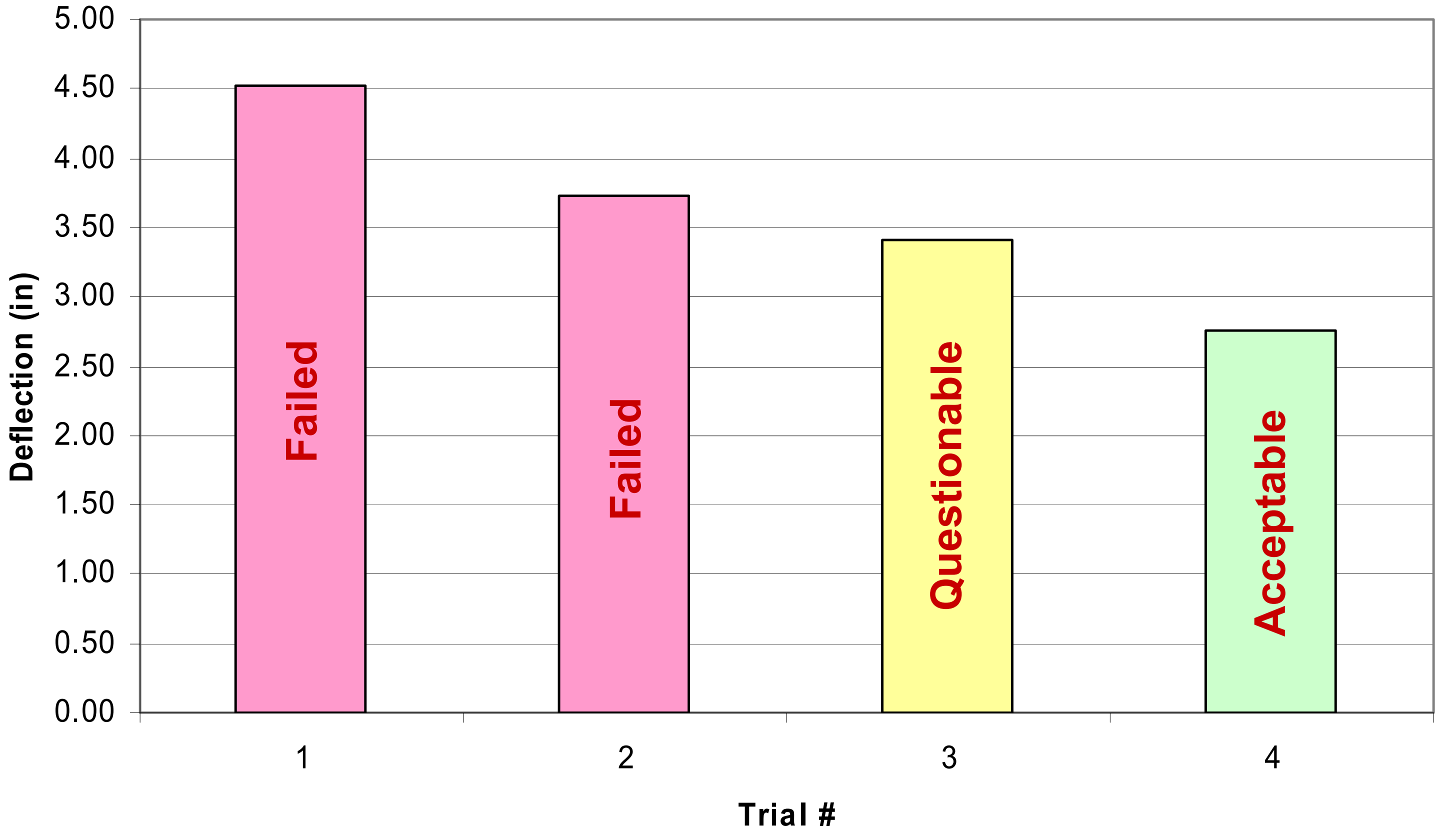


ETABS Model

Virtual Work



Deflections



Construction Documents

Member Group	Weight (tons) 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

Member Group	Weight (tons) 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

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

Structure weight

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

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

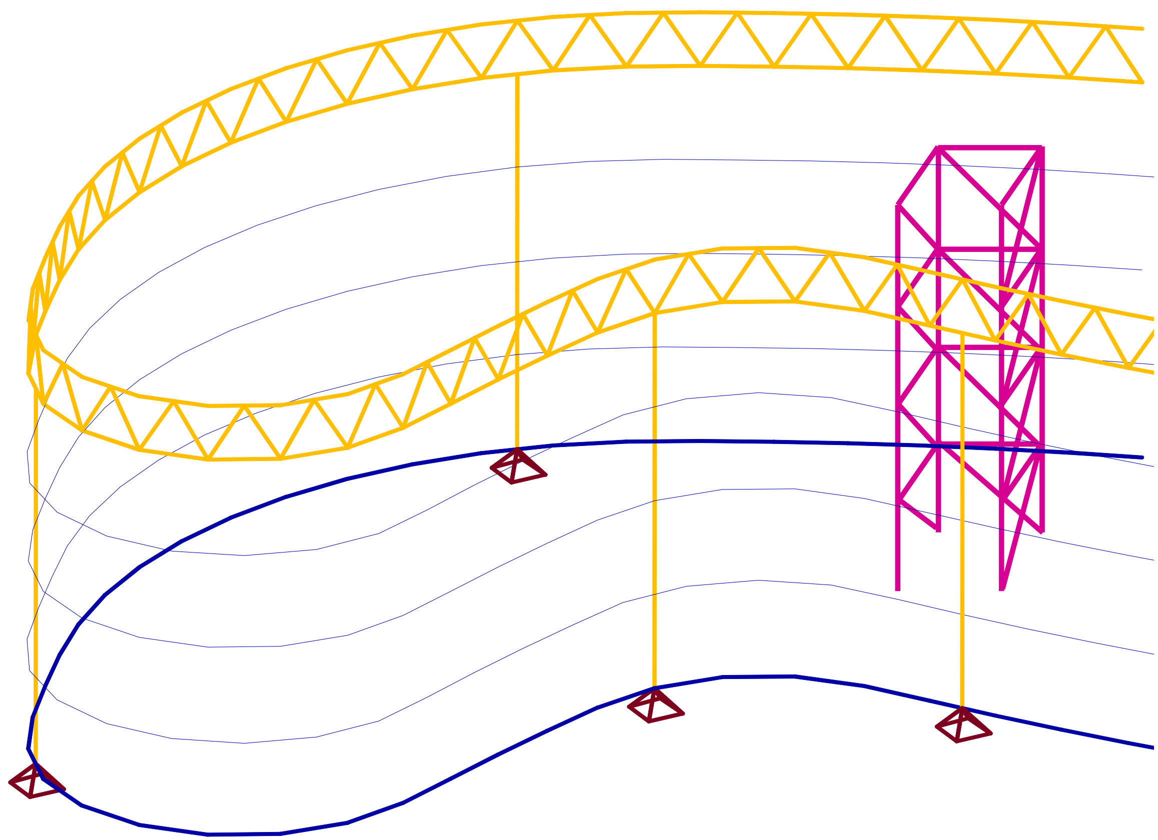
Perimeter Truss reduces structural steel weight by **16%**

Conclusions

	Undesirable Impact	Little or no Change	Reasonable Success
Reduce structure weight			●
Reduce connection complexity			●
Increase viewable window area			●
Maintain building shape	●		
Maintain interior layout	●		
Maintain floor system		●	
Maintain floor height			●
Penetration of open spaces		●	
Placement of columns		●	

Structural Redesign

The Perimeter Truss and Braced Frame system is an acceptable alternative.



