Samantha deVries

Advisor: Dr. Thomas Boothby

Department of Architectural Engineering

The Pennsylvania State University

Structural Option

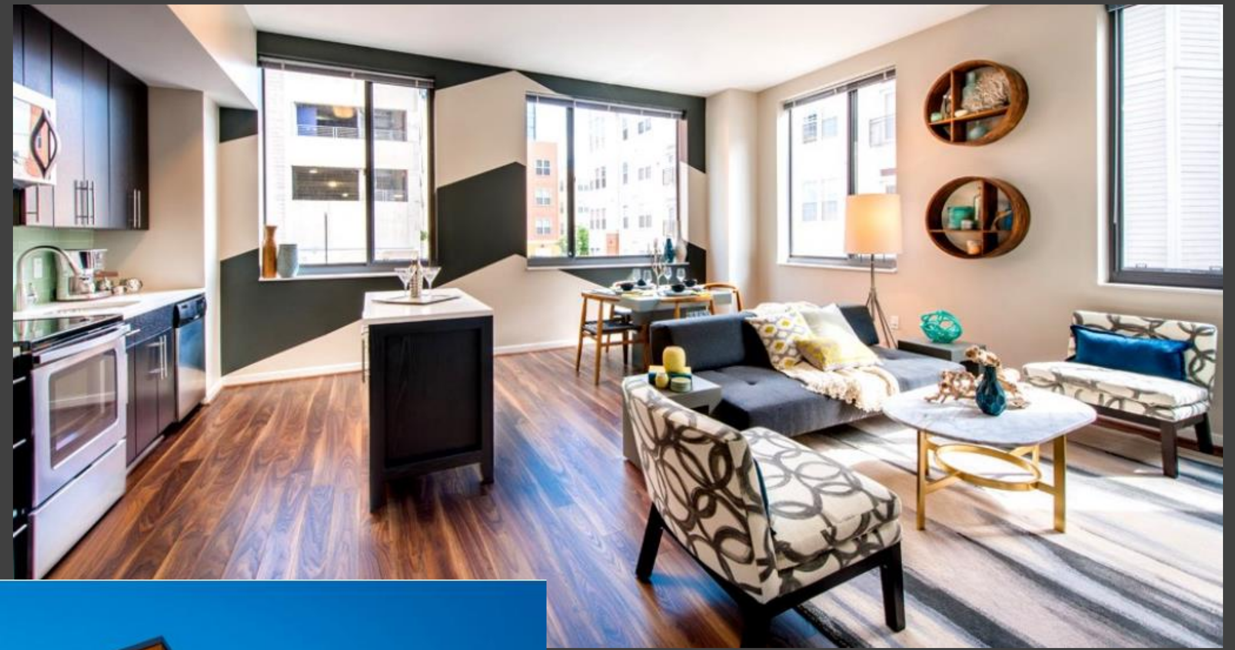
Spring 2015

# 11141 Georgia Ave

Wheaton, Maryland

# Building Overview

- 158 Feet
- 14 Stories
- 180,000 Gross Square Feet
- $44 Million
- Constructed Feb. 2013 – Aug. 2014
- Apartment Building



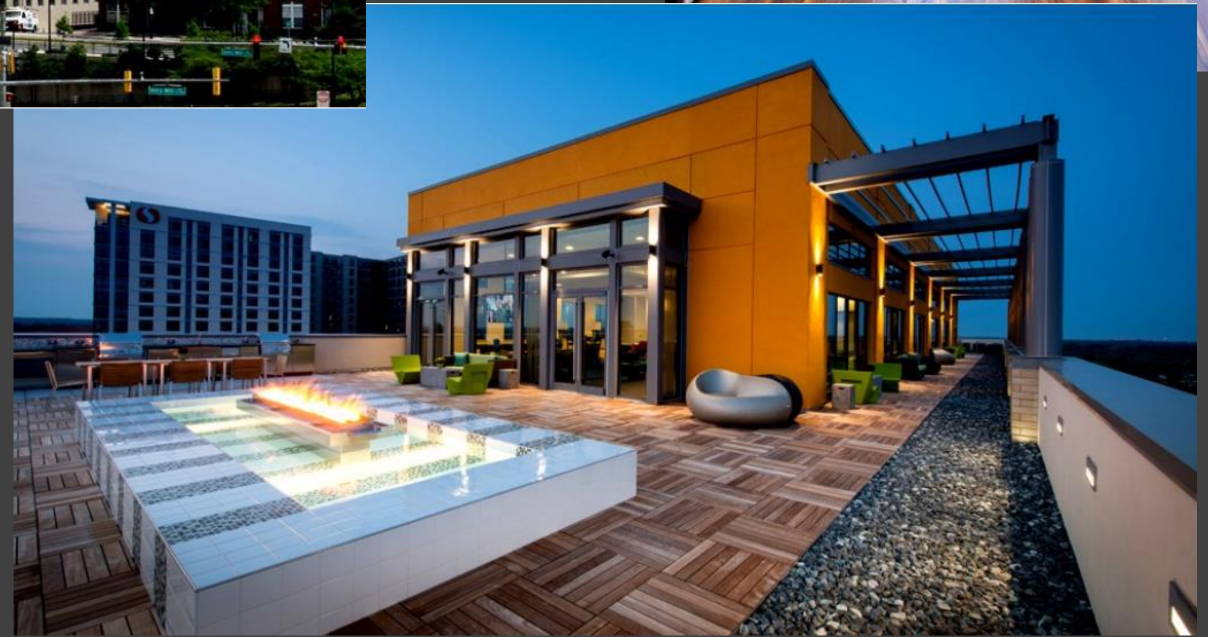


Image Source: The George Apartments online

## Project Team

LOWE ENTERPRISES

Owner

Bonstra | Haresign ARCHITECTS

Architect

WT

General Contractor and CM

Structural Engineer

## Site Information

- Wheaton, MD
- North of D.C.
- Close to Metro Station

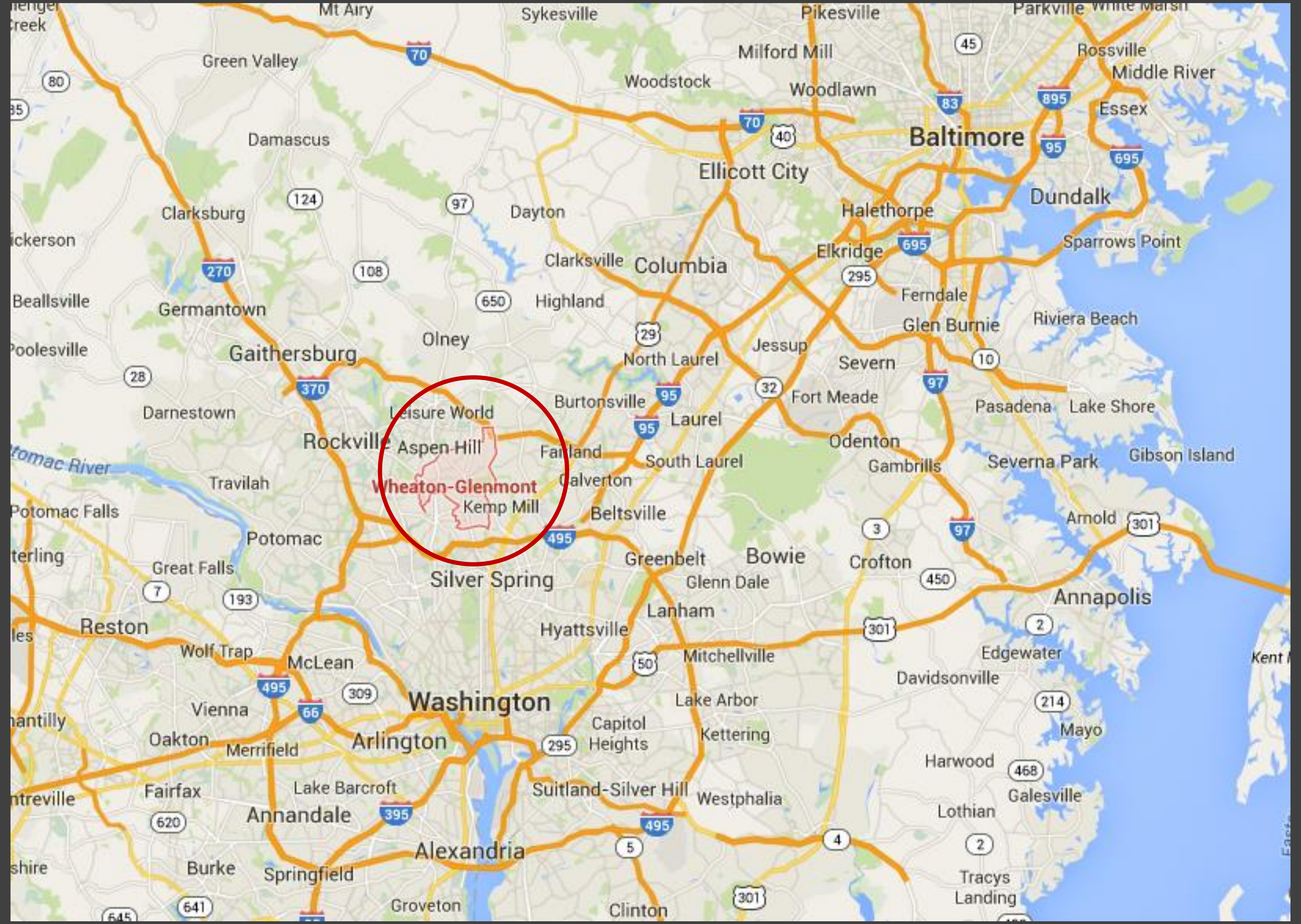


Image Source: Google Maps

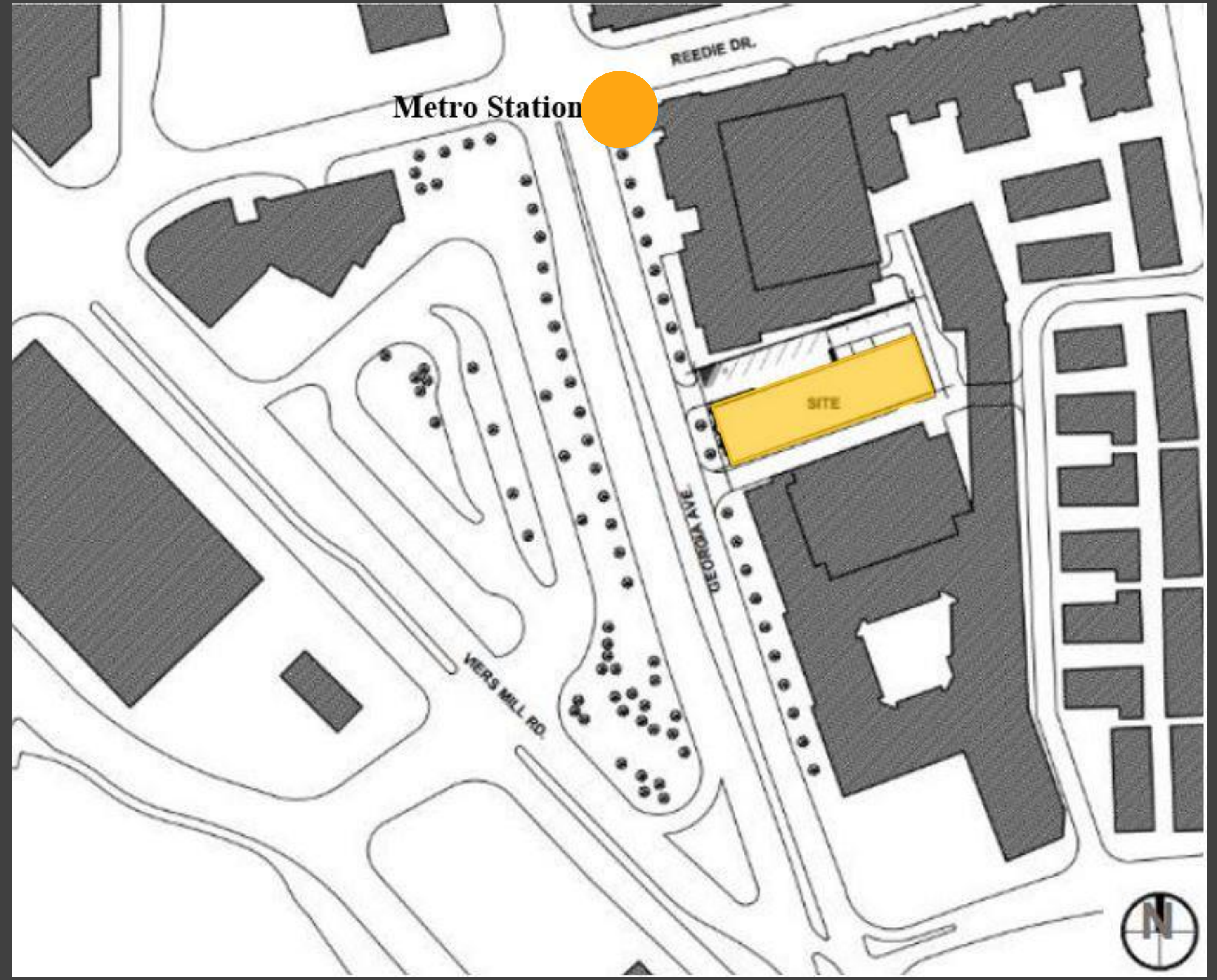


Image Source: Architectural Documents

## Existing Structural System

- 1960's Concrete Office Building
- Renovation
- Concrete Layout
- Steel Addition Layout

Image Source: Whiting Turner Progress Photos

# Existing Structural System

- 1960's Concrete Office Building
- Renovation
- Concrete Layout
- Steel Addition Layout

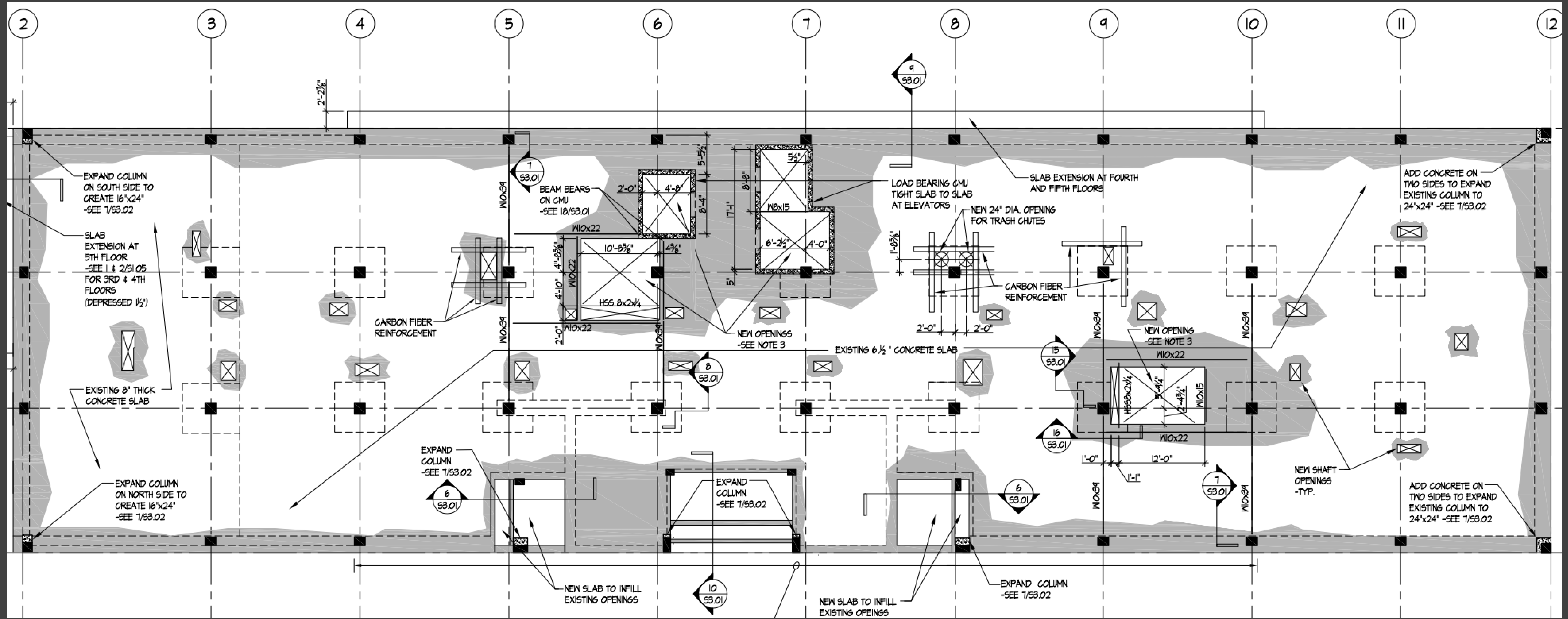



Image Source: Structural Building Documents

# Existing Structural System

- 1960's Concrete Office Building
- Renovation
- Concrete Layout
- Steel Addition Layout

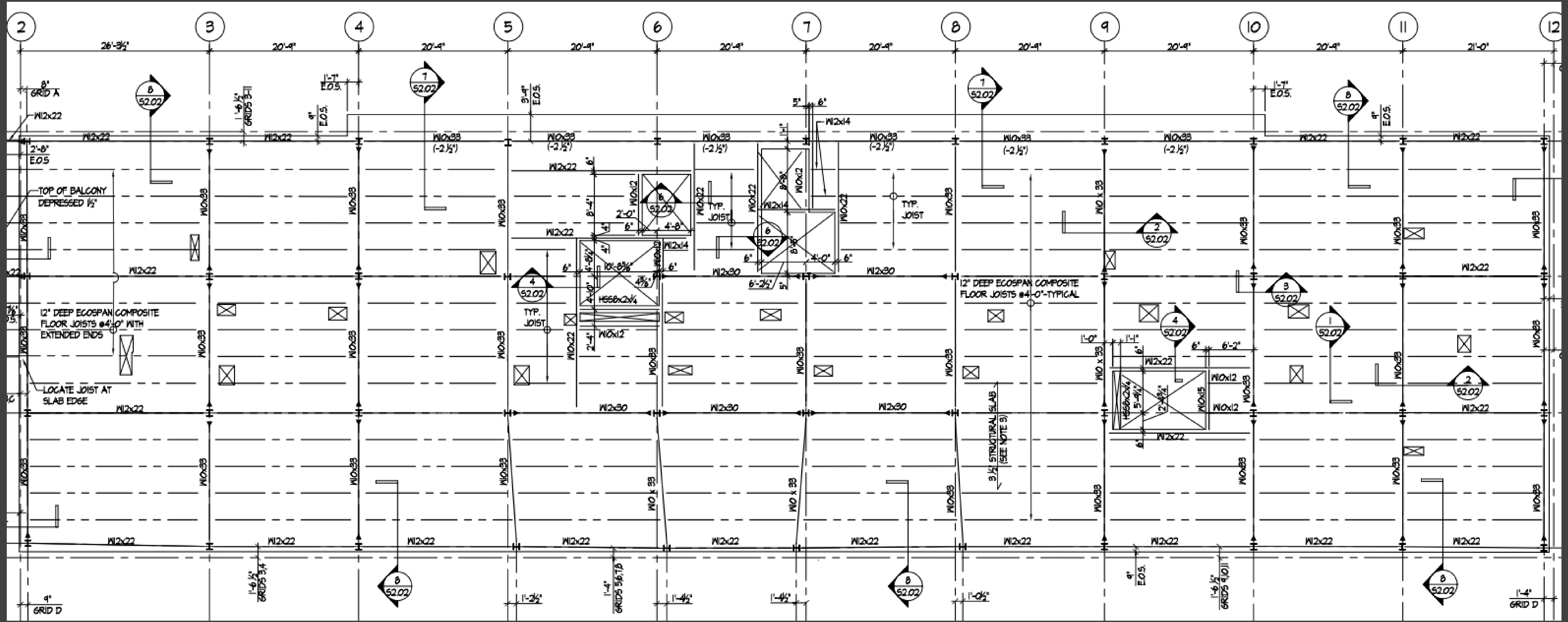


Image Source: Structural Building Documents

# Existing Structural System

- 1960's Concrete Office Building
- Renovation
- Concrete Layout
- Steel Addition Layout

