AE Senior Thesis 2004
University of Cincinnati Athletic Center

Structural Redesign of a Perimeter Diagrid Lateral System

Brian Genduso
Structural Option
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
General Information

Multi-use
8 stories - 220,000 ft²
$50.7 million
Design Architect – Bernard Tschumi Architects
Design Engineer – Arup, New York
Site
University of Cincinnati “Varsity Village” – Cincinnati, Ohio
Building Introduction

Architectural Layout

Curved perimeter
5-story atrium
Partially above existing facilities
1) Building Introduction
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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
Structural System Description

Braced Frames
Four types
Help carry lateral load from bottom of diagrid to foundation
East-West direction only
1) Building Introduction
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8) Construction Study
9) Recommendation
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
1) Building Introduction
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4) Design Philosophy
5) Redesign Approach
   a) Structural Redesign
6) Daylighting Study
7) Construction Study
8) Recommendation
Design Philosophy

Become an “architect-engineer”
Aesthetic quality
Practical application

Innovative architecture demands innovative engineering solutions!

Unique yet sensible
Alter the look and feel
Maintain shape, height, space layout
Topic Outline

1) Building Introduction
2) Structural System Description
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5) Redesign Approach
6) Structural Redesign
7) Daylighting Study
8) Construction Study
9) Recommendation
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
1) Building Introduction
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5 different materials

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

Solution Area I

Changing Diagrid
## Structural Redesign

### Tabular Results

<table>
<thead>
<tr>
<th>Material</th>
<th>Mat. Cost</th>
<th>Availability</th>
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</table>
Structural Redesign

Overall Results

- Wide Flanges: 88.6
- HSS: 87.1
- Glulam Timber: 65.7
- Precast: 77.1
- Cast-in-place: 79.4

Stick with steel wide flanges
Structural Redesign

Two main ways to accomplish this:

1) Open up the grid

2) Adjust configuration

John Hancock Center

Central China Television Tower
Structural Redesign

Configurations
Structural Redesign

Considerations

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

2D STAAD Model
### Tabular Results

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<tr>
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<td>0.90</td>
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### 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.
Structural Redesign

Overall Results

Score

Case

0 1 2 3 4 5a 5b 5c 6

87.5 77.6 67.7 82.0 64.4 82.6 74.8 69.4 90.4
Structural Redesign

Conclusion

Original

Stick with the original diagrid configuration!
Structural Redesign

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
## Structural Redesign

### Pro-Con Comparison

#### Gravity System

<table>
<thead>
<tr>
<th>Option</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior Hat Truss</td>
<td>Hidden, flexible, can be applied over whole building</td>
<td>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</td>
<td>2</td>
</tr>
<tr>
<td>Cantilevers Over</td>
<td>Invisible structure, no height increases</td>
<td>Backpinning will be a major issue, no columns can be put through auditorium</td>
<td>6</td>
</tr>
<tr>
<td>Columns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cantilevers Over</td>
<td>Hidden, flexible, no height increases</td>
<td>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</td>
<td>5</td>
</tr>
<tr>
<td>Girders</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 600 Truss</td>
<td>Truss can be deep and efficient through mechanical room</td>
<td>Truss will interfere with some mechanical equipment, layout of some public space will have to be replanned, combination of tensile and compression columns</td>
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<tr>
<td>Perimeter Truss</td>
<td>Out of the way of the rest of the building, very efficient, can be applied over whole building</td>
<td>Height increase, construction sequence will be an issue, tensile columns</td>
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<tr>
<td>Reverse Truss</td>
<td>Provides both gravity and lateral stiffness, fairly efficient, no height increase</td>
<td>Not flexible, diagonals will interfere with spaces and atrium layout will have to change</td>
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</tr>
</tbody>
</table>