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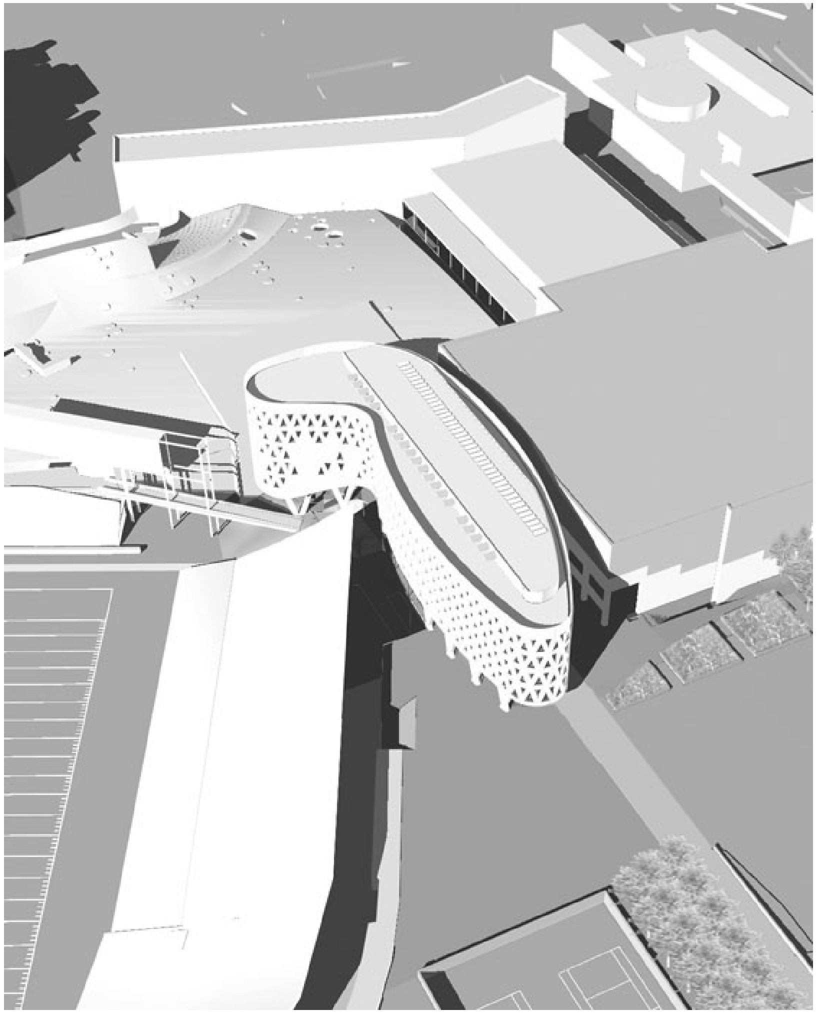
Daylighting

Benefits

- Increased worker productivity
- Potentially lower operating costs
- Environmentally sound
- Increased heat gain in winter



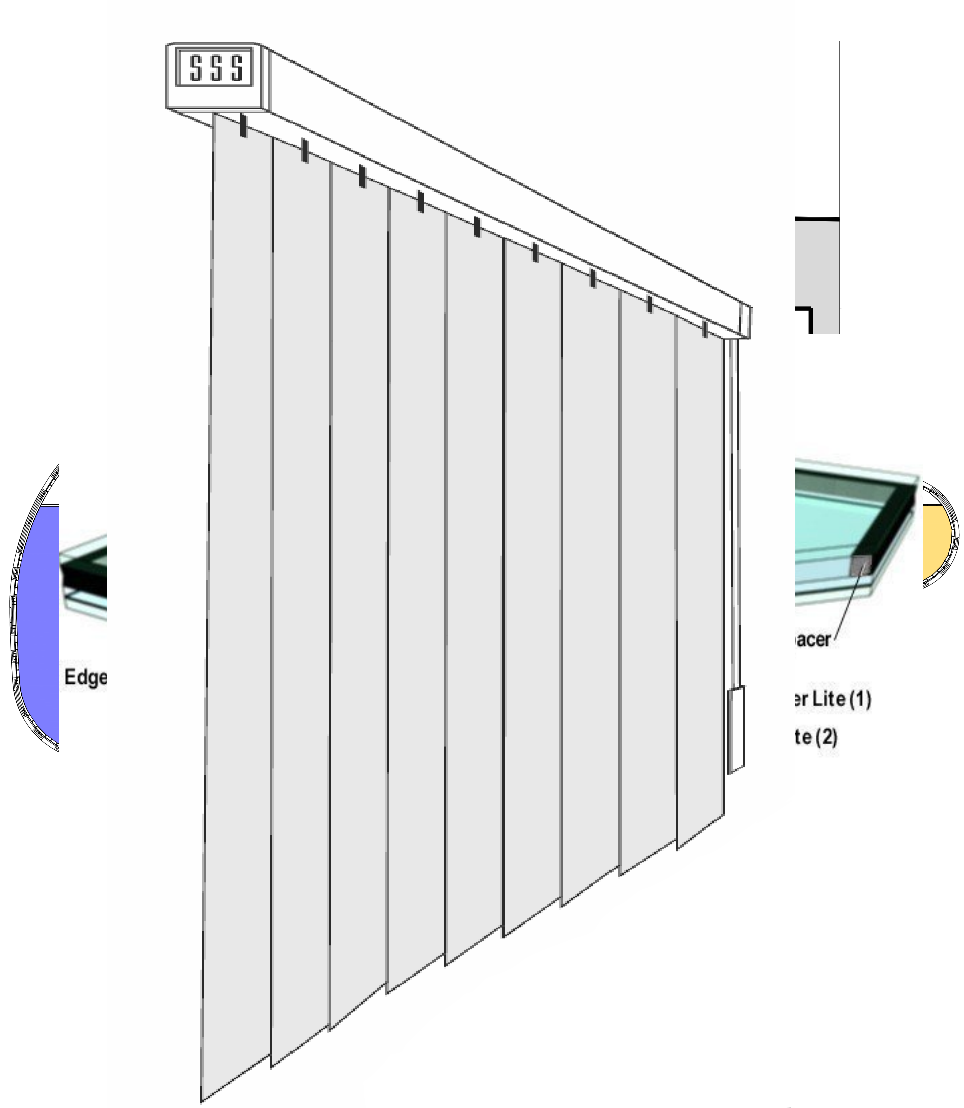
Challenges

- Discipline coordination
- Increased building glare
- Thermal discomfort
- Summer heat gain