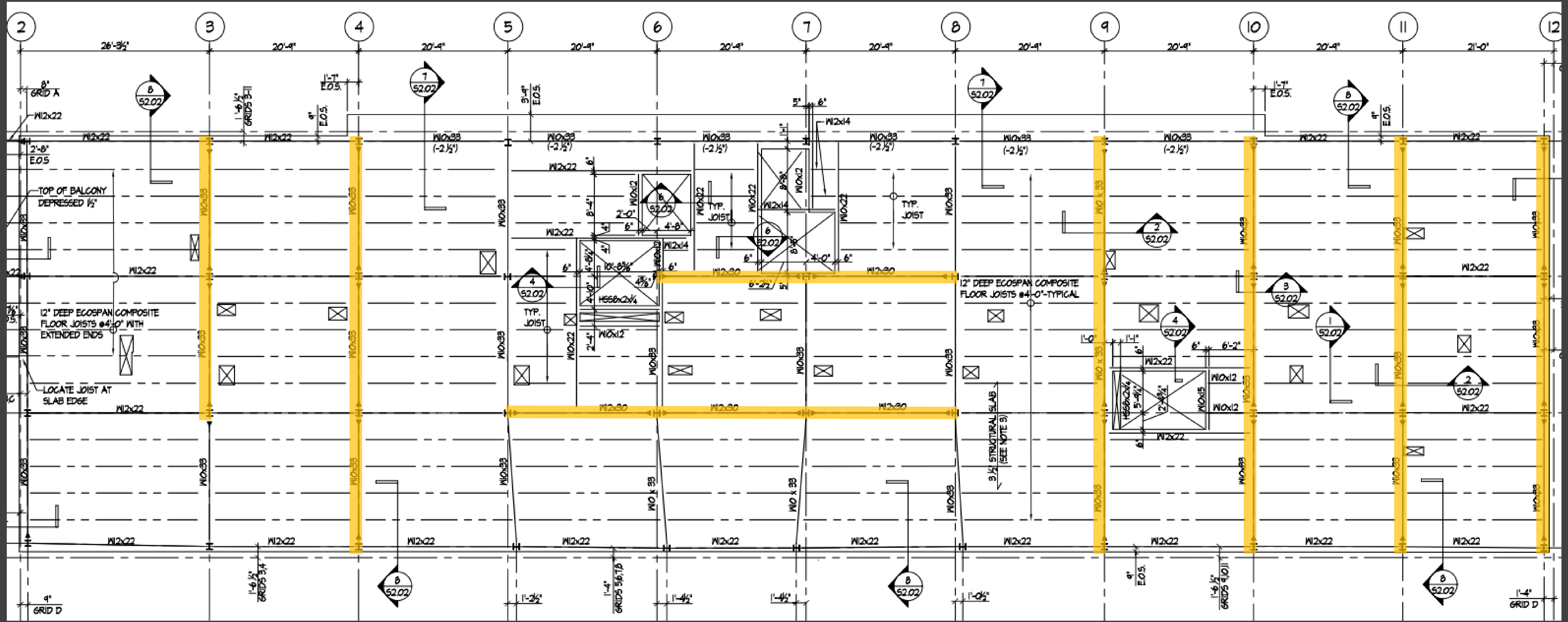


Image Source: Structural Building Documents

## Redesign the Addition

- Building Reuse and Renovation
- Lightweight Addition
- Sustainable Alternative


Image Source: Whiting Turner Progress Photos

## Intro to Tall Timber

- Current Tall Wood Buildings
- Cross Laminated Timber
- Benefits and Challenges of tall wood

Image Source: Herald Sun Online

Melbourne, Australia

- 10-story apartment building
- Forte at Victoria Harbour

## Intro to Tall Timber

- Current Tall Wood Buildings
- Cross Laminated Timber
- Benefits and Challenges of tall wood

Image Source: Green Building Online

Berlin, Germany

- 7-story apartment building
- E3 Project

## Intro to Tall Timber

- Current Tall Wood Buildings
- Cross Laminated Timber
- Benefits and Challenges of tall wood

Image Source: Rendering from the Nordic Page

### Future Potential Tall Buildings

- 14-stories under construction in Norway
- 18-stories proposed in Canada
- 34-stories proposed in Sweden

- Current Tall Wood Buildings
- Cross Laminated Timber
- Benefits and Challenges of tall wood

Image Source: archi-expo.com

## Cross Laminated Timber

- Engineered Wood Panel Product
- Layers glued perpendicular (dimensional stability)
- At least 3 plies between 5/8" and 2" thick
- Max manufactured size 10' x 40'

## Intro to Tall Timber

- Current Tall Wood Buildings
- Cross Laminated Timber
- Benefits and Challenges of tall wood

Image Source: woodwindowstoday.blogspot.com

### Cross Laminated Timber

- Engineered Wood Panel Product
- Layers glued perpendicular (dimensional stability)
- At least 3 plies between 5/8" and 2" thick
- Max manufactured size 10' x 40'

## Intro to Tall Timber

- Current Tall Wood Buildings
- Cross Laminated Timber
- Benefits and Challenges of tall wood

### Challenges of Using Wood in Tall Buildings

- Combustion during fire
- Connection details (steel loses strength in fire)
- Doesn’t meet code for buildings over 4-6 stories
- Historical fires in wood buildings
- Not used widely in US, therefore knowledge is limited
- Several topics require further research

## Intro to Tall Timber

- Current Tall Wood Buildings
- Cross Laminated Timber
- Benefits and Challenges of tall wood

### Challenges of Using Wood in Tall Buildings

- Combustion during fire
- Connection details (steel loses strength in fire)
- Doesn’t meet code for buildings over 4-6 stories
- Historical fires in wood buildings
- Not used widely in US, therefore knowledge is limited
- Several topics require further research

### Benefits of Using Wood in Tall Buildings

- Renewable construction material (sustainable)
- Versatile material
- Lightweight
- Fast construction time
- Aesthetically pleasing if left exposed
- Heavy Timber burns slowly

# Proposed Solution

Image Source: Sourceable Industry New & Analysis

## Proposed Structural System

- CLT Panels Span between Glulam Girders
- Glulam Girders span to Glulam Columns
- Concrete Shear Walls

# Gravity Redesign

- CLT Floor Panel Design
- Glulam Girder Design
- Glulam Column Design
- Design Summary
- Comparison to Existing System

## Flexure

$$M = \frac{wl^2}{8}$$

$$S_{required} = \frac{M}{F_b}$$

$$M \leq F_b \times S_{required}$$

$C_M = 1.0$
$C_T = 1.0$
$C_i = 1.0$
$C_D = 0.9$ for Dead Load
$C_D = 1.0$ for Live Load
$C_D = 1.6$ for Fire Performance

# Gravity Redesign

- CLT Floor Panel Design
- Glulam Girder Design
- Glulam Column Design
- Design Summary
- Comparison to Existing System

## Flexure

$$M = \frac{wl^2}{8}$$

$$S_{required} = \frac{M}{F_b}$$

$$M \leq F_b \times S_{required}$$

$C_M$ = 1.0
$C_T$ = 1.0
$C_i$ = 1.0
$C_D$ = 0.9 for Dead Load
$C_D$ = 1.0 for Live Load
$C_D$ = 1.6 for Fire Performance

## Deflections

$$\Delta = \frac{5wl^4}{384EI}$$

Live Load Deflection Limit:
l/360
Dead and Live Deflection Limit"
l/240

# Gravity Redesign

- CLT Floor Panel Design
- Glulam Girder Design
- Glulam Column Design
- Design Summary
- Comparison to Existing System

## Flexure

$$M = \frac{wl^2}{8}$$

$$S_{required} = \frac{M}{F_b}$$

$$M \leq F_b \times S_{required}$$

$C_M = 1.0$
$C_T = 1.0$
$C_i = 1.0$
$C_D = 0.9$ for Dead Load
$C_D = 1.0$ for Live Load
$C_D = 1.6$ for Fire Performance

## Deflections

$$\Delta = \frac{5wl^4}{384EI}$$

Live Load Deflection Limit:
l/360
Dead and Live Deflection Limit"
l/240

## Fire Performance (using encapsulation method)

| Required Fire Resistance | Effective Charring Rate, $\beta_{eff}$ (in./hr) | Visual Char Layer Thickness (in.) | Zero-strength Layer (in.) | Effective Char Layer Thickness, $a_{char}$ (in.) |
|---|---|---|---|---|
| 45 min (¾-h) | 1.90 | 1.19 | 0.24 | 1.42 |
| 60 min (1-h) | 1.80 | 1.50 | 0.30 | 1.80 |
| 90 min (1½-h) | 1.67 | 2.09 | 0.42 | 2.50 |
| 120 min (2-h) | 1.58 | 2.64 | 0.53 | 3.16 |

$$(D+L)_{reduced} = (0.75D) + (0.4L)$$

$$M = \frac{(D+L)_{reduced}\, l^2}{8}$$

$$\#plies_{residual} = \#plies_{original} - 2$$

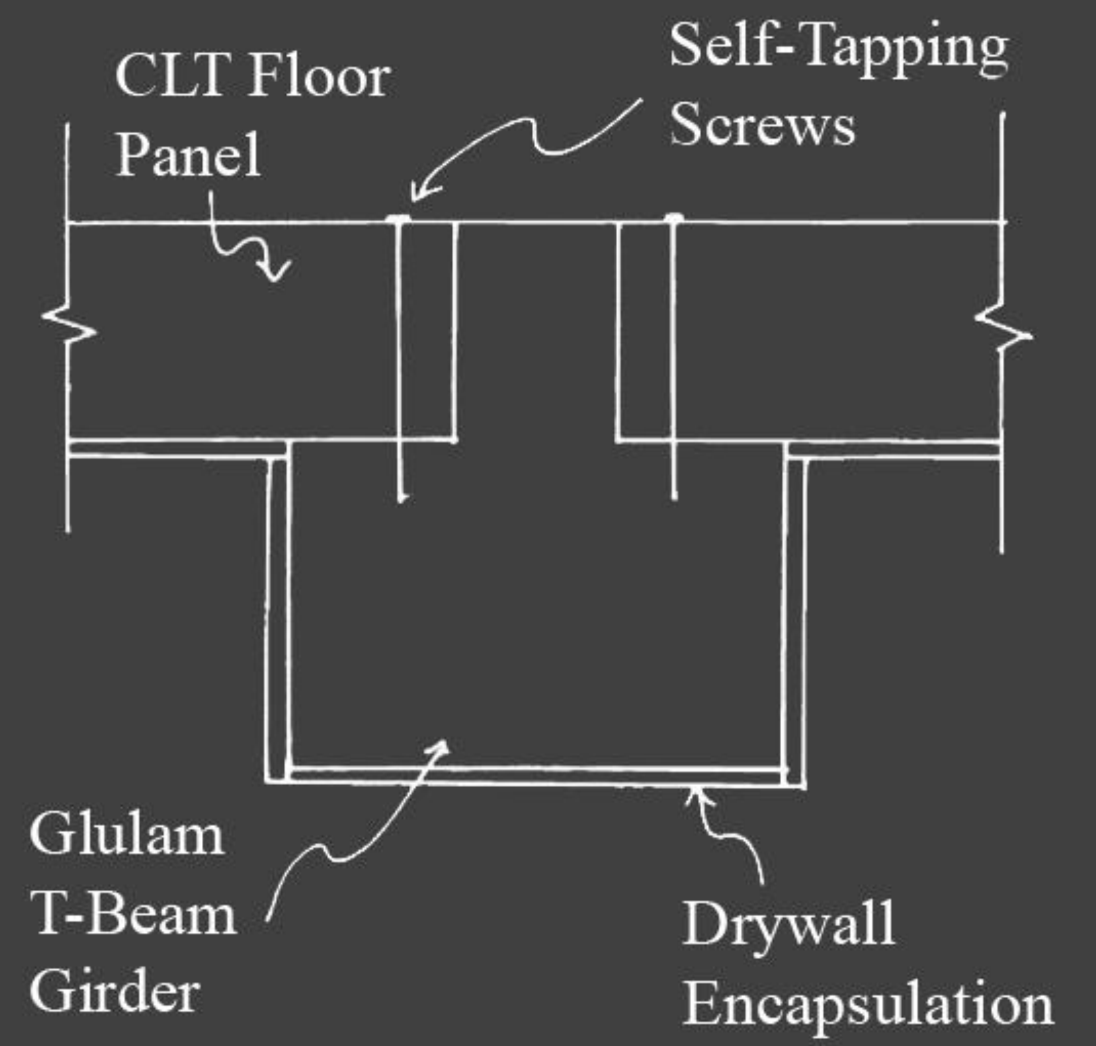
$$M_{fire} \leq (F_b \times S_{required})_{resid.}$$

## Gravity Redesign

- CLT Floor Panel Design
- Glulam Girder Design
- Glulam Column Design
- Design Summary
- Comparison to Existing System

Glulam Girder Design Process Same as CLT Except:

- More sides of material lost in fire performance design
- Volume factor, Cv used in design
- Assumed to be fully braced by floor

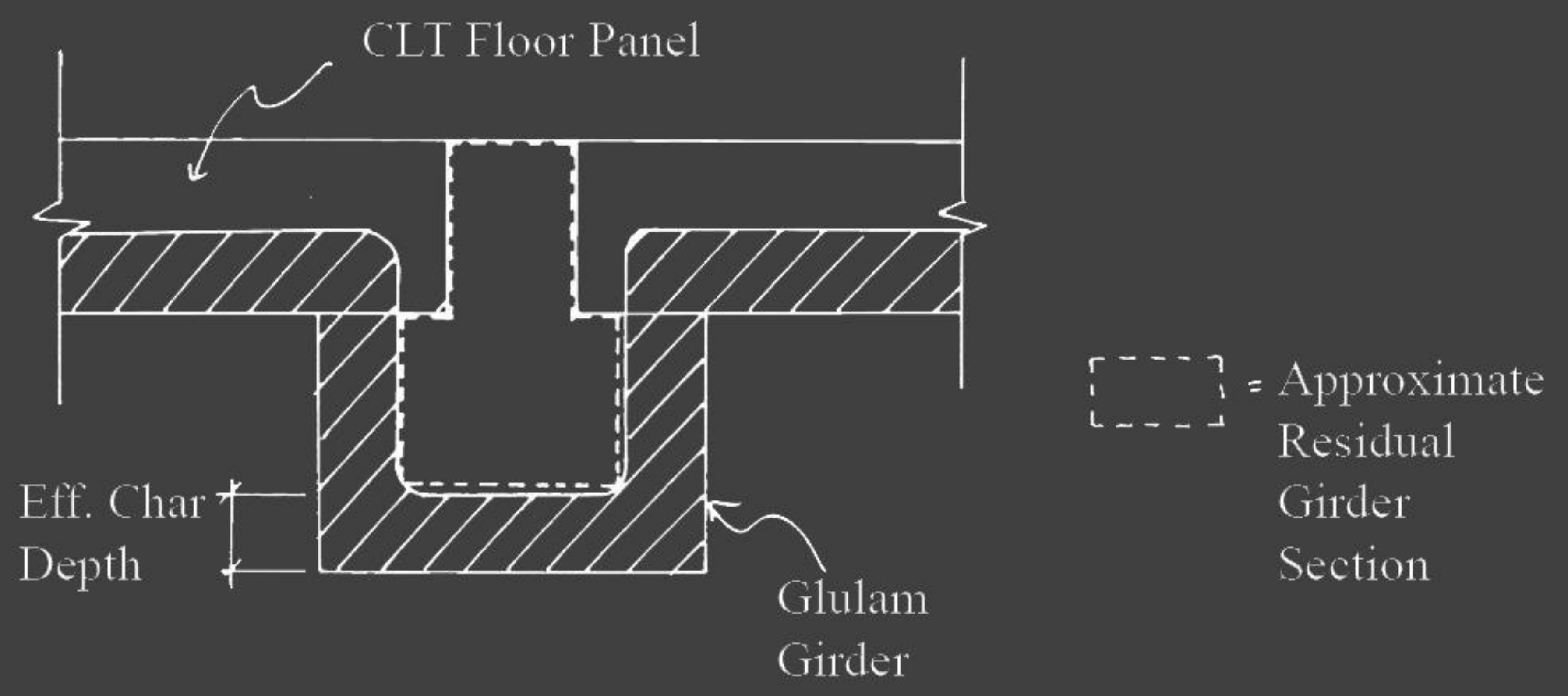


## Gravity Redesign

- CLT Floor Panel Design
- Glulam Girder Design
- Glulam Column Design
- Design Summary
- Comparison to Existing System

### Glulam Girder Design Process Same as CLT Except:

- More sides of material lost in fire performance design
- Volume factor, Cv used in design
- Assumed to be fully braced by floor



# Gravity Redesign

- CLT Floor Panel Design
- Glulam Girder Design
- Glulam Column Design
- Design Summary
- Comparison to Existing System

## Compressive Strength

$$F_c^* = C_V F_c$$

$$E'_{min} = E'(1 - 1.645COV_E(1.05))/1.66$$

$$C_p = \frac{1 + (F_{cE}/F_c^*)}{2c} - \sqrt{\left[\frac{1 + (F_{cE}/F_c^*)}{2c}\right]^2 - \frac{F_{cE}/F_c^*}{c}}$$

$$F_c' = F_c^* \times C_p$$

$$f_c = \frac{P}{A}$$

$$f_c \leq F_c'$$

## Fire Performance

- 4 sides now exposed to fire

$$F_c^* = C_V C_D F_c$$

$$A_{residual} = (b - 5") \times (d - 5")$$

$$f_c = \frac{P_{reduced}}{A_{residual}}$$

# Gravity Redesign

- CLT Floor Panel Design
- Glulam Girder Design
- Glulam Column Design
- Design Summary
- Comparison to Existing System

**Design Summary**

| Structural Floor Elements | | | | |
|---|---|---|---|---|
| **Element** | **Typical Level** | **12th Level** | **Penthouse Roof** | **# Gyp Layers** |
| Typ. CLT Floor Panel | 5-ply | 7-ply | 5-ply | 1 |
| Typ. Glulam Girder* | 15" deep | 18" deep | 15" deep | 1 |
| Floor Panel (26' bay) | 7-ply | 9-ply | 7-ply | 1 |
| **Typical Column** | **Interior** | | **Exterior** | - |
| At addition base | 12" x 12 3/8" | | 12" x 12 3/8" | 1 |

| Non-Typical Girders* | | | | | |
|---|---|---|---|---|---|
| **Girder Type** | | **Typical Level** | **12th Level at Parapet** | **12th Level at Penthouse** | **Penthouse Roof** |
| **Perimeter Girders** | **E-W dir.** | 15" | 13" | 15" | 13" |
| | **E side** | 19 1/2" | 19 1/2" | 25 1/2" | 18" |
| | **W side** | 19 1/2" | 21" | 25 1/2" | 18" |

| Non-Typical Columns and Columns at Other Levels** | | | | |
|---|---|---|---|---|
| **Column Type** | **Levels 7&8** | **Levels 9&10** | **Levels 11&12** | **Penthouse** |
| **Typ. Int.** | 12 3/8" | 10 1/2" | 8 1/2" | 8 1/2" |
| **Typ. Ext.** | 12 3/8" | 10 1/2" | 8 1/2" | - |
| **A** | 12 3/8" | 10 1/2" | 8 1/2" | 8 1/2" |
| **B** | 10 1/2" | 8 1/2" | 8 1/2" | - |
| **C** | 10 1/2" | 10 1/2" | 8 1/2" | 8 1/2" |
| **D** | 10 1/2" | 8 1/2" | 8 1/2" | 8 1/2" |
| **E** | 12 3/8" | 10 1/2" | 8 1/2" | - |
| **F** | 12 3/8" | 10 1/2" | 8 1/2" | - |

*Note: All girders have bf = 12" and bw = 4" for improved connection constructability