#### Lateral System

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

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
Structural Redesign

Virtual Work
Deflections

- Trial 1: Failed (Deflection 4.50 in)
- Trial 2: Failed (Deflection 3.50 in)
- Trial 3: Questionable (Deflection 3.00 in)
- Trial 4: Acceptable (Deflection 1.00 in)
## Structural Redesign

### Construction Documents

<table>
<thead>
<tr>
<th>Member Group</th>
<th>Trial #1</th>
<th>Trial #2</th>
<th>Trial #3</th>
<th>Trial #4</th>
<th>Trial #5</th>
<th>Trial #6</th>
<th>Trial #7</th>
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<tbody>
<tr>
<td>Truss Horizontals</td>
<td>39.1</td>
<td>47.6</td>
<td>57.2</td>
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<td>79.9</td>
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<td>Truss Diagonals</td>
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<td>49.8</td>
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<td>54.5</td>
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<td>Truss Columns</td>
<td>75.2</td>
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<td><strong>189.9</strong></td>
<td><strong>209.9</strong></td>
<td><strong>223.7</strong></td>
<td><strong>223.7</strong></td>
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*Assumed at 50% of above grade sum

<table>
<thead>
<tr>
<th>Member Group</th>
<th>Trial #1</th>
<th>Trial #2</th>
<th>Trial #3</th>
<th>Trial #4</th>
<th>Trial #5</th>
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<td>Above Grade Braces</td>
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*Assumed at 50% of above grade sum

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<tr>
<th>Length</th>
<th>Pieces per floor</th>
<th>Total Length</th>
<th>Weight lb/ft</th>
<th>Total weight tons</th>
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### Structural Redesign

#### Structure weight

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<tr>
<th>Perimeter Truss</th>
<th>Tons</th>
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<tbody>
<tr>
<td>Truss Horizontals</td>
<td>85.2</td>
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<tr>
<td>Truss Diagonals</td>
<td>54.5</td>
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<tr>
<td>Columns</td>
<td>83.9</td>
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<tr>
<td>Filler Beams</td>
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<tr>
<td>Bracing</td>
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<td><strong>Total Weight</strong></td>
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<table>
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<tr>
<th>Original System</th>
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<td>V columns</td>
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<td>Bracing</td>
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<tr>
<td><strong>Total Weight</strong></td>
<td><strong>516.2</strong></td>
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</table>

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

<table>
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<tr>
<th></th>
<th>Undesirable Impact</th>
<th>Little or no Change</th>
<th>Reasonable Success</th>
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<tr>
<td>Reduce structure weight</td>
<td></td>
<td></td>
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<tr>
<td>Reduce connection complexity</td>
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<td>Increase viewable window area</td>
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<td>▶️</td>
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<td>Maintain interior layout</td>
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<td>Penetration of open spaces</td>
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<td>Placement of columns</td>
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</table>
The Perimeter Truss and Braced Frame system is an acceptable alternative.
1) Building Introduction
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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
**Daylighting**

## Conclusions

<table>
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<tr>
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<th>Disadvantage</th>
<th>Either</th>
<th>Advantage</th>
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<tr>
<td>Views</td>
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</table>

Daylighting is an owner/architect decision

Brian Genduso – AE Senior Thesis 2004

University of Cincinnati Athletic Center
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Column Deformation Incompatibility

Perimeter Truss

Compression Columns

\[ 5\Delta_1 \]

\[ \Delta_1 \]

Tension Columns

\[ 5\Delta_1 + \Delta_2 \]
### Construction Study

#### Erection Sequence

**Bottom up**

<table>
<thead>
<tr>
<th>Level</th>
<th>500</th>
<th>500-600</th>
<th>500-700</th>
<th>500-800</th>
<th>Total</th>
<th>Total after installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>1Δ</td>
<td>1Δ</td>
<td>1Δ</td>
<td>1Δ</td>
<td>4Δ</td>
<td>0</td>
</tr>
<tr>
<td>700</td>
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<td>2Δ</td>
<td>2Δ</td>
<td>1Δ</td>
<td>7Δ</td>
<td>1Δ</td>
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<tr>
<td>600</td>
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<td>3Δ</td>
<td>2Δ</td>
<td>1Δ</td>
<td>9Δ</td>
<td>3Δ</td>
</tr>
<tr>
<td>500</td>
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<td>3Δ</td>
<td>2Δ</td>
<td>1Δ</td>
<td>10Δ</td>
<td>6Δ</td>
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**Top Down**