Daylighting

Considerations

- Spaces daylighted
- Window quantity
- Window geometry
- Glazing material
- Window covering
- Façade material
- Artificial lighting control
- Interior finishes



Conclusions

	Disadvantage	Either	Advantage
Worker productivity			●
Operating costs		●	
Initial cost			●
Environmental Impact		●	
Design coordination	●		
Glare	●		
Thermal discomfort	●		
Heat gain		●	
Views			●

Daylighting is an owner/architect decision

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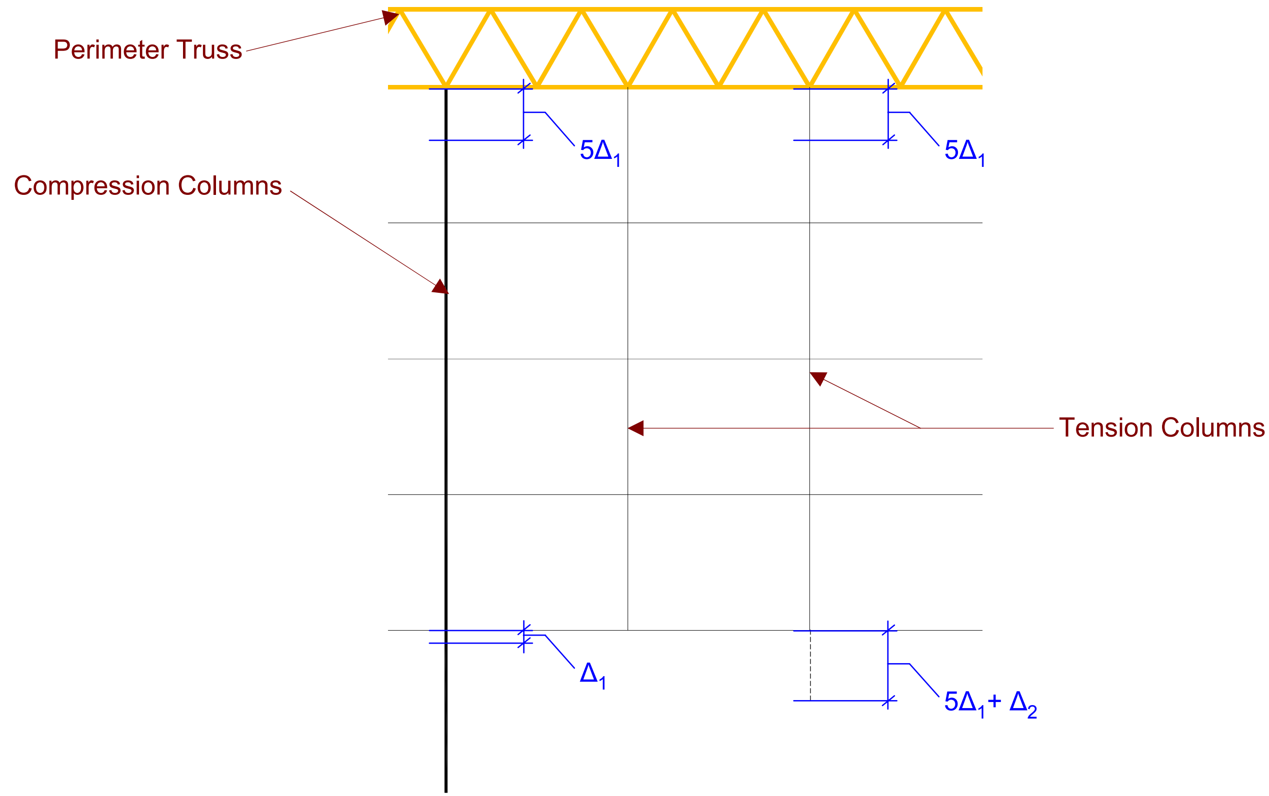
Column Deformation Incompatibility



Erection Sequence

Bottom up

	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

Top Down

	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

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7 Daylighting Study
Construction Study
Recommendation