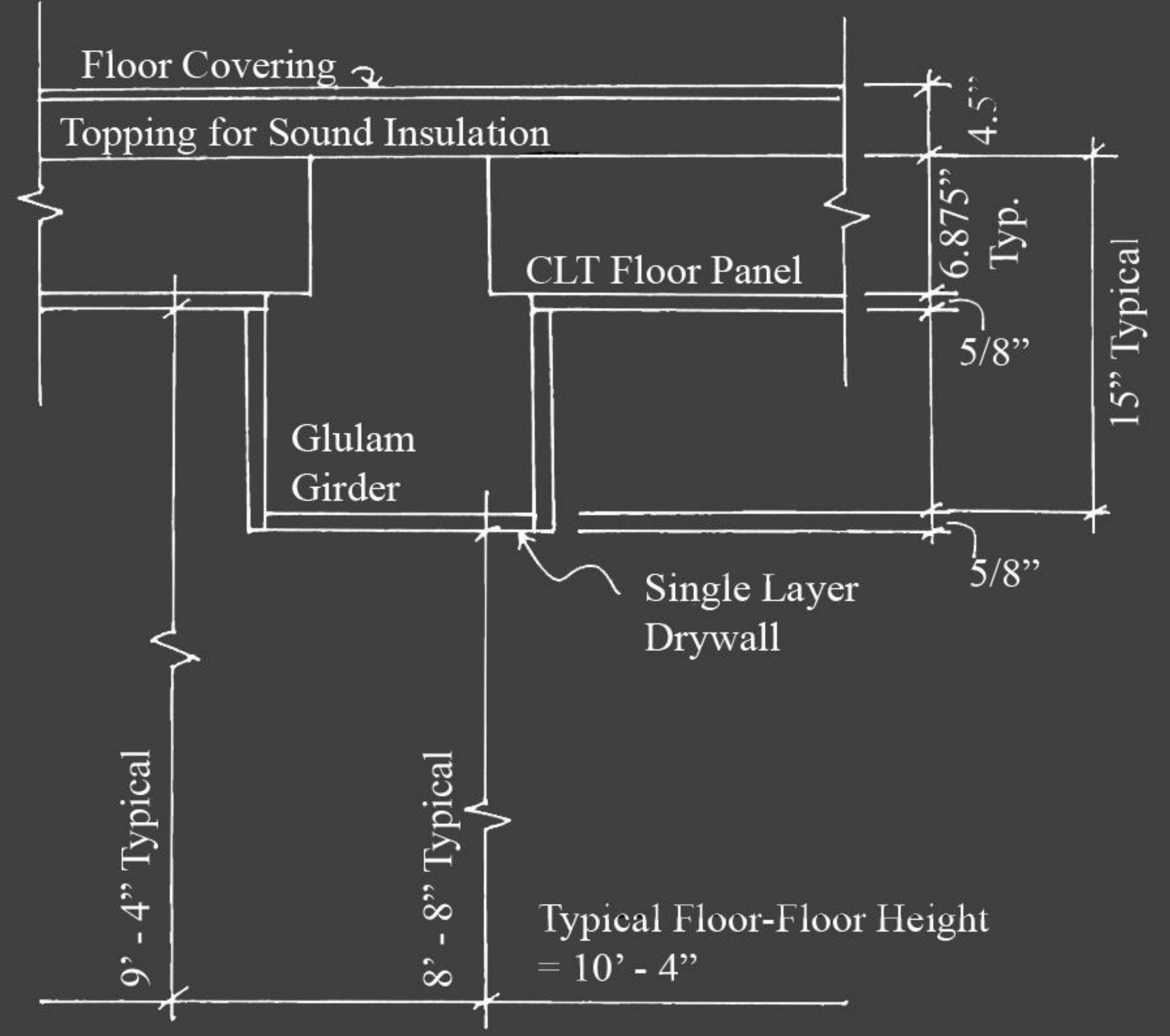
**All columns have bw = 12 to match the girder flange width

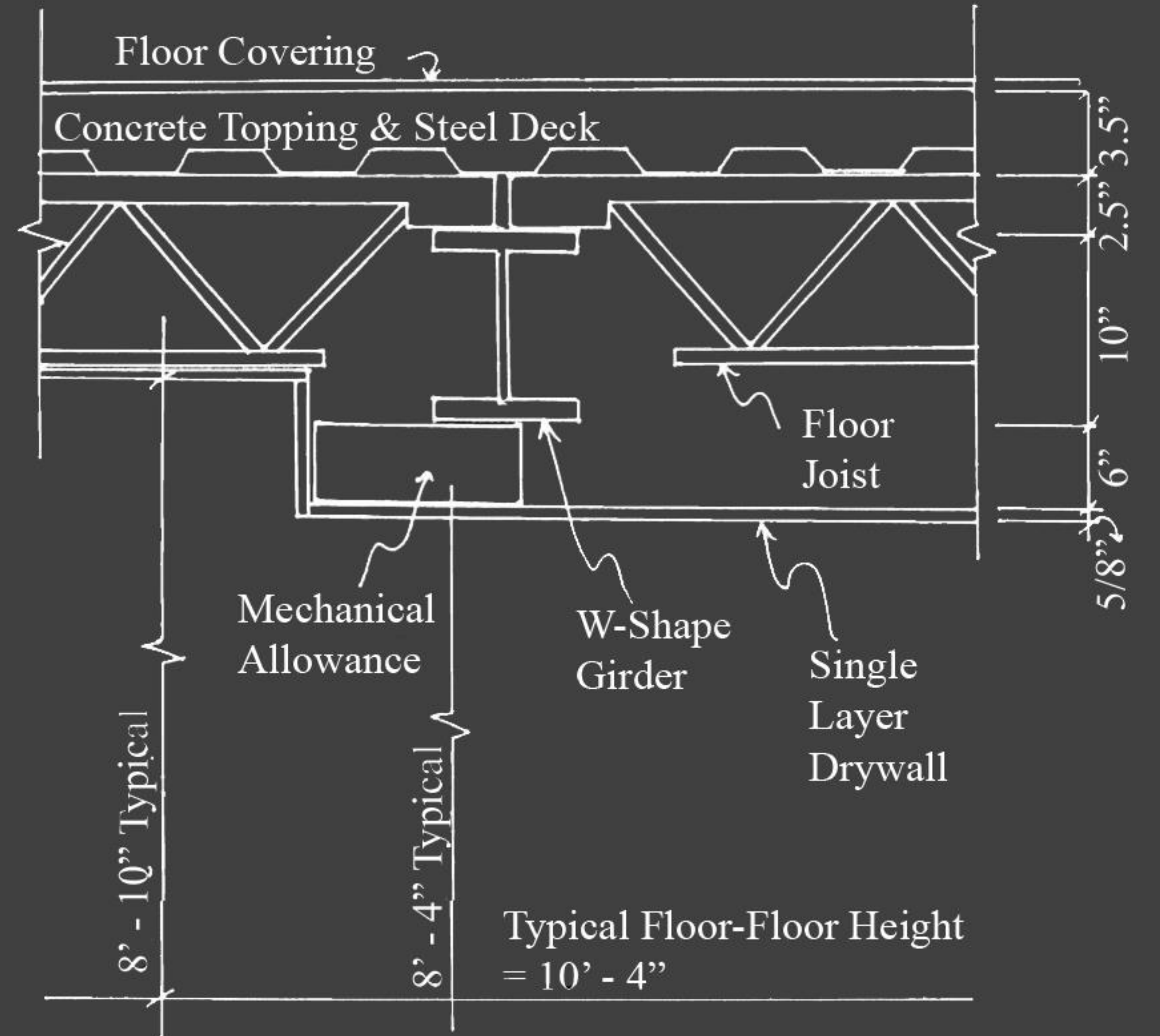
## Design Summary

- 12th Level
  - 7-ply panel on 12th level
  - 18" deep girder
- All other levels
  - 5-ply panel
  - Typical girder 15" deep
- Typical Column 12" x 10 1/2" at base

# Gravity Redesign

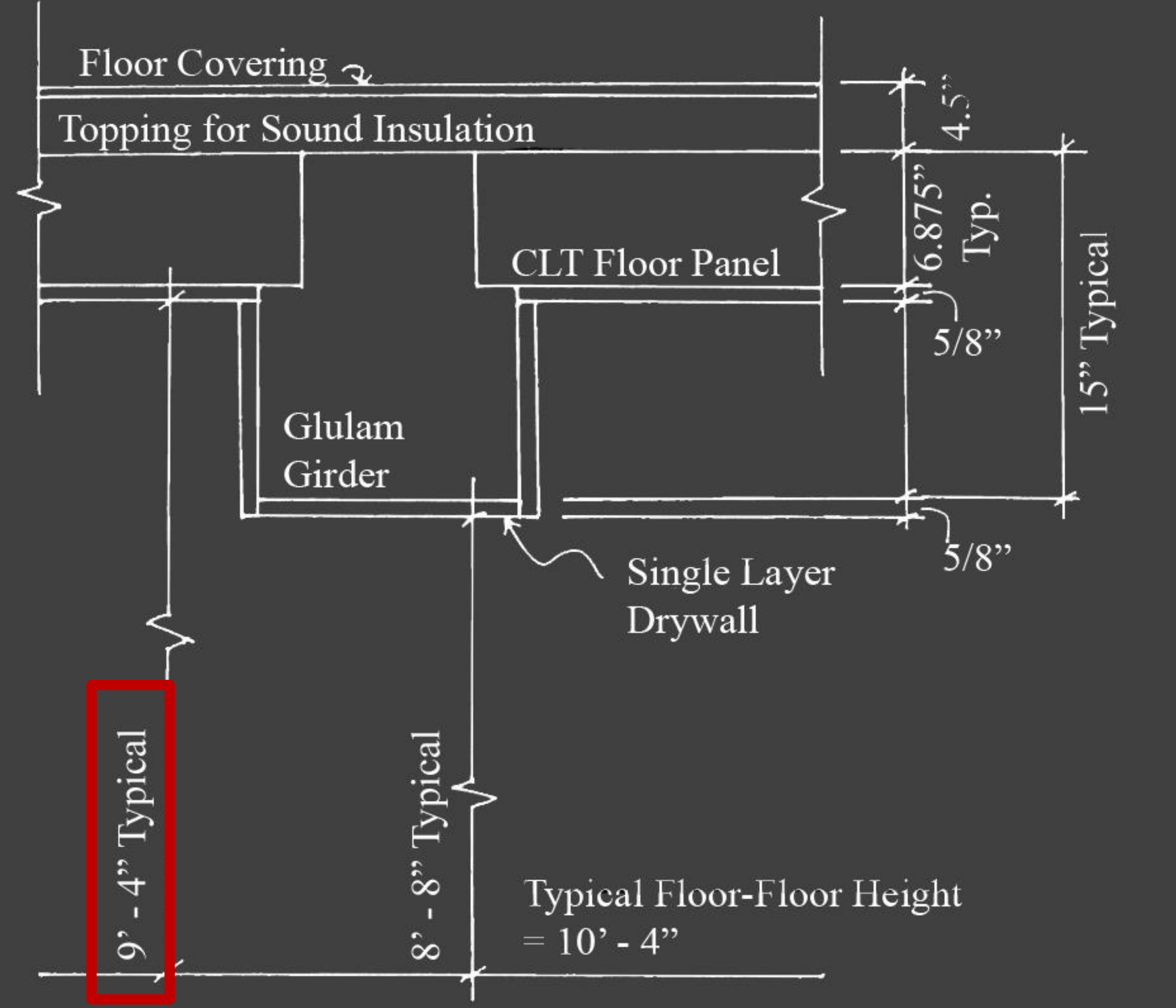
- CLT Floor Panel Design
- Glulam Girder Design
- Glulam Column Design
- Design Summary
- Comparison to Existing System

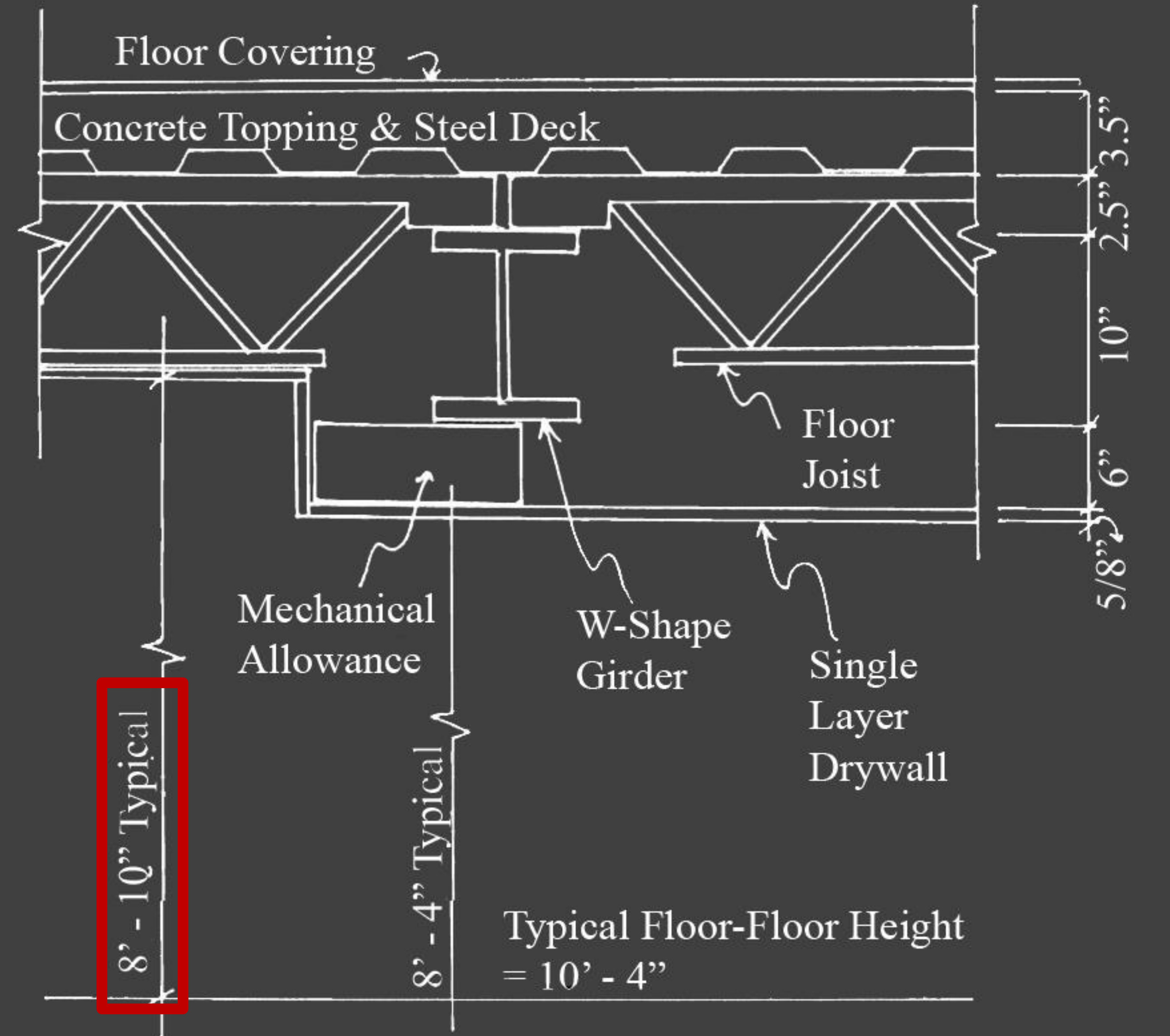


# Gravity Redesign

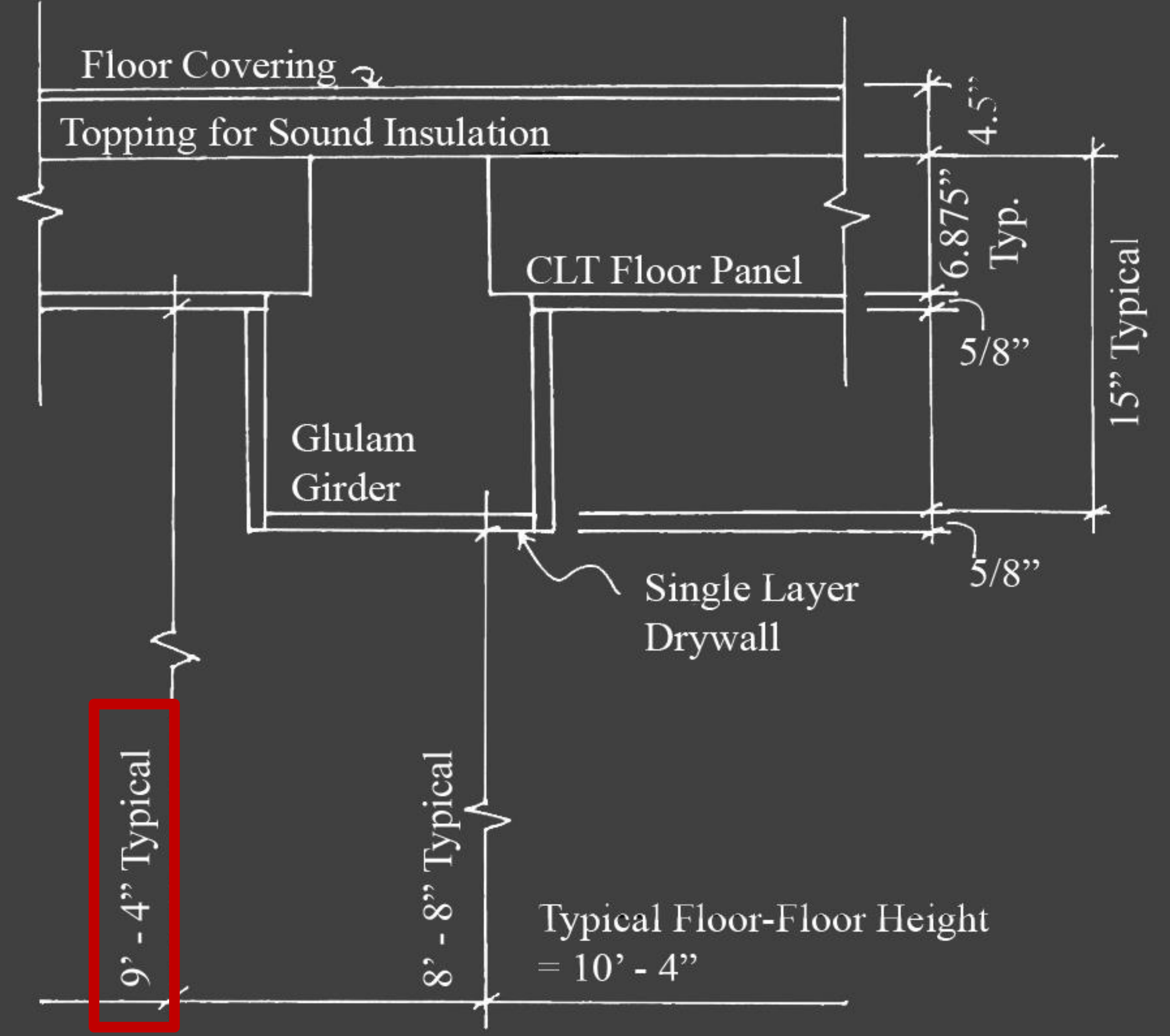
- CLT Floor Panel Design
- Glulam Girder Design
- Glulam Column Design
- Design Summary
- Comparison to Existing System