<table>
<thead>
<tr>
<th>Level</th>
<th>500</th>
<th>500-600</th>
<th>500-700</th>
<th>500-800</th>
<th>Total</th>
<th>Total after installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>1Δ</td>
<td>1Δ</td>
<td>1Δ</td>
<td>1Δ</td>
<td>4Δ</td>
<td>3Δ</td>
</tr>
<tr>
<td>700</td>
<td>1Δ</td>
<td>2Δ</td>
<td>2Δ</td>
<td>2Δ</td>
<td>7Δ</td>
<td>4Δ</td>
</tr>
<tr>
<td>600</td>
<td>1Δ</td>
<td>2Δ</td>
<td>3Δ</td>
<td>3Δ</td>
<td>9Δ</td>
<td>3Δ</td>
</tr>
<tr>
<td>500</td>
<td>1Δ</td>
<td>2Δ</td>
<td>3Δ</td>
<td>4Δ</td>
<td>10Δ</td>
<td>0</td>
</tr>
</tbody>
</table>
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
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

9 foot width

18 foot width

27 foot width
Additional Information

Original layout

Changed span direction

Heavy cross beam
Additional Information

Supporting Column

Torsion applied to column

Applied loads
### East-West Direction

<table>
<thead>
<tr>
<th>Level</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 4</th>
<th>Trial 5</th>
<th>Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 900</td>
<td>0.65</td>
<td>0.61</td>
<td>0.54</td>
<td>0.42</td>
<td>0.42</td>
<td>0.46</td>
</tr>
<tr>
<td>Level 800</td>
<td>0.60</td>
<td>0.57</td>
<td>0.52</td>
<td>0.38</td>
<td>0.38</td>
<td>0.46</td>
</tr>
<tr>
<td>Level 700</td>
<td>0.60</td>
<td>0.56</td>
<td>0.50</td>
<td>0.34</td>
<td>0.34</td>
<td>0.46</td>
</tr>
<tr>
<td>Level 600</td>
<td>0.54</td>
<td>0.49</td>
<td>0.42</td>
<td>0.26</td>
<td>0.26</td>
<td>0.46</td>
</tr>
<tr>
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<td>0.29</td>
<td>0.18</td>
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<tr>
<td>Total Drift</td>
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<td>2.58</td>
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<td>1.58</td>
<td>2.09</td>
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### North-South Direction

<table>
<thead>
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<th>Level</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 4</th>
<th>Trial 5</th>
<th>Acceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 900</td>
<td>0.47</td>
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<td>0.40</td>
<td>0.29</td>
<td>0.32</td>
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<tr>
<td>Level 800</td>
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<td>0.35</td>
<td>0.32</td>
<td>0.25</td>
<td>0.28</td>
<td>0.46</td>
</tr>
<tr>
<td>Level 700</td>
<td>0.41</td>
<td>0.37</td>
<td>0.34</td>
<td>0.23</td>
<td>0.26</td>
<td>0.46</td>
</tr>
<tr>
<td>Level 600</td>
<td>0.41</td>
<td>0.35</td>
<td>0.30</td>
<td>0.18</td>
<td>0.22</td>
<td>0.46</td>
</tr>
<tr>
<td>Level 500</td>
<td>0.22</td>
<td>0.19</td>
<td>0.15</td>
<td>0.09</td>
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<td>Total Drift</td>
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<td>1.70</td>
<td>1.50</td>
<td>1.04</td>
<td>1.20</td>
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