Recommendation

Perimeter Truss is an excellent alternative to the diagrid

Lighter

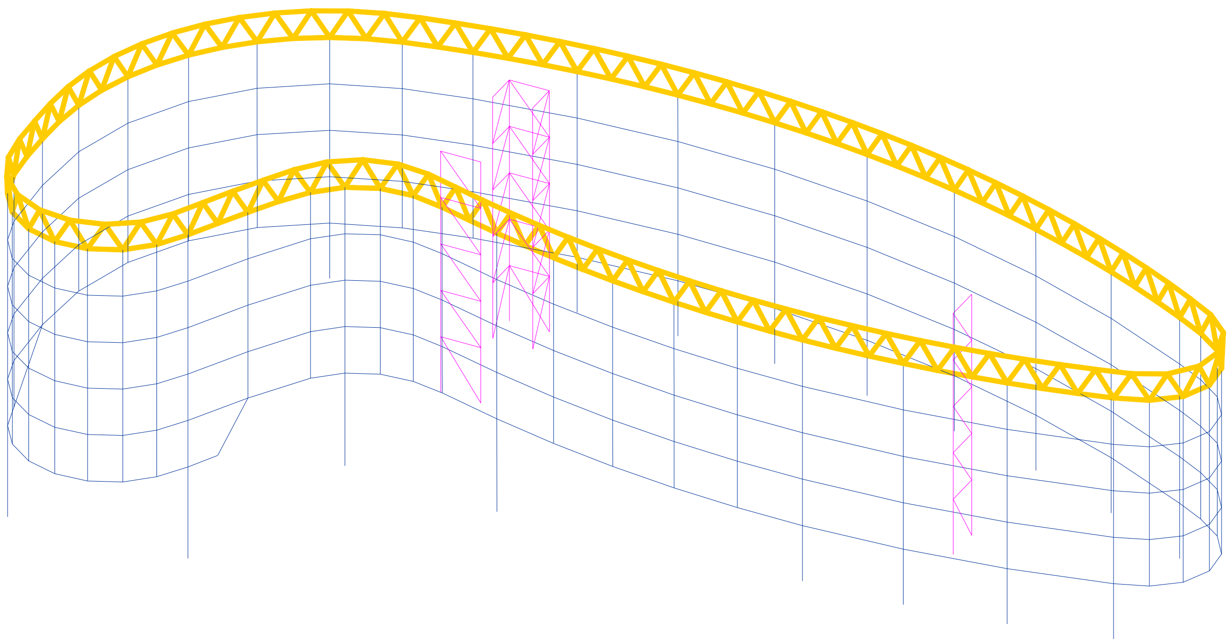
Less connections

Better window views

Minimal impact to existing systems

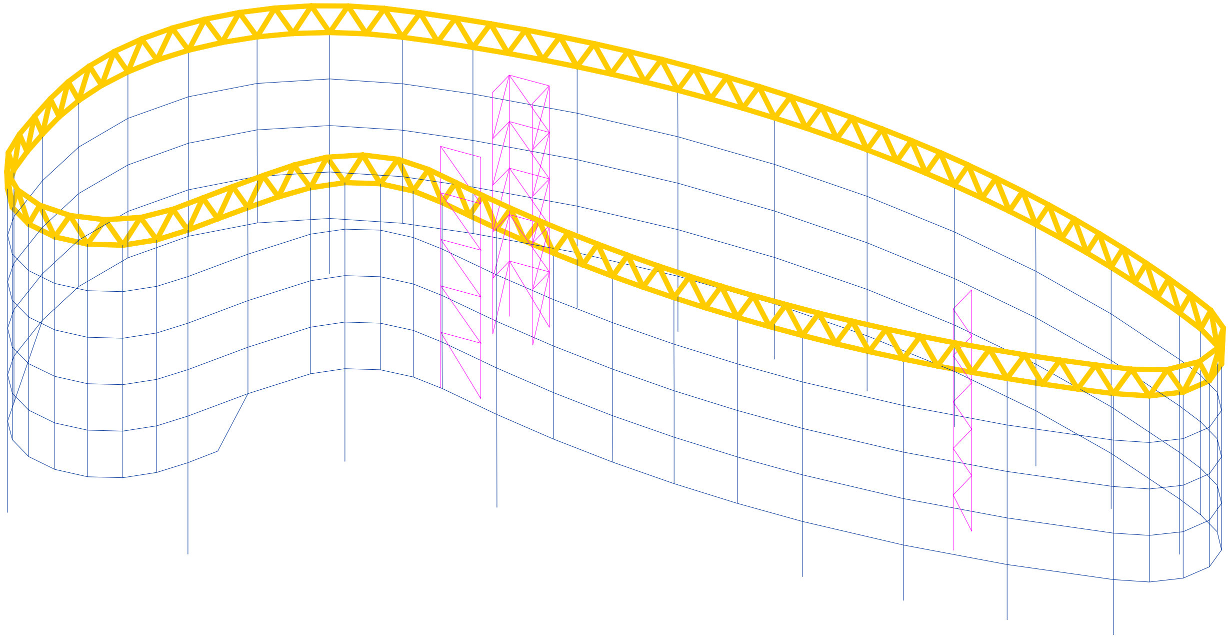
Personal goal accomplished!

Unique yet sensible



Thank You

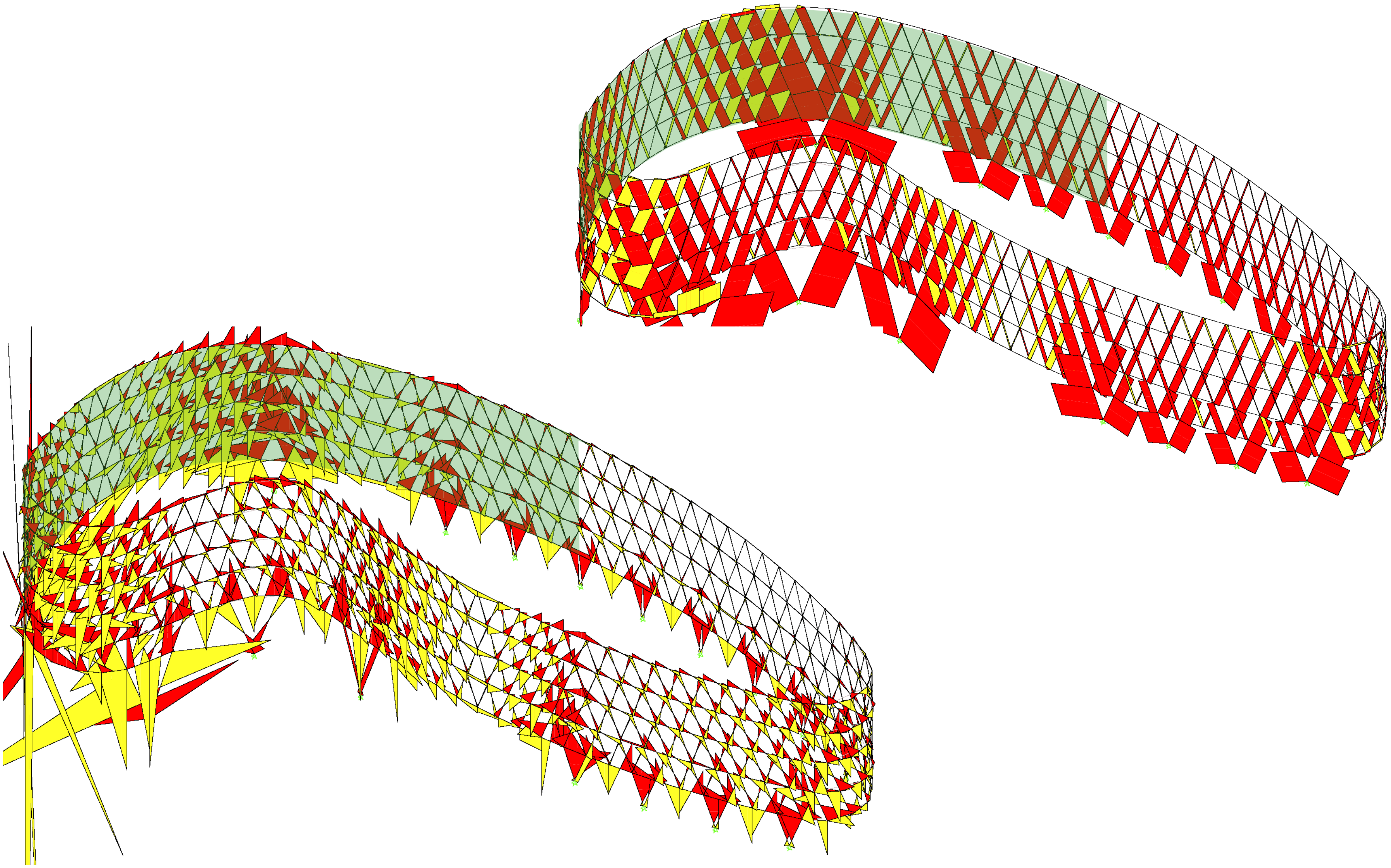
Family
Friends
AE Professors
Dr. Linda Hanagan
Kevin Parfitt
Jonathan Dougherty
Ricardo Pittella
Michael Tavolaro
Industry consultants



Picture credits
Bernard Tschumi Architects
Glaserworks
Arup

?