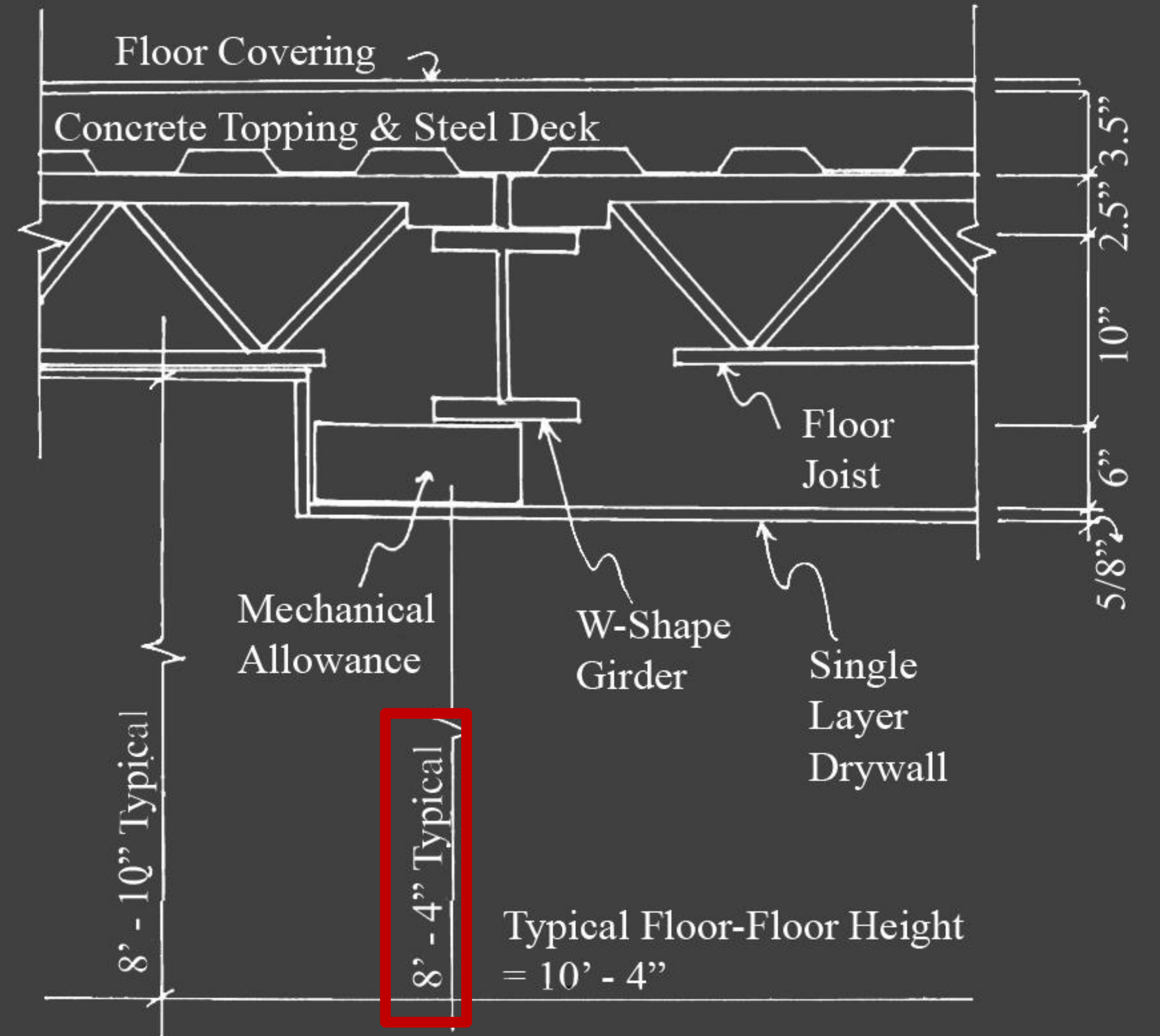


## Gravity Redesign

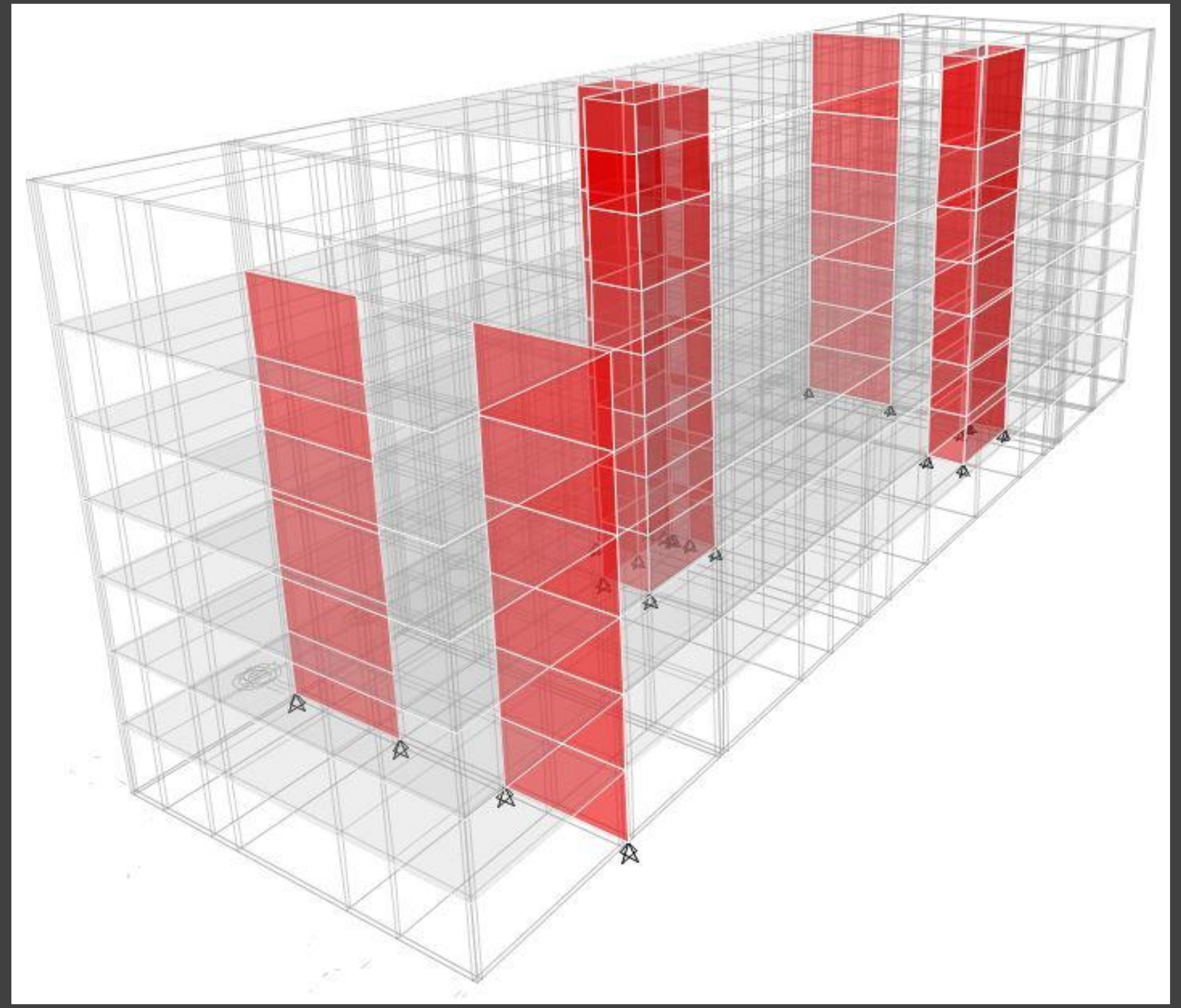
- CLT Floor Panel Design
- Glulam Girder Design
- Glulam Column Design
- Design Summary
- Comparison to Existing System

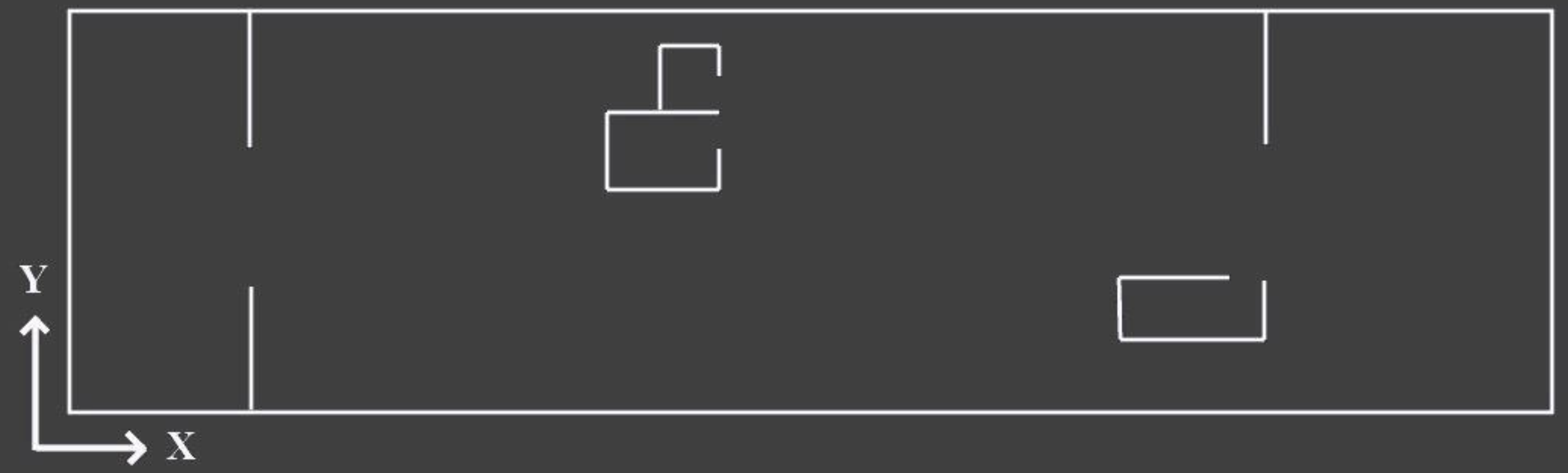


# Lateral Redesign

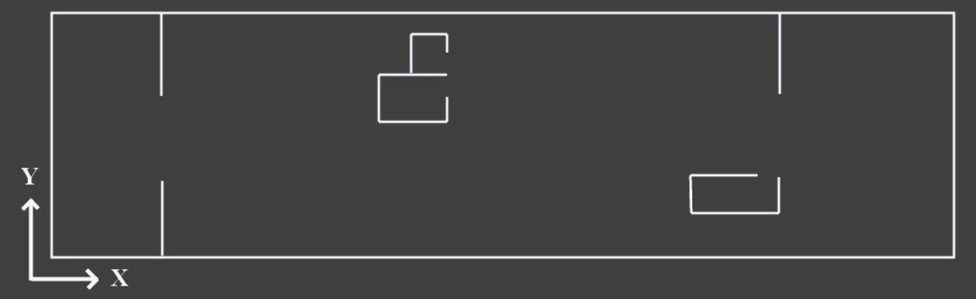
- Lateral Introduction
- Lateral System Behavior
- Shear Wall Design
- Lateral Design Summary



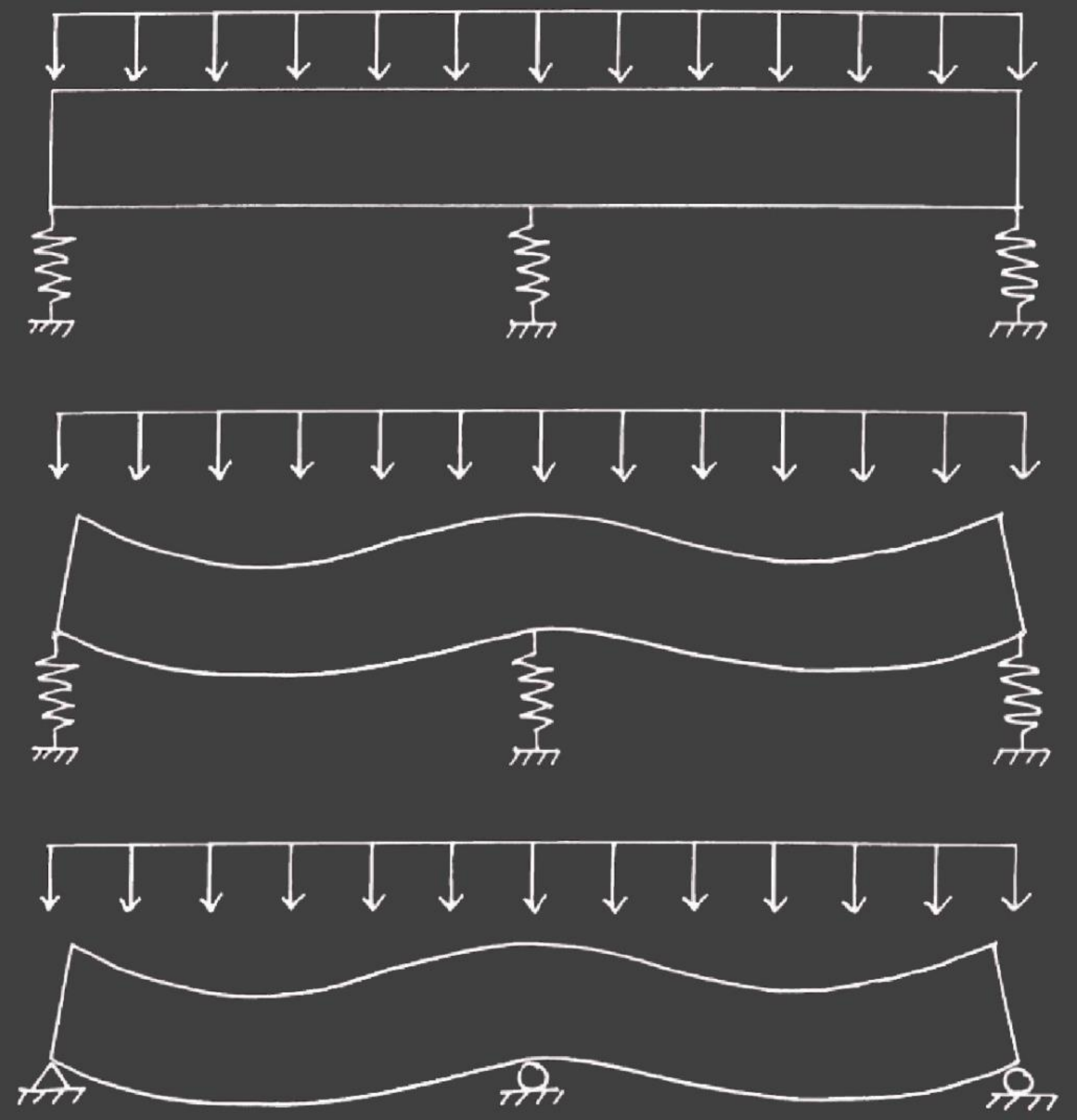


## Lateral Redesign

- Lateral Introduction
- Lateral System Behavior
- Shear Wall Design
- Lateral Design Summary

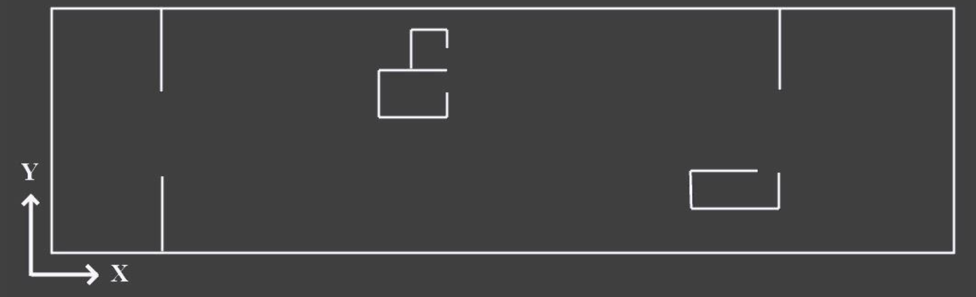



- Rigid Diaphragm
- Semi-Rigid
- Flexible

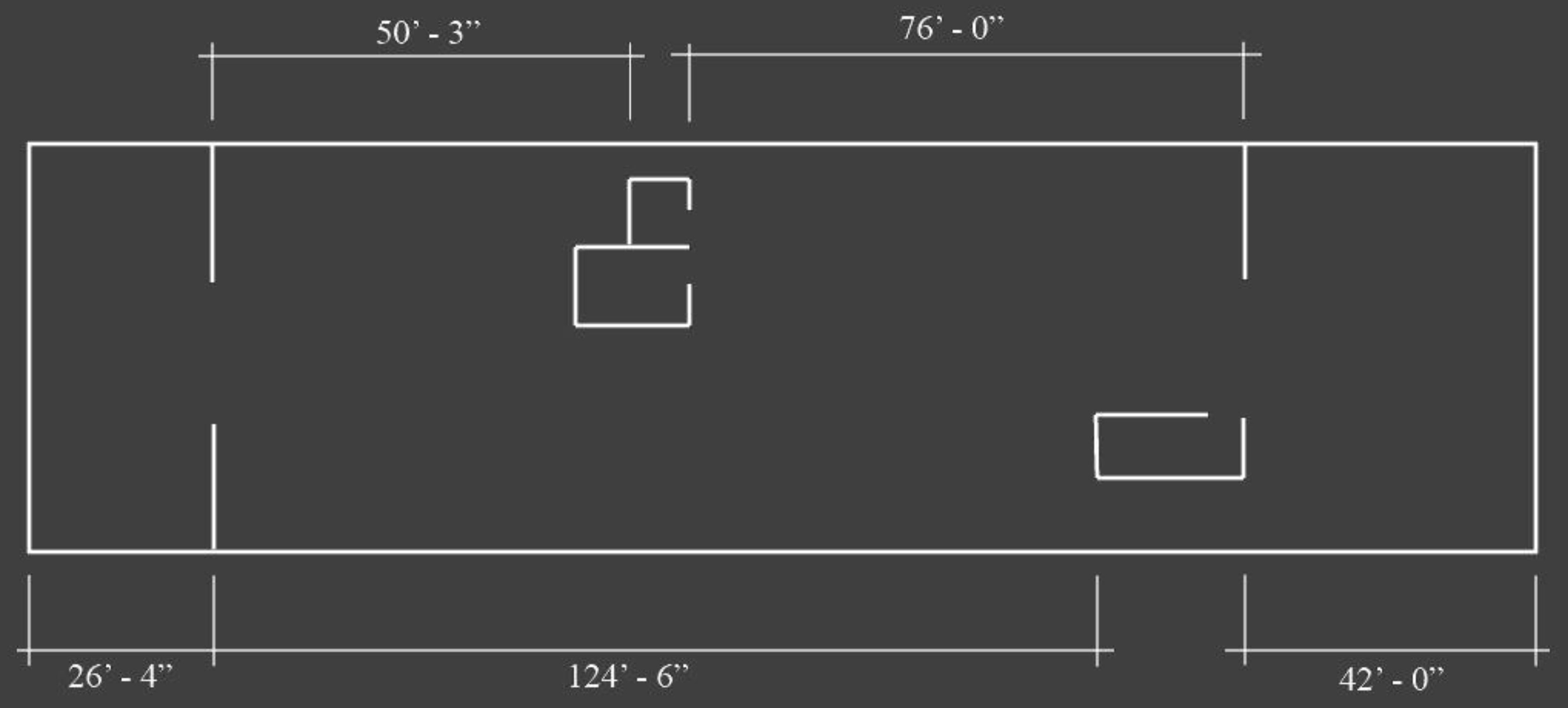


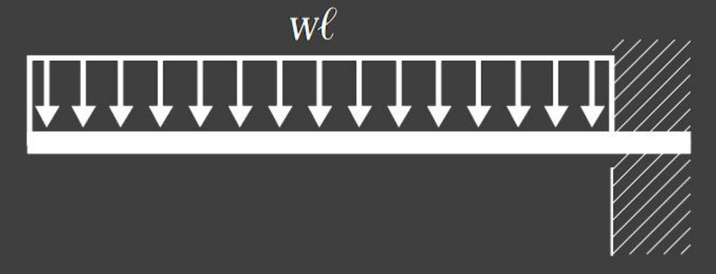
## Lateral Redesign

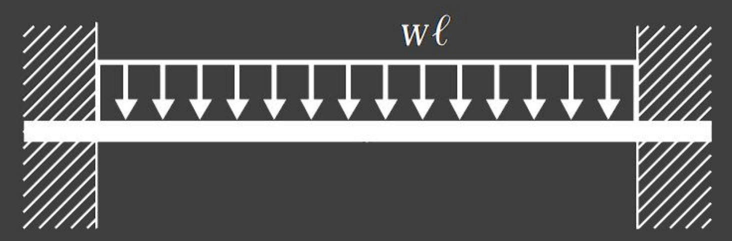
- Lateral Introduction
- Lateral System Behavior
- Shear Wall Design
- Lateral Design Summary