Additional Information



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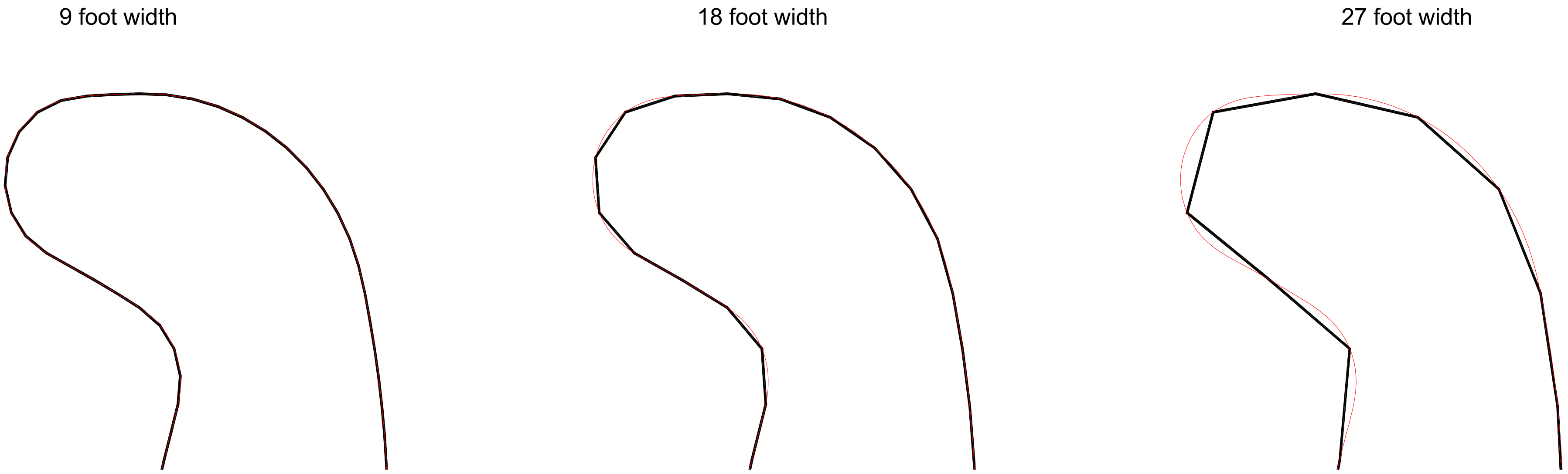
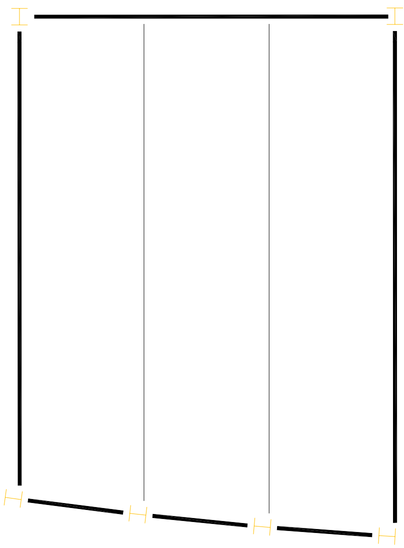
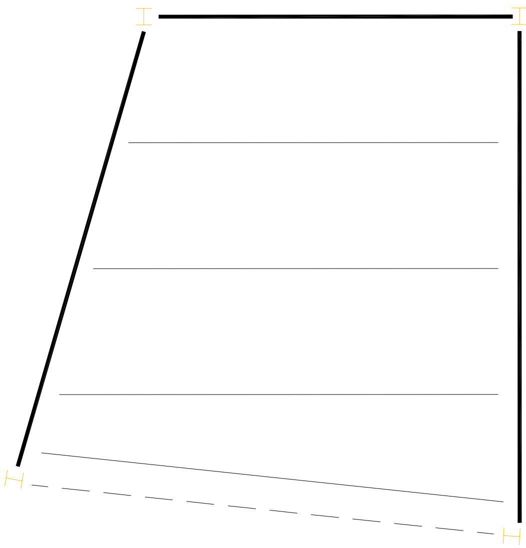


Additional Information

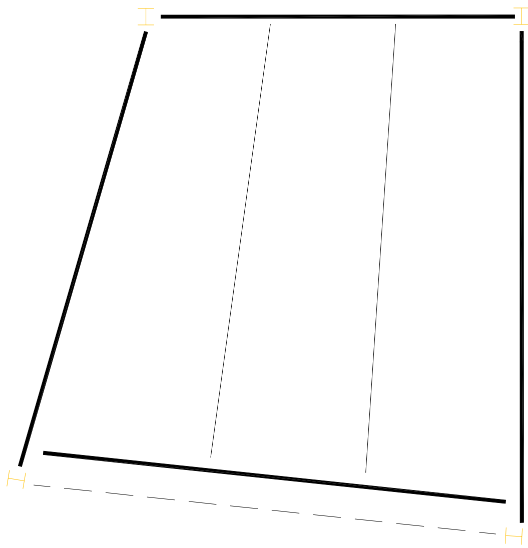
Original layout



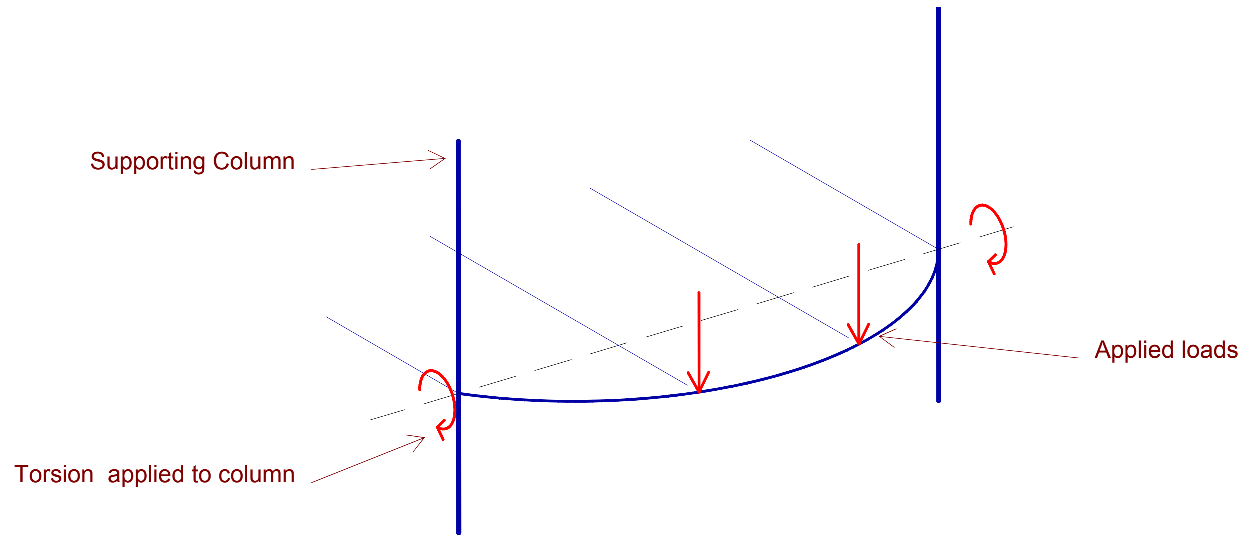
Changed span direction

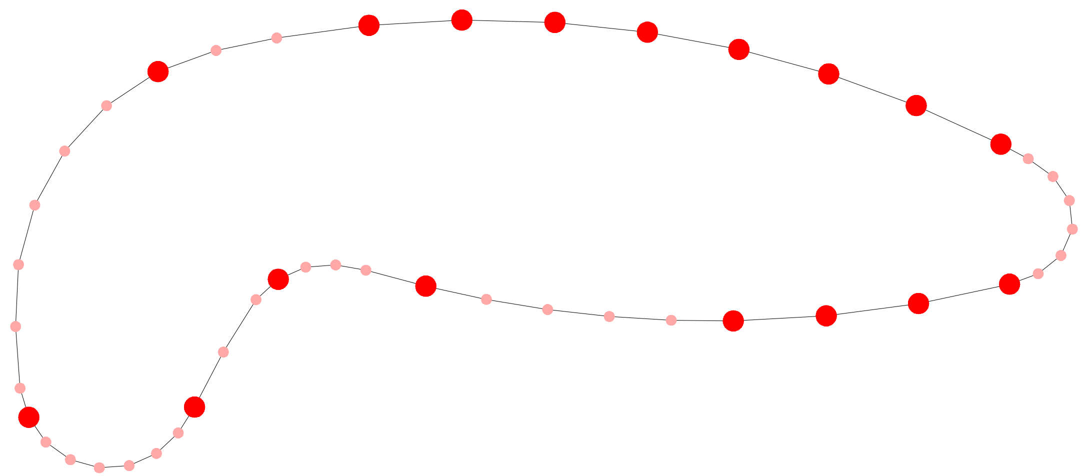


Heavy cross beam



Additional Information





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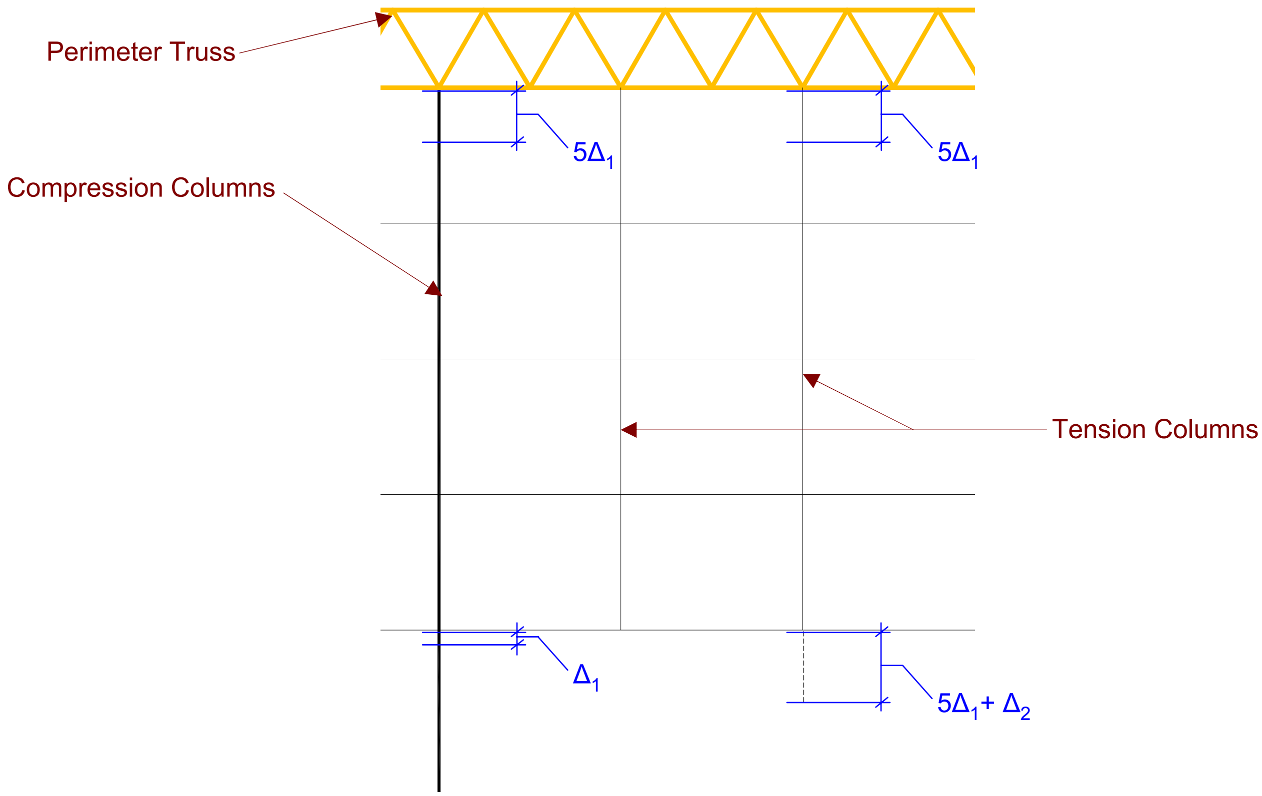

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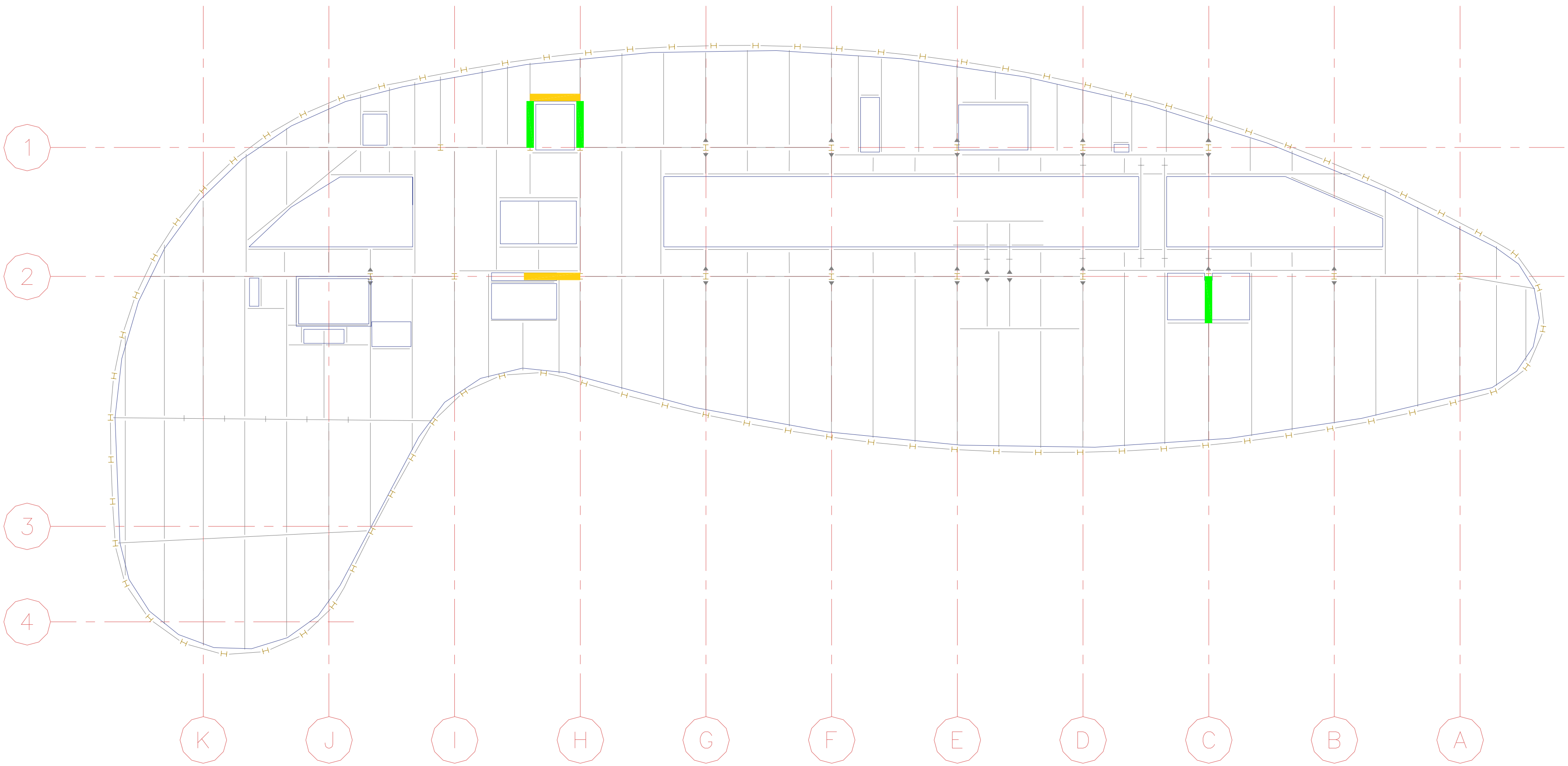