### In-Plane Deflections

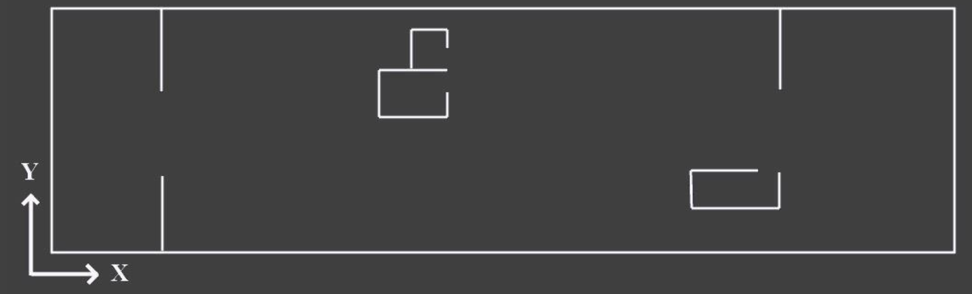


# Lateral Redesign

- Lateral Introduction
- Lateral System Behavior
- Shear Wall Design
- Lateral Design Summary

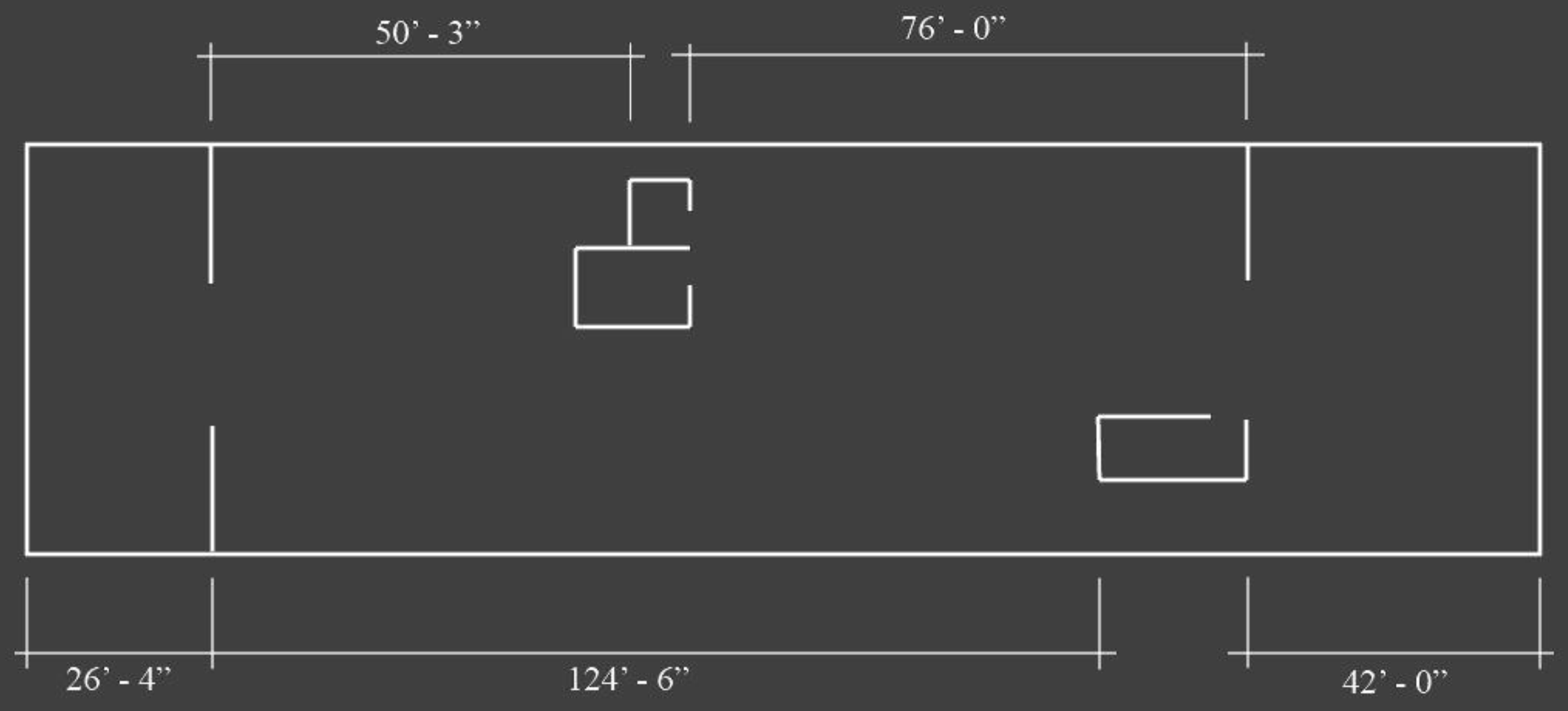


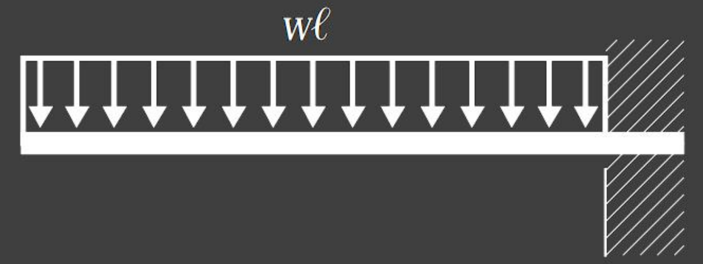

## In-Plane Deflections

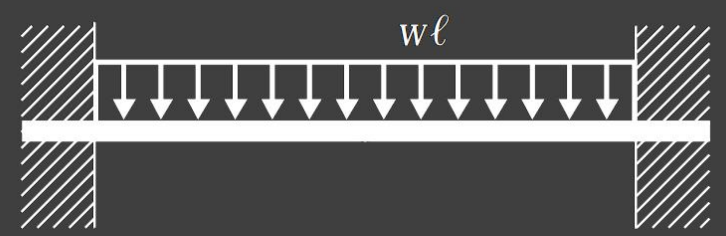
- From ETABS Model
- Compare to L/360

**In-Plane Floor Deflection Checks**

| Location | "Length" | Max Displ. | Avg. lat. Disp. | Eff. Disp. | allowable disp. | OK? |
|---|---|---|---|---|---|---|
| **Grid 2-3** | 26.3 | 0.901 | 0.078 | 0.823 | 0.877 | ok |
| **Grid 3-5** | 50.25 | 0.270 | 0.220 | 0.050 | 1.675 | ok |
| **Grid 3-9** | 124.5 | 0.26 | 0.108 | 0.152 | 4.150 | ok |
| **Grid 6a-10** | 76 | 0.178 | 0.225 | -0.047 | 2.533 | ok |
| **Grid 10-12** | 42 | 1.58 | 0.190 | 1.39 | 1.400 | ok |

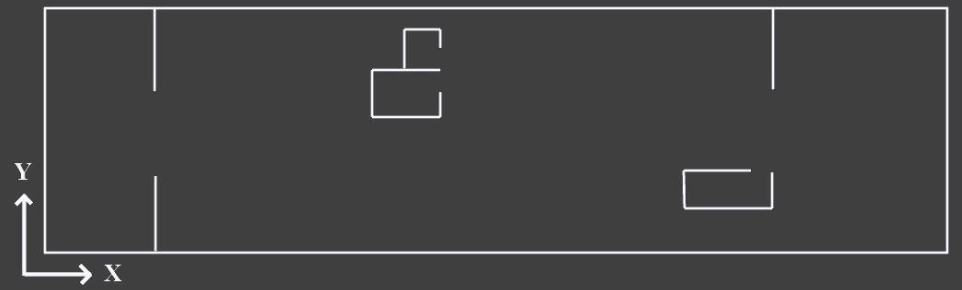


## Lateral Redesign

- Lateral Introduction
- Lateral System Behavior
- Shear Wall Design
- Lateral Design Summary

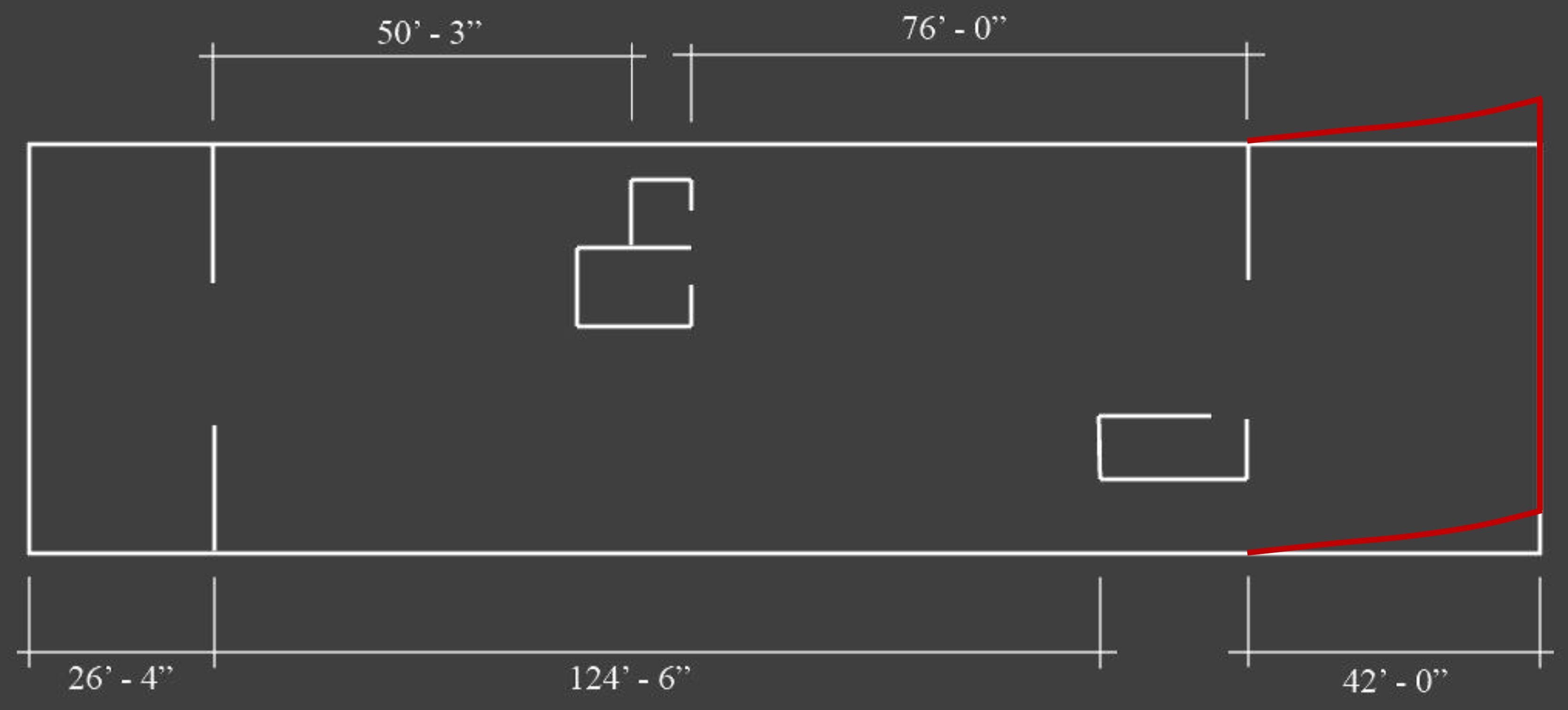


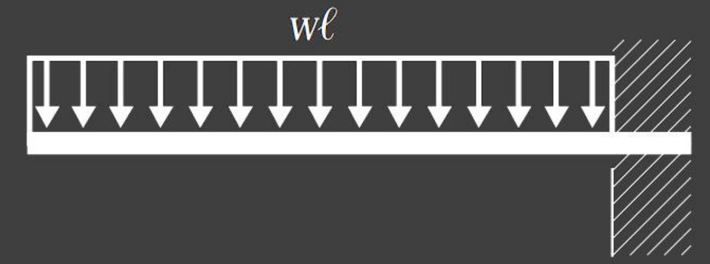

## In-Plane Deflections

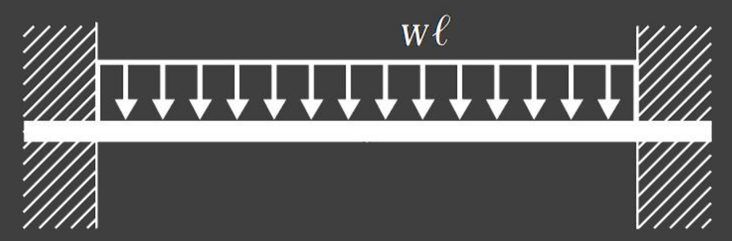
- From ETABS Model
- Compare to L/360

**In-Plane Floor Deflection Checks**

| Location | "Length" | Max Displ. | Avg. lat. Disp. | Eff. Disp. | allowable disp. | OK? |
|---|---|---|---|---|---|---|
| **Grid 2-3** | 26.3 | 0.901 | 0.078 | 0.823 | 0.877 | ok |
| **Grid 3-5** | 50.25 | 0.270 | 0.220 | 0.050 | 1.675 | ok |
| **Grid 3-9** | 124.5 | 0.26 | 0.108 | 0.152 | 4.150 | ok |
| **Grid 6a-10** | 76 | 0.178 | 0.225 | -0.047 | 2.533 | ok |
| **Grid 10-12** | 42 | 1.58 | 0.190 | 1.39 | 1.400 | ok |

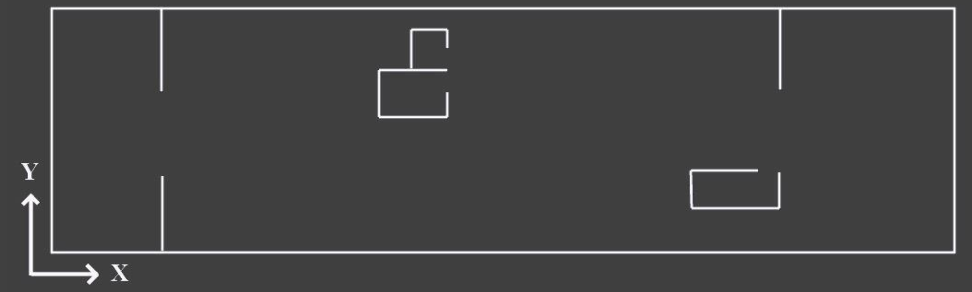


# Lateral Redesign

- Lateral Introduction
- Lateral System Behavior
- Shear Wall Design
- Lateral Design Summary



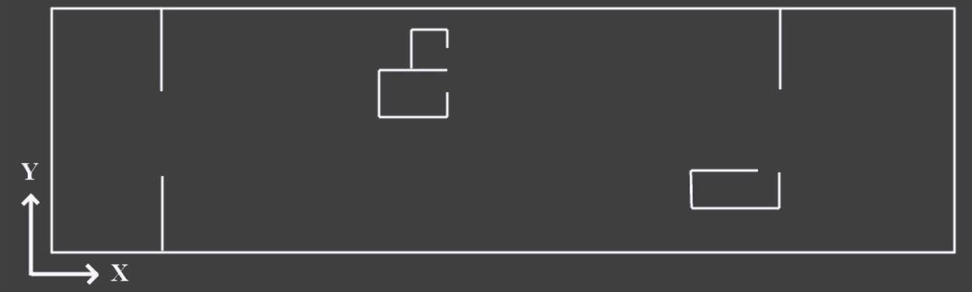

## Drift Check (L/400)

- Deflection of Lateral Elements Only

| Drift Check at Shear Walls | | | | | | | |
|---|---|---|---|---|---|---|---|
| Shear Wall | Height (ft) | X-direction | | Y-direction | | Allow. | Drift |
| | | Disp. | Drift | Displ. | Drift | Drift | Check |
| Elev/ Stair Core | 80 | 0.135 | 0.000141 | 0.542 | 0.000565 | 0.003 | ok |
| Stair Core | 80 | 0.123 | 0.000128 | 0.238 | 0.000248 | 0.003 | ok |
| Grid 3 AB | 63.3 | 0.078 | 0.000103 | 0.087 | 0.000115 | 0.003 | ok |
| Grid 3 CD | 63.3 | 0.11 | 0.000145 | 0.066 | 0.000087 | 0.003 | ok |
| Grid 10 | 63.3 | 0.105 | 0.000138 | 0.265 | 0.000349 | 0.003 | ok |

## Lateral Redesign

- Lateral Introduction
- Lateral System Behavior
- Shear Wall Design
- Lateral Design Summary




## Drift Check (L/400)

- Deflection of Lateral Elements Only

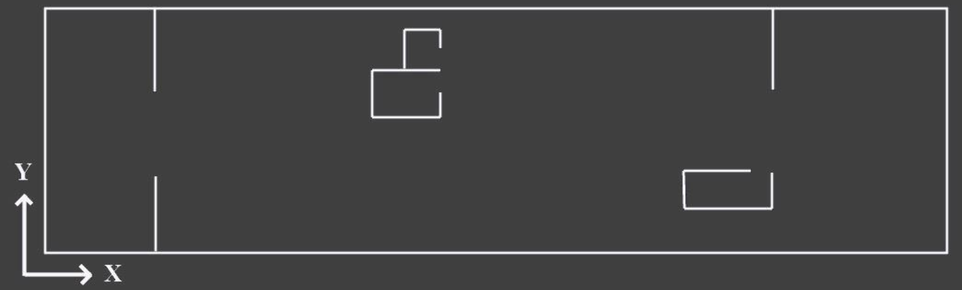
| Drift Check at Shear Walls | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Shear Wall | Height (ft) | X-direction | | Y-direction | | Allow. | Drift |
| | | Disp. | Drift | Displ. | Drift | Drift | Check |
| Elev/ Stair Core | 80 | 0.135 | 0.000141 | 0.542 | 0.000565 | 0.003 | ok |
| Stair Core | 80 | 0.123 | 0.000128 | 0.238 | 0.000248 | 0.003 | ok |
| Grid 3 AB | 63.3 | 0.078 | 0.000103 | 0.087 | 0.000115 | 0.003 | ok |
| Grid 3 CD | 63.3 | 0.11 | 0.000145 | 0.066 | 0.000087 | 0.003 | ok |
| Grid 10 | 63.3 | 0.105 | 0.000138 | 0.265 | 0.000349 | 0.003 | ok |

- Drift due to both Diaphragm and Lateral Elements
- 1.0D + 0.5L + 0.7W for total building drift

| Overal Drift Check (Including Diphragm Deflection | | | | | |
|---|---|---|---|---|---|
| Level | Height (ft) | Disp. | Drift | Allow. | Check |
| Penthouse | 80 | 0.42 | 0.00044 | 0.0025 | ok |
| Level 12 | 63.33 | 1.5 | 0.00197 | 0.0025 | ok |

## Lateral Redesign

- Lateral Introduction
- Lateral System Behavior
- Shear Wall Design
- Lateral Design Summary




## Drift Check (L/400)

- Deflection of Lateral Elements Only

**Drift Check at Shear Walls**

| Shear Wall | Height (ft) | X-direction | | Y-direction | | Allow. | Drift |
|---|---|---|---|---|---|---|---|
| | | Disp. | Drift | Displ. | Drift | Drift | Check |
| **Elev/ Stair Core** | 80 | 0.135 | 0.000141 | 0.542 | 0.000565 | 0.003 | ok |
| **Stair Core** | 80 | 0.123 | 0.000128 | 0.238 | 0.000248 | 0.003 | ok |
| **Grid 3 AB** | 63.3 | 0.078 | 0.000103 | 0.087 | 0.000115 | 0.003 | ok |
| **Grid 3 CD** | 63.3 | 0.11 | 0.000145 | 0.066 | 0.000087 | 0.003 | ok |
| **Grid 10** | 63.3 | 0.105 | 0.000138 | 0.265 | 0.000349 | 0.003 | ok |

- Drift due to both Diaphragm and Lateral Elements
- 1.0D + 0.5L + 0.7W for total building drift
- 3/8" interstory drift for non-structural elements

**Overal Drift Check (Including Diphragm Deflection**

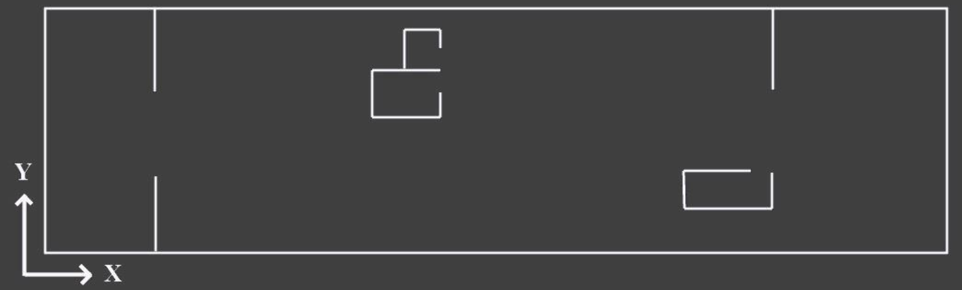
| Level | Height (ft) | Disp. | Drift | Allow. | Check |
|---|---|---|---|---|---|
| **Penthouse** | 80 | 0.42 | 0.00044 | 0.0025 | ok |
| **Level 12** | 63.33 | 1.5 | 0.00197 | 0.0025 | ok |

**Interstory Drift**

| Level | Height (ft) | Disp. | Allow. (in) | Check |
|---|---|---|---|---|
| **Penthouse** | 80 | 0.16 | 0.375 | ok |
| **Level 12** | 63.33 | 0.37 | 0.375 | ok |
| **Level 11** | 51.33 | 0.13 | 0.375 | ok |
| **Level 10** | 41.33 | 0.07 | 0.375 | ok |
| **Level 9** | 31 | 0.08 | 0.375 | ok |
| **Level 8** | 20 | 0.18 | 0.375 | ok |
| **Level 7** | 10.33 | 0.66 | 0.375 | No Good |

# Lateral Redesign

- Lateral Introduction
- Lateral System Behavior
- Shear Wall Design
- Lateral Design Summary




## Drift Check (L/400)

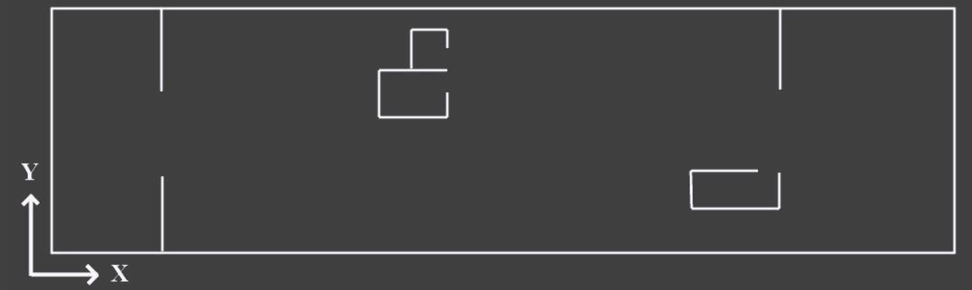
- Deflection of Lateral Elements Only

| Drift Check at Shear Walls | | | | | | | |
|---|---|---|---|---|---|---|---|
| Shear Wall | Height (ft) | X-direction | | Y-direction | | Allow. | Drift |
| | | Disp. | Drift | Displ. | Drift | Drift | Check |
| Elev/ Stair Core | 80 | 0.135 | 0.000141 | 0.542 | 0.000565 | 0.003 | ok |
| Stair Core | 80 | 0.123 | 0.000128 | 0.238 | 0.000248 | 0.003 | ok |
| Grid 3 AB | 63.3 | 0.078 | 0.000103 | 0.087 | 0.000115 | 0.003 | ok |
| Grid 3 CD | 63.3 | 0.11 | 0.000145 | 0.066 | 0.000087 | 0.003 | ok |
| Grid 10 | 63.3 | 0.105 | 0.000138 | 0.265 | 0.000349 | 0.003 | ok |

- Drift due to both Diaphragm and Lateral Elements
- 1.0D + 0.5L + 0.7W for total building drift
- 3/8" interstory drift for non-structural elements

| Overal Drift Check (Including Diphragm Deflection | | | | | |
|---|---|---|---|---|---|
| Level | Height (ft) | Disp. | Drift | Allow. | Check |
| Penthouse | 80 | 0.42 | 0.00044 | 0.0025 | ok |
| Level 12 | 63.33 | 1.5 | 0.00197 | 0.0025 | ok |

| Interstory Drift | | | | |
|---|---|---|---|---|
| Level | Height (ft) | Disp. | Allow. (in) | Check |
| Penthouse | 80 | 0.16 | 0.375 | ok |
| Level 12 | 63.33 | 0.37 | 0.375 | ok |
| Level 11 | 51.33 | 0.13 | 0.375 | ok |
| Level 10 | 41.33 | 0.07 | 0.375 | ok |
| Level 9 | 31 | 0.08 | 0.375 | ok |
| Level 8 | 20 | 0.18 | 0.375 | ok |
| Level 7 | 10.33 | 0.66 | 0.375 | No Good |

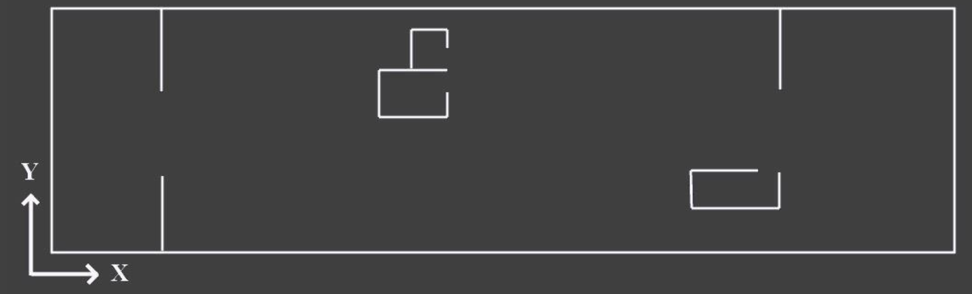



## Overturning Moment

- Has been an issue in taller wood buildings due to low mass
- Typically design for uplift
- Original concrete portion very heavy
- OTM not an issue for this building

# Lateral Redesign

- Lateral Introduction
- Lateral System Behavior
- Shear Wall Design
- Lateral Design Summary




## Hand Spot Check of Shear Wall Design

- Checked at critical section
- Enough concrete for shear
- Minimum reinforcing provided in field of wall
- Design controlled by flexure
- Reinforcing required at ends

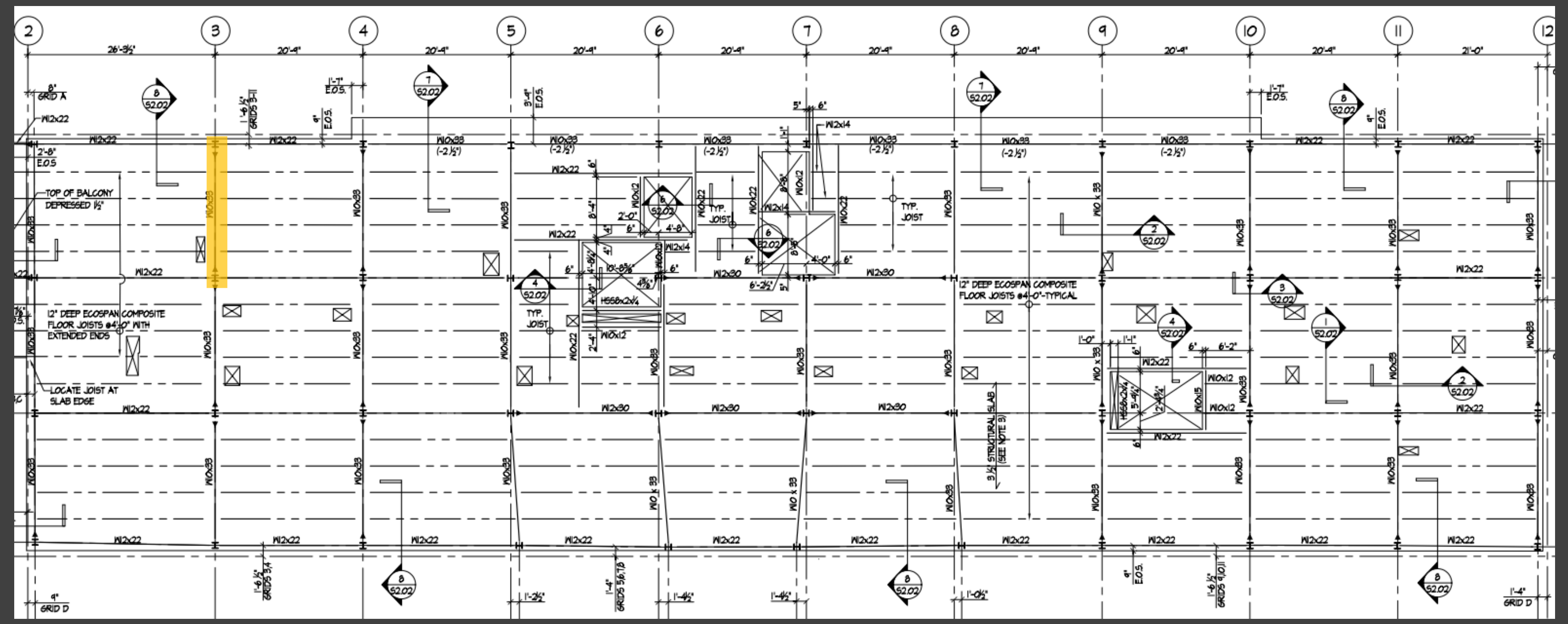
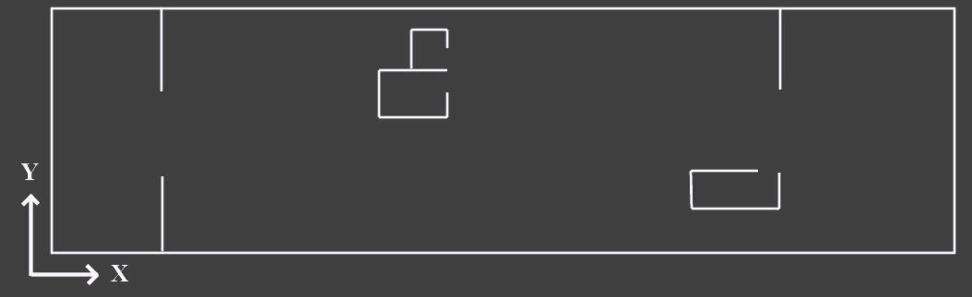
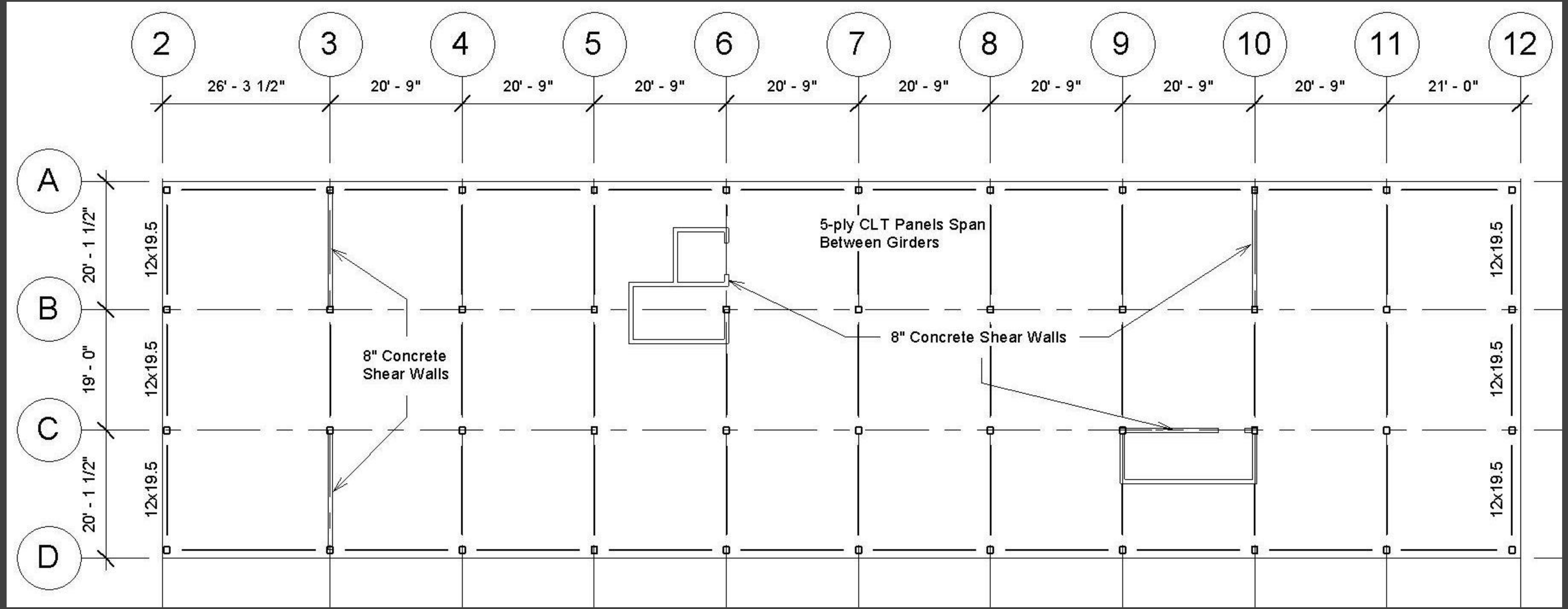


Image Source: Structural Building Documents

# Lateral Redesign

- Lateral Introduction
- Lateral System Behavior
- Shear Wall Design
- Lateral Design Summary




## Wall Design

- 8" concrete wall w/ 2 curtains rebar
- #4's at 18" o.c. Vertical
- #4's at 10" o.c. Horizontal
- Typ. #6's in the Corners and Ends

# Construction Management

- Introduction
- Schedule Analysis
- Cost Analysis
- System Comparison

Breadth Topics:

- Mechanical
  - No concealed spaces, mechanical is exposed
  - Chose new mechanical system
- Construction Management
  - Schedule Analysis
  - Cost Analysis

## Construction Management

- Introduction
- Schedule Analysis
- Cost Analysis
- System Comparison

### CM Scope

- Structure in Addition
- Partitions
- Shear walls for full building
- Sound insulation

## Construction Management

- Introduction
- Schedule Analysis
- Cost Analysis
- System Comparison

### Schedule Assumptions

- Pre-fabricated panels
- CLT not found in RS Means
- Construction similar to precast concrete
- Steel Addition Concrete topping needs to cure

### Estimated Schedule Time:

- Steel: 9 months
- Wood: 4 months

# Construction Management

- Introduction
- Schedule Analysis
- Cost Analysis
- System Comparison

## Cost Assumptions

- CLT product from Structurlam product info
- All other cost information from RS Means
- 5% estimate added to labor (not many CLT buildings in US)
- No addition for waste included due to prefabrication
- Lower General Conditions Costs in Wood

## Estimated Cost:

- Steel: $2.17 Million
- Wood: $2.76 Million

# Construction Management

- Introduction
- Schedule Analysis
- Cost Analysis
- System Comparison

## Schedule Estimate

- Wood Addition: 9 months
- Existing Steel Addition: 4 months
- 5 months shorter for wood addition
- Approx. 19 months to 14 months

## Cost Estimate

- Wood Addition: $2.76 Million ($25 per SF)
- Existing Steel Addition: $2.17 Million ($19 per SF)
- 30% increase for wood addition
- $44 million total cost to $44.59 million (1.5% increase)

## Conclusions

- Summary
- Acknowledgements

### Proposed Goals

- Redesign Addition Gravity System in Wood
- Design appropriate shear wall system for gravity design
- Investigate feasibility of wood in design for fire performance
- Investigate cost and schedule feasibility

# Conclusions

- Summary
- Acknowledgements

## Proposed Goals

- Redesign Addition Gravity System in Wood → Gravity system met goals for redesign
- Design appropriate shear wall system for gravity design
- Investigate feasibility of wood in design for fire performance
- Investigate cost and schedule feasibility

# Conclusions

- Summary
- Acknowledgements

## Proposed Goals

- Redesign Addition Gravity System in Wood → Gravity system met goals for redesign
- Design appropriate shear wall system for gravity design → Lateral design met strength and deflection requirements
- Investigate feasibility of wood in design for fire performance
- Investigate cost and schedule feasibility

## Conclusions

- Summary
- Acknowledgements

### Proposed Goals

- Redesign Addition Gravity System in Wood → Gravity system met goals for redesign
- Design appropriate shear wall system for gravity design → Lateral design met strength and deflection requirements
- Investigate feasibility of wood in design for fire performance → Deflection and vibration controlled over fire performance
- Investigate cost and schedule feasibility

# Conclusions

- Summary
- Acknowledgements

## Proposed Goals

- Redesign Addition Gravity System in Wood → Gravity system met goals for redesign
- Design appropriate shear wall system for gravity design → Lateral design met strength and deflection requirements
- Investigate feasibility of wood in design for fire performance → Deflection and vibration controlled over fire performance
- Investigate cost and schedule feasibility → Wood redesign 30% more expensive, but can be built in less than half the schedule

## Conclusions

- Summary
- Acknowledgements

Thank you to the following people:

- The engineers at Rathgeber/Goss Associates
- My parents
- The AE faculty and my advisor Dr. Thomas Boothby
- My classmates and friends

# Thank You

# Appendix

- Appendix Contents

## Gravity System

- Sound and Vibrations
- Typical Opening
- Floor Tables
- Beam Tables
- Column Tables
- Design Values

## Lateral System

- Drift
- In-Place Deflections
- Shear Wall Reinforcement
- Overturning Moment
- Hand Spot Check

## CM Breadth

- CLT Cost Table
- Quantity Tables
- Cost Tables
- Schedule Tables
- Schedule

## Mech Breadth

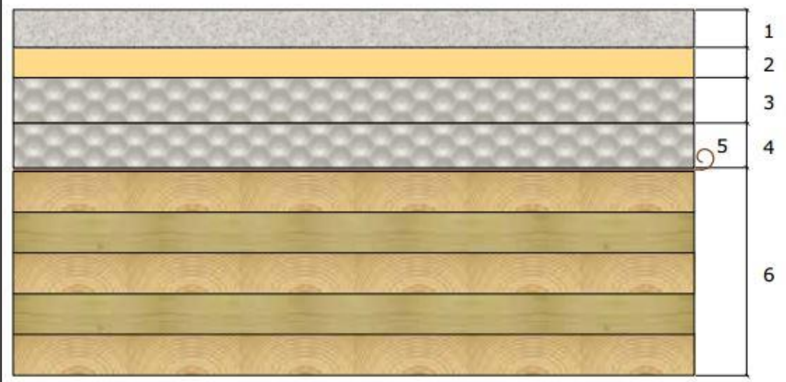
- Plans
- Sample Apartment
- Hand Calculations

# Appendix

- Sound and Vibrations

## Sound Performance

- Topping required for sound insulation
- Additional weight and height included in design




| | Assembly Description from Top to Bottom (7.1) | STC | IIC |
|---|---|---|---|
| 1 | Gypsum fiberboard FERMACELL of 1.0 in. (25 mm) | 62 | 59 |
| 2 | Sub-floor ISOVER EP3 of 0.79 in. (20 mm) | | |
| 3 | Honeycomb acoustic infill FERMACELL of 1.18 in. (30 mm) | | |
| 4 | Honeycomb acoustic infill FERMACELL of 1.18 in. (30 mm) | | |
| 5 | Kraft paper underlayment | | |
| 6 | 5-layer CLT panel of 5 5/16 in. (135 mm) | | |