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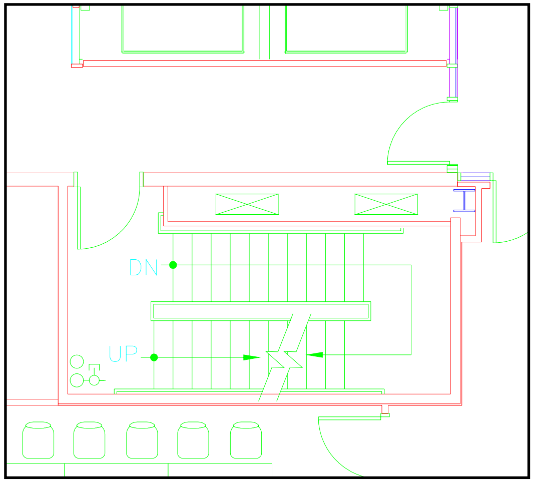
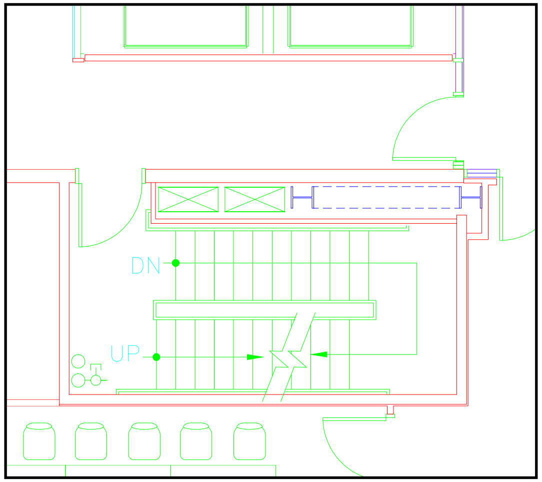
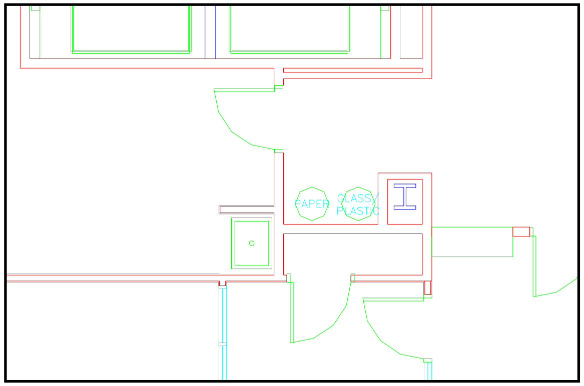
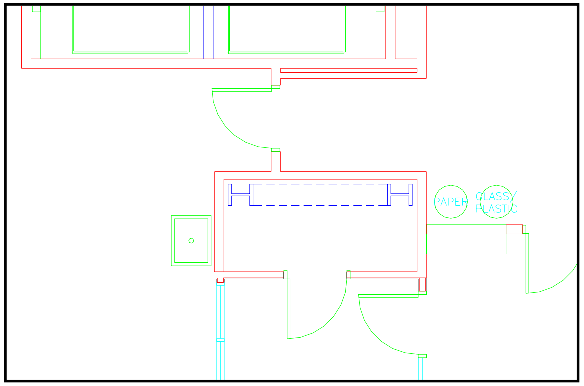