Image Source: CLT Handbook

## Vibration Performance

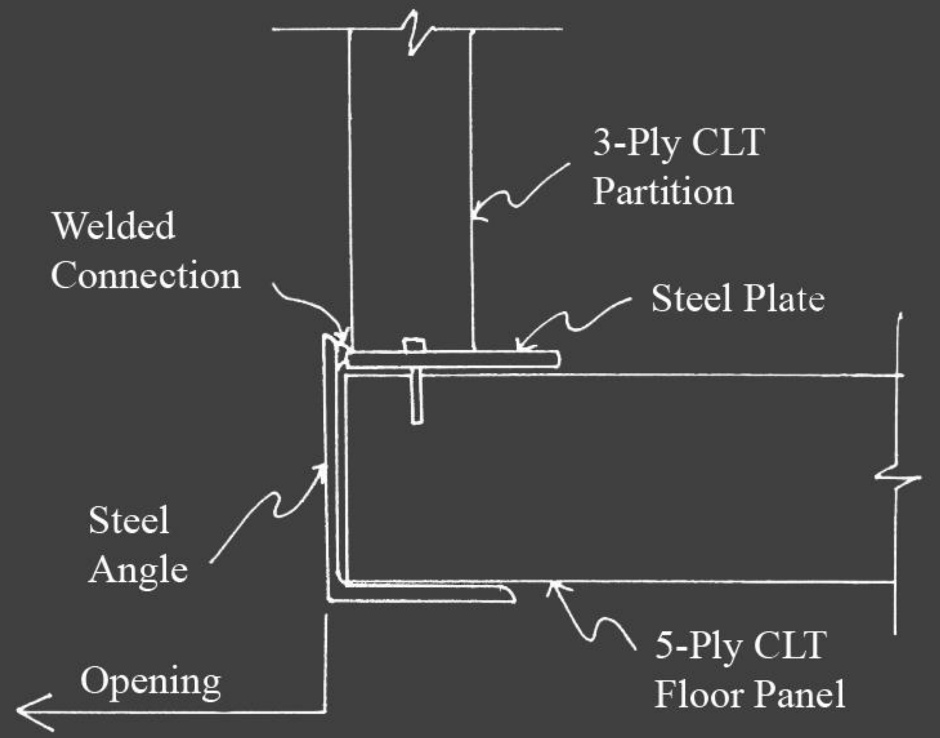
- Single spans isolated apartments from each other
- Vibrations not as important for residential
- Thicker panel required for 12th level, assembly occupation

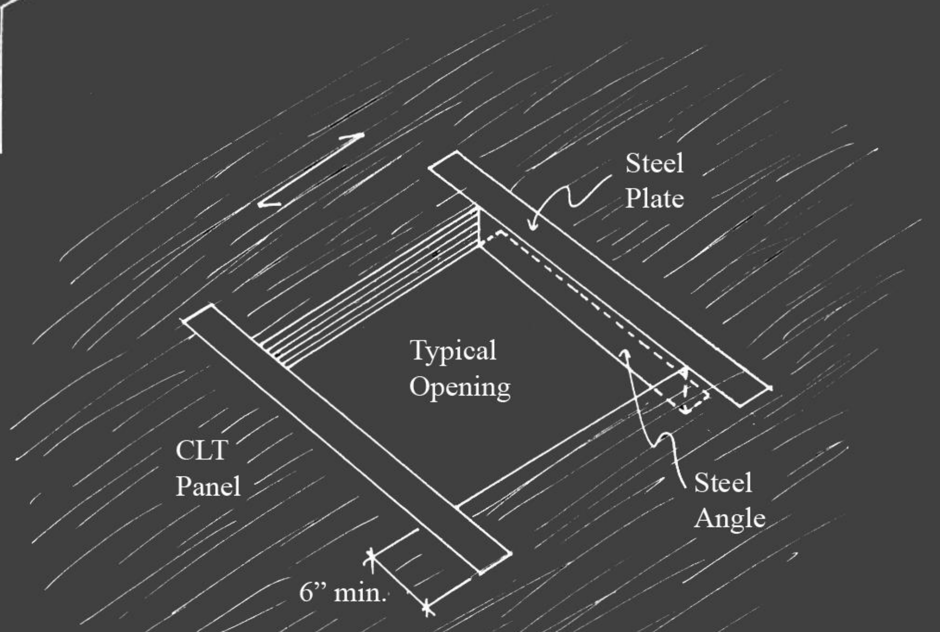
| Type of CLT | Thickness (in.) | Vibration Controlled Span, L (ft.) | Equivalent UDL Criterion |
|---|---|---|---|
| 5-layer (5s) | 5 1/2 | 15.6 | Span/417 |
| 5-layer (5s) | 7 3/16 | 18.0 | Span/497 |
| 7-layer (7ss) | 9 | 23.0 | Span/606 |

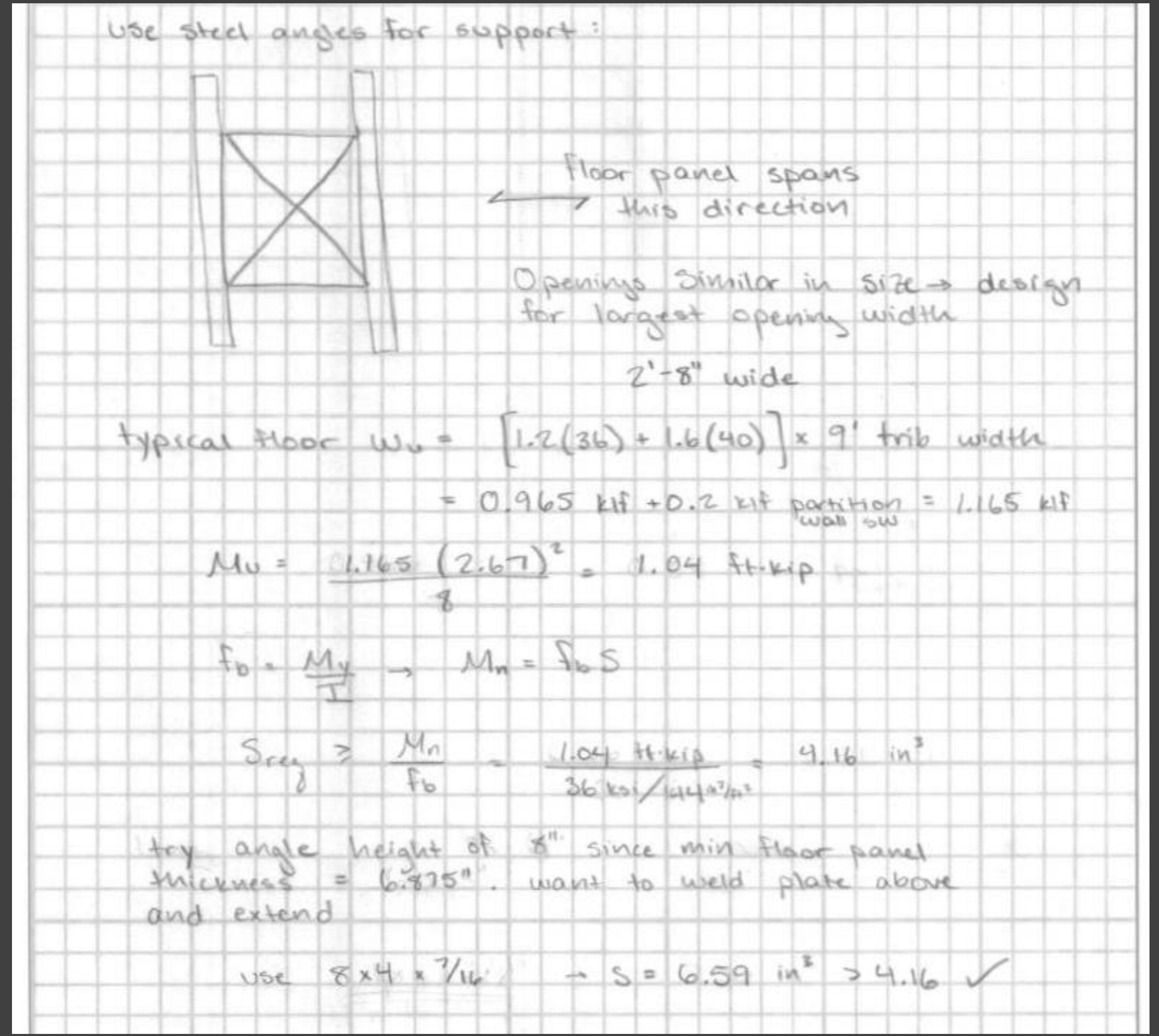
Image Source: CLT Handbook

# Appendix

- Typical Opening



use steel anges for support:

floor panel spans this direction

Openings similar in size → design for largest opening width

2'-8" wide

typical floor $w_u = [1.2(36) + 1.6(40)] \times 9'$ trib width

$= 0.965$ klf $+ 0.2$ klf partition wall sw $= 1.165$ klf

$M_u = \frac{1.165\,(2.67)^2}{8} = 1.04$ ft-kip

$f_b = \frac{My}{I} \rightarrow M_n = f_b S$

$S_{req} \geq \frac{M_n}{f_b} = \frac{1.04 \text{ ft-kip}}{36 \text{ ksi}/144 \text{ in}^2/\text{ft}^2} = 4.16 \text{ in}^3$

try angle height of 8" since min floor panel thickness = 6.875". want to weld plate above and extend

use $8 \times 4 \times 7/16$ → $S = 6.59 \text{ in}^3 > 4.16$ ✓

# Appendix

- Floor Tables

| Typical CLT Floor Panel Design | | | | | | | |
|---|---|---|---|---|---|---|---|
| Strength Checks | | | | | | | |
| Level | Span | Panel | FbSeff* | D+L* | Cd | M | Ok? |
| Typical Level | 20.8 | 5-ply | 10400 | 76 | 1 | 4090.3 | good |
| 12th Level | 20.8 | 7-ply | 18375 | 140 | 1 | 7534.8 | good |
| Penthouse Roof | 20.8 | 5-ply | 10400 | 66 | 1 | 3552.1 | good |

*9-ply would have higher FbSeff, however value was not tabulated and 7-ply value worked,

| Deflection Checks | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Level | Span | Panel | EI | D | L | Defl L | Defl D+L | L limit | D+L limt | L OK? | D OK? |
| Typical Level | 20.8 | 5-ply | 4.40E+08 | 36 | 40 | 0.38 | 1.03 | 0.69 | 1.04 | good | good |
| 12th Level | 20.8 | 7-ply | 1.09E+09 | 40 | 100 | 0.38 | 0.69 | 0.69 | 1.04 | good | good |
| Penthouse Roof | 20.8 | 5-ply | 4.40E+08 | 36 | 30 | 0.28 | 0.97 | 0.69 | 1.04 | good | good |

| Fire Design Check | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Level | Span | Panel | Orig. h | Resid. H | Approx | FbSeff | D+L* | M | OK? |
| Typical Level | 26 | 5-ply | 9.625 | 7.125 | 5-ply | 10400 | 43 | 3634 | good |
| 12th Level | 26 | 7-ply | 12.375 | 9.875 | 7-ply | 18375 | 70 | 5915 | good |
| Penthouse Roof | 26 | 5-ply | 9.625 | 7.125 | 5-ply | 10400 | 39 | 3296 | good |

*D+L is reduced using the same assumptions as before

| Non Typical CLT Floor Panel Design | | | | | | | |
|---|---|---|---|---|---|---|---|
| Strength Checks | | | | | | | |
| Level | Span | Panel | FbSeff* | D+L* | Cd | M | Ok? |
| Typical Level | 26 | 7-ply | 18375 | 80 | 1 | 6760 | good |
| 12th Level | 26 | 9-ply | 18375 | 144 | 1 | 12168 | good |
| Penthouse Roof | 26 | 7-ply | 18375 | 70 | 1 | 5915 | good |

*D+L controlled over other combinations
*9-ply would have higher FbSeff, however value was not tabulated and 7-ply value worked, so new FbSeff was not calculated to save time

| Deflection Checks | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Level | Span | Panel | EI | D | L | Defl L | Defl D+L | L limit | D+L limt | L OK? | D OK? |
| Typical Level | 26 | 7-ply | 1.09E+09 | 40 | 40 | 0.38 | 1.13 | 0.87 | 1.30 | good | good |
| 12th Level | 26 | 9-ply | 1.60E+09 | 44 | 100 | 0.64 | 1.21 | 0.87 | 1.30 | good | good |
| Penthouse Roof | 26 | 7-ply | 1.09E+09 | 40 | 30 | 0.28 | 1.04 | 0.87 | 1.30 | good | good |

| Fire Design Check | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Level | Span | Panel | Orig. h | Resid. H | Approx | FbSeff | D+L* | M | OK? |
| Typical Level | 26 | 7-ply | 9.625 | 7.125 | 5-ply | 10400 | 46 | 3887 | good |
| 12th Level | 26 | 9-ply | 12.375 | 9.875 | 7-ply | 18375 | 73 | 6169 | good |
| Penthouse Roof | 26 | 7-ply | 9.625 | 7.125 | 5-ply | 10400 | 42 | 3549 | good |

*D+L is reduced using the same assumptions as before

# Appendix

- Girder Tables

| | bw | bf | dc | dt | dtc | NA | I | St | Sb | EI |
|---|---|---|---|---|---|---|---|---|---|---|
| Normal Conditions | 4 | 12 | 6.875 | 27 | 20.125 | 11.44 | 12758.8 | 820.1 | 1115.0 | 2.30E+10 |
| | 4 | 12 | 6.875 | 25.5 | 18.625 | 10.71 | 10549.8 | 713.3 | 985.1 | 1.90E+10 |
| | 4 | 12 | 6.875 | 24 | 17.125 | 9.98 | 8623.1 | 615.0 | 864.1 | 1.55E+10 |
| | 4 | 12 | 6.875 | 22.5 | 15.625 | 9.25 | 6958.3 | 525.2 | 752.1 | 1.25E+10 |
| | 4 | 12 | 6.875 | 21 | 14.125 | 8.53 | 5535.1 | 443.8 | 649.0 | 9.96E+09 |
| | 4 | 12 | 6.875 | 19.5 | 12.625 | 7.81 | 4333.2 | 370.7 | 554.8 | 7.80E+09 |
| | 4 | 12 | 6.875 | 18 | 11.125 | 7.10 | 3332.2 | 305.7 | 469.3 | 6.00E+09 |
| | 4 | 12 | 6.875 | 16.5 | 9.625 | 6.40 | 2511.8 | 248.7 | 392.5 | 4.52E+09 |
| | 4 | 12 | 6.875 | 15 | 8.125 | 5.71 | 1851.3 | 199.3 | 324.1 | 3.33E+09 |
| | 4 | 12 | 6.875 | 13.5 | 6.625 | 5.05 | 1330.0 | 157.4 | 263.5 | 2.39E+09 |
| | 4 | 12 | 6.875 | 12 | 5.125 | 4.42 | 927.0 | 122.2 | 209.9 | 1.67E+09 |
| | 4 | 12 | 6.875 | 10.5 | 3.625 | 3.85 | 620.3 | 93.2 | 161.3 | 1.12E+09 |
| Residual Section during Fire | 4 | 7 | 6.875 | 24.5 | 17.625 | 11.05 | 6676.6 | 496.2 | 604.5 | 1.20E+10 |
| | 4 | 7 | 6.875 | 23 | 16.125 | 10.32 | 5478.5 | 431.9 | 531.1 | 9.86E+09 |
| | 4 | 7 | 6.875 | 21.5 | 14.625 | 9.59 | 4438.1 | 372.6 | 462.8 | 7.99E+09 |
| | 4 | 7 | 6.875 | 20 | 13.125 | 8.87 | 3543.7 | 318.3 | 399.7 | 6.38E+09 |
| | 4 | 7 | 6.875 | 18.5 | 11.625 | 8.15 | 2783.4 | 268.9 | 341.6 | 5.01E+09 |
| | 4 | 7 | 6.875 | 17 | 10.125 | 7.44 | 2145.3 | 224.4 | 288.4 | 3.86E+09 |
| | 4 | 7 | 6.875 | 15.5 | 8.625 | 6.74 | 1617.4 | 184.6 | 240.1 | 2.91E+09 |
| | 4 | 7 | 6.875 | 14 | 7.125 | 6.05 | 1187.9 | 149.4 | 196.3 | 2.14E+09 |
| | 4 | 7 | 6.875 | 12.5 | 5.625 | 5.38 | 844.6 | 118.7 | 156.9 | 1.52E+09 |
| | 4 | 7 | 6.875 | 11 | 4.125 | 4.75 | 575.3 | 92.0 | 121.2 | 1.04E+09 |
| | 4 | 7 | 6.875 | 9.5 | 2.625 | 4.16 | 367.4 | 68.8 | 88.3 | 6.61E+08 |
| | 4 | 7 | 6.875 | 8 | 1.125 | 3.67 | 207.1 | 47.9 | 56.4 | 3.73E+08 |

**Typical Girder Redesign for Inverted T-Shape**

| | Level | Span | Gird. sw | Floor L+D | D+L** | M (in-lbs) | bf | bw | Depth | Cv | Sact | Sreq | OK? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Strength Design | Typical Level | 20 | 26 | 700 | 726 | 435600 | 12 | 4 | 15 | 0.90 | 324.1 | 201.1 | good |
| | 12th Level | 20 | 50 | 1400 | 1450 | 870000 | 12 | 4 | 18 | 0.89 | 469.3 | 409.0 | good |
| | Penthouse Roof | 20 | 50 | 660 | 710 | 426000 | 12 | 4 | 15 | 0.90 | 324.1 | 196.7 | good |

| | Level | Span | L (plf) | D+L | EI | Defl. L | Defl. D+L | Lim. L | Lim. D+L | L OK? | D+L OK? |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Defl. Design | Typical Level | 20 | 400 | 726 | 3.33E+09 | 0.432 | 0.96 | 0.667 | 1.0 | good | good |
| | 12th Level | 20 | 1000 | 1450 | 6.00E+09 | 0.600 | 1.00 | 0.667 | 1.0 | good | good |
| | Penthouse Roof | 20 | 300 | 710 | 3.33E+09 | 0.324 | 0.989 | 0.667 | 1.0 | good | good |

| | Level | Span | D+L | Orig w | Orig h | Resid w | Resid h | Seff | Red. Load | M (in-lb) | Sreq | OK? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fire/ Char Design | Typical Level | 20 | 726 | 12 | 15 | 7 | 12.5 | 182.3 | 404.5 | 242700 | 70 | good |
| | 12th Level | 20 | 1450 | 12 | 18 | 7 | 15.5 | 280.3 | 737.5 | 442500 | 130 | good |
| | Penthouse Roof | 20 | 710 | 12 | 15 | 7 | 12.5 | 182.3 | 427.5 | 256500 | 74 | good |

*Or along Grid 4 at 12th Level and Penthouse

# Appendix

- Girder Tables

**Perimeter Girder Along Grid 2* (West side)**

| | Level | Span | Wall sw | Gird. sw | Floor L+D | D+L** | M (in-lbs) | bf | Depth | Cv | Sact | Sreq | OK? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Strength Design | Typical Level | 20 | 450 | 50 | 1092 | 1592 | 955200 | 12 | 19.5 | 0.88 | 554.8 | 452.7 | good |
| | 12th Level parapet | 20 | 200 | 50 | 1872 | 2122 | 1273200 | 12 | 21 | 0.87 | 649.0 | 607.9 | good |
| | 12th Level penthouse | 20 | 350 | 50 | 2880 | 3280 | 1968000 | 12 | 25.5 | 0.86 | 985.1 | 958.0 | good |
| | Penthouse Roof | 20 | 200 | 50 | 962 | 1212 | 727200 | 12 | 18 | 0.89 | 469.3 | 341.9 | good |

| | Level | Span | L (plf) | D+L | EI | Defl. L | Defl. D+L | Lim. L | Lim. D+L | L OK? | D+L OK? |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Defl. Design | Typical Level | 20 | 520 | 1592 | 7.80E+09 | 0.240 | 0.982 | 0.667 | 1 | good | good |
| | 12th Level parapet | 20 | 1300 | 2122 | 9.96E+09 | 0.470 | 0.915 | 0.667 | 1 | good | good |
| | 12th Level penthouse | 20 | 2000 | 3280 | 1.90E+10 | 0.379 | 0.743 | 0.667 | 1 | good | good |
| | Penthouse Roof | 20 | 390 | 1212 | 6.00E+09 | 0.234 | 0.974 | 0.667 | 1 | good | good |

| | Level | Span | D+L | Orig w | Orig h | Resid bf | Resid h | Resid bw | Seff | Red. Load | M (in-lb) | Sreq | OK? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fire/ Char Design | Typical Level | 20 | 1592 | 12 | 19.5 | 7 | 17 | 4 | 240.1 | 1012.0 | 607200 | 179.9 | good |
| | 12th Level parapet | 20 | 2122 | 12 | 21 | 7 | 18.5 | 4 | 341.6 | 1136.5 | 681900 | 203.5 | good |
| | 12th Level penthouse | 20 | 3280 | 12 | 25.5 | 7 | 23 | 4 | 531.1 | 1280.0 | 768000 | 233.7 | good |
| | Penthouse Roof | 20 | 1212 | 12 | 18 | 7 | 15.5 | 4 | 196.3 | 772.5 | 463500 | 136.2 | good |