Additional Information

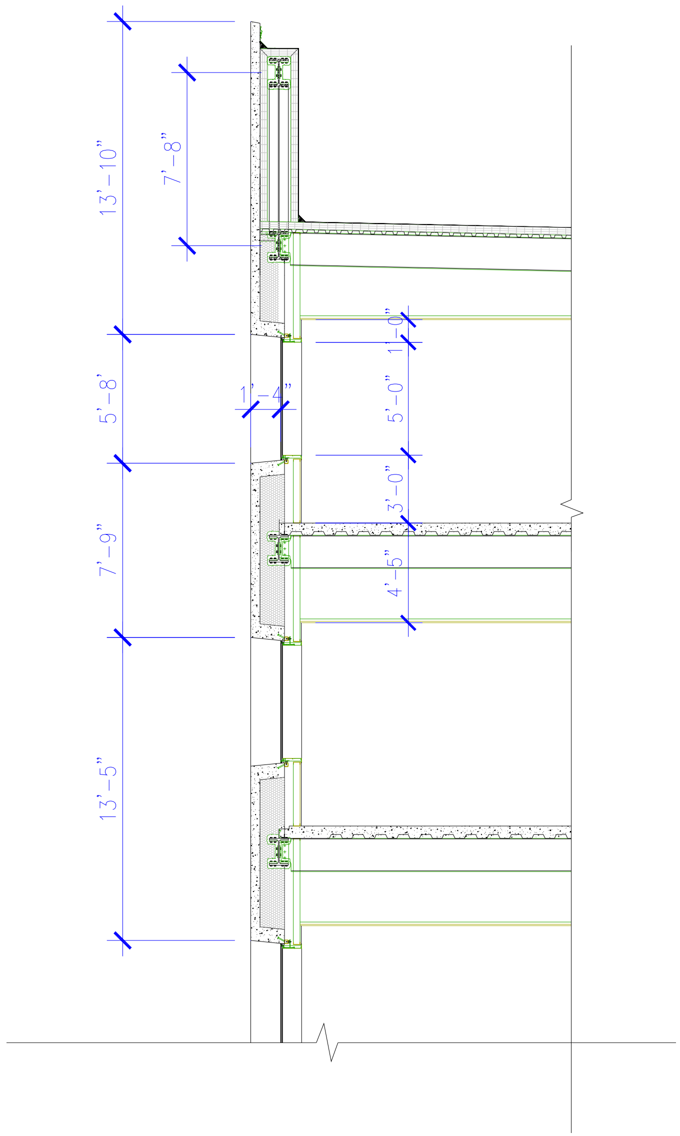
East-West Direction

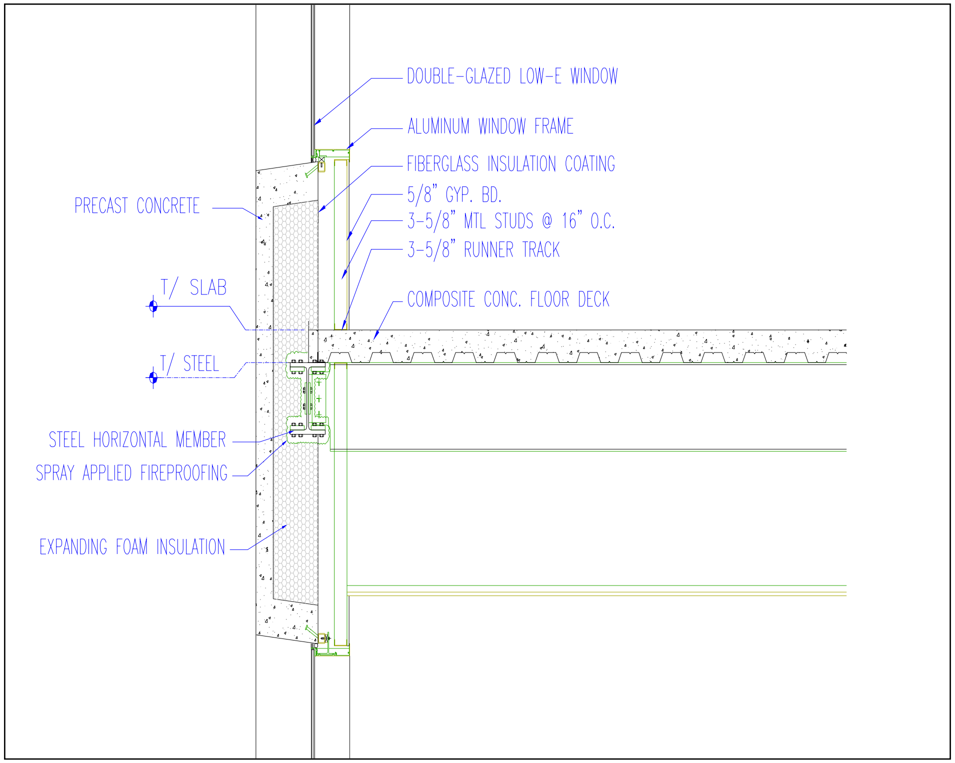
	Story Drift (inches)					
	Trial 1	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Acceptable**
Level 900	0.65	0.61	0.54	0.42	0.42	0.46
Level 800	0.60	0.57	0.52	0.38	0.38	0.46
Level 700	0.60	0.56	0.50	0.34	0.34	0.46
Level 600	0.54	0.49	0.42	0.26	0.26	0.46
Level 500	0.38	0.35	0.29	0.18	0.17	0.55
Total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

North-South Direction

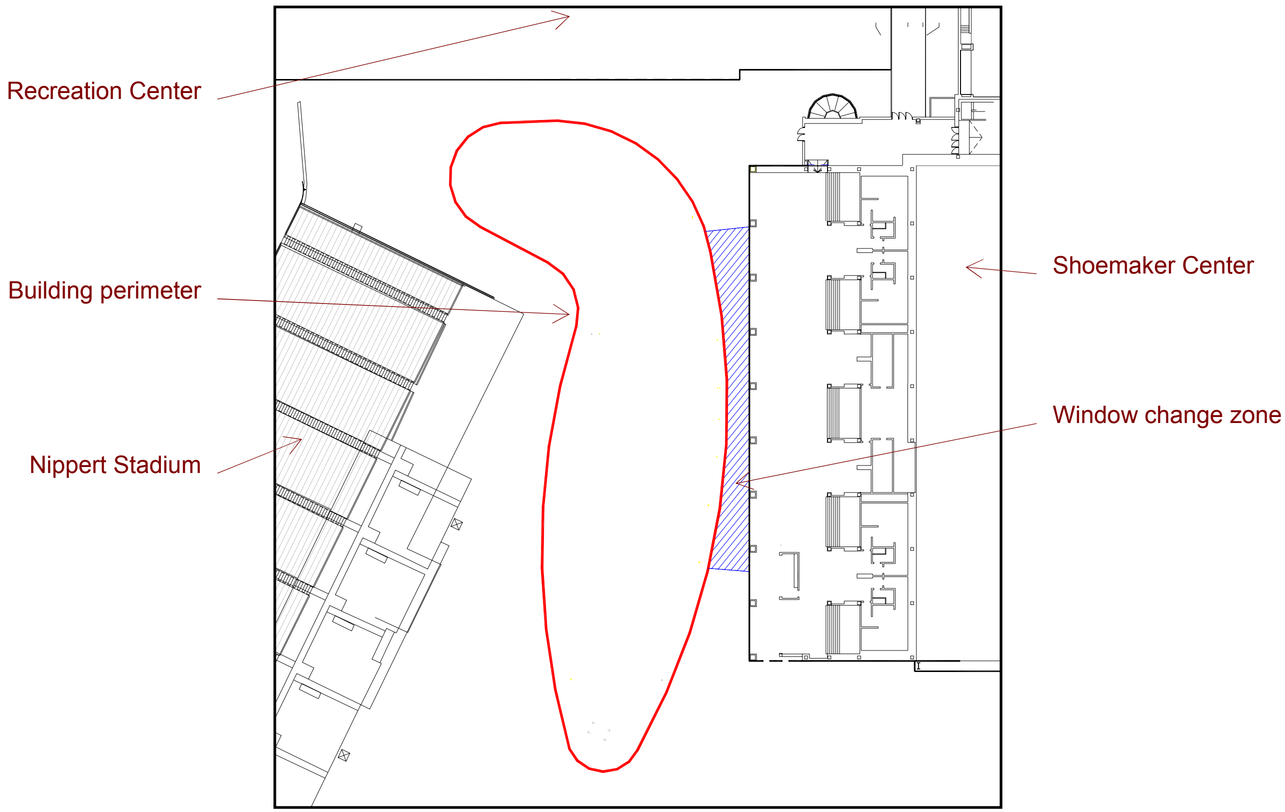
	Story Drift (inches)					
	Trial 1	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Acceptable**
Level 900	0.47	0.44	0.40	0.29	0.32	0.46
Level 800	0.39	0.35	0.32	0.25	0.28	0.46
Level 700	0.41	0.37	0.34	0.23	0.26	0.46
Level 600	0.41	0.35	0.30	0.18	0.22	0.46
Level 500	0.22	0.19	0.15	0.09	0.12	0.55
Total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

Additional Information





Additional Information



Additional Information