*Or along Grid 4 at 12th Level and Penthouse

**D+L was the controlling case for other girders, and will therefore be the only case considered in non typical giders

**Perimeter Girder Along Grid 12* (East side)**

| | Level | Span | Wall sw | Gird. sw | Floor L+D | D+L** | M (in-lbs) | bf | Depth | Cv | Sact | Sreq | OK? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Strength Design | Typical Level | 20 | 450 | 50 | 840 | 1340 | 804000 | 12 | 19.5 | 0.88 | 554.8 | 381.0 | good |
| | 12th Level parapet | 20 | 200 | 50 | 1512 | 1762 | 1057200 | 12 | 19.5 | 0.88 | 554.8 | 501.0 | good |
| | 12th Level penthouse | 20 | 350 | 50 | 2880 | 3280 | 1968000 | 12 | 25.5 | 0.86 | 985.1 | 958.0 | good |
| | Penthouse Roof | 20 | 200 | 50 | 735 | 985 | 591000 | 12 | 18 | 0.89 | 469.3 | 277.9 | good |

| | Level | Span | L (plf) | D+L | EI | Defl. L | Defl. D+L | Lim. L | Lim. D+L | L OK? | D+L OK? |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Defl. Design | Typical Level | 20 | 420 | 1340 | 7.80E+09 | 0.194 | 0.831 | 0.667 | 1 | good | good |
| | 12th Level parapet | 20 | 1050 | 1762 | 7.80E+09 | 0.485 | 0.978 | 0.667 | 1 | good | good |
| | 12th Level penthouse | 20 | 2000 | 3280 | 1.90E+10 | 0.379 | 0.743 | 0.667 | 1 | good | good |
| | Penthouse Roof | 20 | 315 | 985 | 6.00E+09 | 0.189 | 0.792 | 0.667 | 1 | good | good |

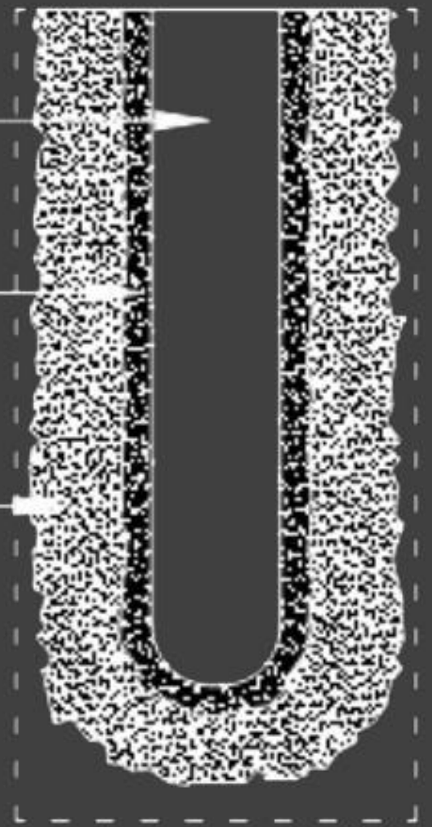
| | Level | Span | D+L | Orig w | Orig h | Resid bf | Resid h | Resid bw | Seff | Red. Load | M (in-lb) | Sreq | OK? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fire/ Char Design | Typical Level | 20 | 1340 | 12 | 19.5 | 7 | 17 | 4 | 240.1 | 858.0 | 514800 | 152 | good |
| | 12th Level parapet | 20 | 1762 | 12 | 19.5 | 7 | 17 | 4 | 288.4 | 954.0 | 572400 | 170 | good |
| | 12th Level penthouse | 20 | 3280 | 12 | 25.5 | 7 | 23 | 4 | 531.1 | 1280.0 | 768000 | 234 | good |
| | Penthouse Roof | 20 | 985 | 12 | 18 | 7 | 15.5 | 4 | 196.3 | 628.5 | 377100 | 111 | good |

*Or along Grid 4 at 12th Level and Penthouse

**D+L was the controlling case for other girders, and will therefore be the only case considered in non typical giders

# Appendix

- Girder Tables




**Typical Perimeter Girder in the E-W Direction**

| | Level | Span | Wall sw | Gird. Sw | D (plf)* | M (in-lbs) | bw | Depth | Cv | Sact | Sreq | OK? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Strength Design | Typical Level | 21 | 450 | 50 | 500 | 330750 | 12 | 15 | 0.90 | 324.1 | 153.4 | good |
| | 12th Level parapet | 21 | 200 | 50 | 250 | 165375 | 12 | 13 | 0.91 | 209.9 | 75.6 | good |
| | 12th Level penthouse | 21 | 350 | 50 | 400 | 264600 | 12 | 15 | 0.90 | 324.1 | 122.7 | good |
| | Penthouse Roof | 21 | 200 | 50 | 250 | 165375 | 12 | 13 | 0.91 | 209.9 | 75.6 | good |

| | Level | Span | D (plf)* | EI | Defl. | Defl. Lim. | OK? |
|---|---|---|---|---|---|---|---|
| Defl. Design | Typical Level | 21 | 500 | 3.33E+09 | 0.985 | 1.05 | good |
| | 12th Level parapet | 21 | 250 | 1.67E+09 | 0.983 | 1.05 | good |
| | 12th Level penthouse | 21 | 400 | 3.33E+09 | 0.788 | 1.05 | good |
| | Penthouse Roof | 21 | 250 | 1.67E+09 | 0.983 | 1.05 | good |

| | Level | Span | D (plf)* | Orig w | Orig h | Resid w | Resid h | Seff | Red. Load | M (in-lb) | Sreq | OK? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fire/ Char Design | Typical Level | 21 | 500 | 12 | 15 | 7 | 12.5 | 182.3 | 121.2 | 80201 | 23.3 | good |
| | 12th Level parapet | 21 | 250 | 12 | 13 | 7 | 10.5 | 128.6 | 56.4 | 37308 | 10.7 | good |
| | 12th Level penthouse | 21 | 400 | 12 | 15 | 7 | 12.5 | 182.3 | 88.3 | 58422 | 16.9 | good |
| | Penthouse Roof | 21 | 250 | 12 | 13 | 7 | 10.5 | 128.6 | 56.4 | 37308 | 10.7 | good |

*Dead Loads here include approx. girder self-weight and exterior wall load. Floor dead and live loads are assumed to be carried to the typical floor girders by the CLT panel and are not included. Therefore there is no live on carried by this girder type.

Image Source: CLT Handbook

# Appendix

- Column Tables

| Gravity Loads (psf, lbs for SW) | | | |
|---|---|---|---|
| Level | Dead | Live | C. SW (per floor) |
| Typical Level | 36 | 40 | 415 |
| 12th Level | 40 | 100 | 470 |
| Roof | 36 | 30 | 670 |

| Floor Heights (ft) | |
|---|---|
| Typical Level | 10.33 |
| 12th Level | 11.67 |
| Roof | 16.75 |

| Wood Properties | |
|---|---|
| Fc (psi) | 1950 |
| E' (psi) | 1.60E+06 |
| Cm | 1 |
| Cd | 1 |
| Ci | 1 |
| Ct | 1 |
| E'min | 8.50E+05 |

| Column and Ext. Wall Load Information | | | | |
|---|---|---|---|---|
| Col. Type* | Trib Area | Wall Load (lbs) | | |
| | | Typ. Level | 12th Level | Roof |
| Typ. Int. | 415 | 0 | 0 | 4150 |
| Typ. Ext. | 208 | 9338 | 10686 | - |
| A | 285 | 9338 | 10686 | 4150 |
| B | 130 | 10350 | 11845 | - |
| C | 335 | 0 | 0 | 0 |
| D | 300 | 0 | 0 | 0 |
| E | 475 | 0 | 0 | - |
| F | 260 | 10350 | 11845 | - |

# Appendix

- Column Tables

**Column Design: Various Levels, Strength, Fire Performance (See Design Summary for Splicing and Final Sizing Choices)**

| Lev | Type* | D+L (lbs) | width | depth | Cv | F*c | Fce | Fce/F*c | Cp | F'c | fc | str ok? | red. D+L | resid. A | fc (fire) | fire ok? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Level 7 | Typ. Int. | 250555 | 12 | 12.375 | 0.98 | 1917 | 6548 | 3.42 | 0.96 | 1844 | 1687 | 0.915 | 131061 | 51.6 | 2539 | 0.860 |
| | Typ. Ext. | 168079 | 12 | 12.375 | 0.98 | 1917 | 6548 | 3.42 | 0.96 | 1844 | 1132 | 0.614 | 113571 | 51.6 | 2200 | 0.745 |
| | A | 231749 | 12 | 12.375 | 0.98 | 1917 | 6548 | 3.42 | 0.96 | 1844 | 1561 | 0.846 | 149435 | 51.6 | 2895 | 0.981 |
| | B | 133740 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1061 | 0.576 | 99434 | 38.5 | 2583 | 0.877 |
| | C | 199525 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1584 | 0.860 | 102911 | 38.5 | 2673 | 0.907 |
| | D | 179015 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1421 | 0.771 | 92411 | 38.5 | 2400 | 0.815 |
| | E | 249545 | 12 | 12.375 | 0.98 | 1917 | 6548 | 3.42 | 0.96 | 1844 | 1680 | 0.911 | 125884 | 51.6 | 2438 | 0.826 |
| | F | 201340 | 12 | 12.375 | 0.98 | 1917 | 6548 | 3.42 | 0.96 | 1844 | 1356 | 0.735 | 133364 | 51.6 | 2583 | 0.875 |
| Level 8 | Typ. Int. | 218600 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1735 | 0.942 | 112905 | 38.5 | 2933 | 0.995 |
| | Typ. Ext. | 142518 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1131 | 0.614 | 94978 | 38.5 | 2467 | 0.837 |
| | A | 200336 | 12 | 12.375 | 0.98 | 1917 | 6548 | 3.42 | 0.96 | 1844 | 1349 | 0.731 | 127531 | 51.6 | 2470 | 0.837 |
| | B | 113095 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 898 | 0.487 | 83183 | 38.5 | 2161 | 0.733 |
| | C | 173650 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1378 | 0.748 | 88195 | 38.5 | 2291 | 0.777 |
| | D | 155800 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1237 | 0.671 | 79200 | 38.5 | 2057 | 0.698 |
| | E | 213030 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1691 | 0.918 | 105148 | 38.5 | 2731 | 0.927 |
| | F | 170815 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1356 | 0.736 | 111523 | 38.5 | 2897 | 0.983 |
| Level 9 | Typ. Int. | 186645 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1481 | 0.804 | 94749 | 38.5 | 2461 | 0.835 |
| | Typ. Ext. | 116958 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 928 | 0.504 | 76385 | 38.5 | 1984 | 0.673 |
| | A | 168924 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1341 | 0.728 | 105628 | 38.5 | 2744 | 0.931 |
| | B | 92450 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 906 | 0.509 | 66931 | 24.5 | 2732 | 0.959 |
| | C | 147775 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1173 | 0.637 | 73479 | 38.5 | 1909 | 0.648 |
| | D | 132585 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 1300 | 0.730 | 65989 | 24.5 | 2693 | 0.946 |
| | E | 176515 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1401 | 0.761 | 84411 | 38.5 | 2193 | 0.744 |
| | F | 140290 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1113 | 0.605 | 89681 | 38.5 | 2329 | 0.791 |
| Level 10 | Typ. Int. | 154690 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1228 | 0.667 | 76593 | 38.5 | 1989 | 0.675 |
| | Typ. Ext. | 91397 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 896 | 0.503 | 57792 | 24.5 | 2359 | 0.828 |
| | A | 137511 | 10.5 | 12 | 1.00 | 1948 | 5013 | 2.57 | 0.95 | 1842 | 1091 | 0.593 | 83724 | 38.5 | 2175 | 0.738 |
| | B | 71805 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 704 | 0.396 | 50680 | 24.5 | 2069 | 0.726 |
| | C | 121900 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 1195 | 0.672 | 58763 | 24.5 | 2398 | 0.842 |
| | D | 109370 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 1072 | 0.602 | 52778 | 24.5 | 2154 | 0.757 |
| | E | 140000 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 1373 | 0.771 | 63675 | 24.5 | 2599 | 0.913 |
| | F | 109765 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 1076 | 0.605 | 67840 | 24.5 | 2769 | 0.972 |
| Level 11 | Typ. Int. | 122735 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 1203 | 0.676 | 58436 | 24.5 | 2385 | 0.838 |
| | Typ. Ext. | 65837 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 645 | 0.363 | 39200 | 24.5 | 1600 | 0.562 |
| | A | 106099 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 1040 | 0.584 | 61820 | 24.5 | 2523 | 0.886 |
| | B | 51160 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 502 | 0.282 | 34429 | 24.5 | 1405 | 0.493 |
| | C | 96025 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 941 | 0.529 | 44046 | 24.5 | 1798 | 0.631 |
| | D | 86155 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 845 | 0.475 | 39566 | 24.5 | 1615 | 0.567 |
| | E | 103485 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 1015 | 0.570 | 42939 | 24.5 | 1753 | 0.615 |
| | F | 79240 | 8.5 | 12 | 1.02 | 1990 | 3285 | 1.65 | 0.89 | 1780 | 777 | 0.437 | 45999 | 24.5 | 1878 | 0.659 |
| Level 12 | Typ. Int. | 90780 | 8.5 | 10.5 | 1.02 | 1992 | 2574 | 1.29 | 0.84 | 1678 | 1017 | 0.606 | 40280 | 19.3 | 2092 | 0.779 |
| | Typ. Ext. | 40276 | 6.75 | 10.5 | 1.05 | 2039 | 1623 | 0.80 | 0.66 | 1355 | 568 | 0.419 | 20607 | 9.6 | 2141 | 0.988 |
| | A | 74686 | 8.5 | 10.5 | 1.02 | 1992 | 2574 | 1.29 | 0.84 | 1678 | 837 | 0.499 | 39916 | 19.3 | 2074 | 0.772 |
| | B | 30515 | 6.75 | 10.5 | 1.05 | 2039 | 1623 | 0.80 | 0.66 | 1355 | 431 | 0.318 | 18178 | 9.6 | 1889 | 0.871 |
| | C | 70150 | 8.5 | 10.5 | 1.02 | 1992 | 2574 | 1.29 | 0.84 | 1678 | 786 | 0.468 | 29330 | 19.3 | 1524 | 0.567 |
| | D | 62940 | 6.75 | 12 | 1.03 | 2012 | 1623 | 0.81 | 0.67 | 1349 | 777 | 0.576 | 26355 | 12.3 | 2151 | 0.997 |
| | E | 66970 | 6.75 | 12 | 1.03 | 2012 | 1623 | 0.81 | 0.67 | 1349 | 827 | 0.613 | 22203 | 12.3 | 1812 | 0.840 |
| | F | 48715 | 6.75 | 12 | 1.03 | 2012 | 1623 | 0.81 | 0.67 | 1349 | 601 | 0.446 | 24158 | 12.3 | 1972 | 0.914 |
| Penthouse | Typ. Int. | 32210 | 8.5 | 10.5 | 0.99 | 1922 | 1250 | 0.65 | 0.57 | 1102 | 361 | 0.328 | 20838 | 19.3 | 1082 | 0.614 |
| | A | 23630 | 8.5 | 10.5 | 0.99 | 1922 | 1250 | 0.65 | 0.57 | 1102 | 265 | 0.240 | 15768 | 19.3 | 819 | 0.465 |
| | C | 22780 | 6.75 | 12 | 1.00 | 1940 | 788 | 0.41 | 0.38 | 742 | 281 | 0.379 | 13568 | 12.3 | 1108 | 0.933 |
| | D | 20470 | 6.75 | 12 | 1.00 | 1940 | 788 | 0.41 | 0.38 | 742 | 253 | 0.341 | 12203 | 12.3 | 996 | 0.839 |

*Column Types are labeled on the following floor plan

Note: As long as "OK?" column values are less than 1.0, the size has passed design checks. (Value is ratio of fp/F'c)

# Appendix

- Design Values

| CLT Grade | CLT Thickness (in.) | Lamination Thickness in CLT Lay-up (in.) | | | | | | | Major Strength Direction | | | Minor Strength Direction | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | = | ⊥ | = | ⊥ | = | ⊥ | = | $F_bS_{eff,0}$ (lb.-ft./ft.) | $EI_{eff,0}$ ($10^6$ lb.-in.²/ft.) | $GA_{eff,0}$ ($10^6$ lb./ft.) | $F_bS_{eff,90}$ (lb.-ft./ft.) | $EI_{eff,90}$ $10^6$ lb.-in.²/ft.) | $GA_{eff,90}$ ($10^6$ lb./ft.) |
| E1 | 4 1/8 | 1 3/8 | 1 3/8 | 1 3/8 | | | | | 4,525 | 115 | 0.46 | 160 | 3.1 | 0.61 |
| | 6 7/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | | | 10,400 | 440 | 0.92 | 1,370 | 81 | 1.2 |
| | 9 5/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 18,375 | 1,089 | 1.4 | 3,125 | 309 | 1.8 |
| E2 | 4 1/8 | 1 3/8 | 1 3/8 | 1 3/8 | | | | | 3,825 | 102 | 0.53 | 165 | 3.6 | 0.56 |
| | 6 7/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | | | 8,825 | 389 | 1.1 | 1,430 | 95 | 1.1 |
| | 9 5/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 15,600 | 963 | 1.6 | 3,275 | 360 | 1.7 |
| E3 | 4 1/8 | 1 3/8 | 1 3/8 | 1 3/8 | | | | | 2,800 | 81 | 0.35 | 110 | 2.3 | 0.44 |
| | 6 7/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | | | 6,400 | 311 | 0.69 | 955 | 61 | 0.87 |
| | 9 5/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 1 3/8 | 11,325 | 769 | 1.0 | 2,180 | 232 | 1.3 |

Image Source: CLT Handbook

| CLT Grade | Laminations in the Major Strength Direction of the CLT | | | | | | Laminations in the Minor Strength Direction of the CLT | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $f_{b,0}$ (psi) | $E_0$ ($10^6$psi) | $f_{t,0}$ (psi) | $f_{c,0}$ (psi) | $f_{v,0}$ (psi) | $f_{s,0}$ (psi) | $f_{b,90}$ (psi) | $E_{90}$ ($10^6$psi) | $f_{t,90}$ (psi) | $f_{c,90}$ (psi) | $f_{v,90}$ (psi) | $f_{s,90}$ (psi) |
| E1 | 4,095 | 1.7 | 2,885 | 3,420 | 425 | 140 | 1,050 | 1.2 | 525 | 1,235 | 425 | 140 |
| E2 | 3,465 | 1.5 | 2,140 | 3,230 | 565 | 190 | 1,100 | 1.4 | 680 | 1,470 | 565 | 190 |
| E3 | 2,520 | 1.2 | 1,260 | 2,660 | 345 | 115 | 735 | 0.9 | 315 | 900 | 345 | 115 |
| E4 | 4,095 | 1.7 | 2,885 | 3,420 | 550 | 180 | 1,205 | 1.4 | 680 | 1,565 | 550 | 180 |
| V1 | 1,890 | 1.6 | 1,205 | 2,565 | 565 | 190 | 1,100 | 1.4 | 680 | 1,470 | 565 | 190 |
| V2 | 1,835 | 1.4 | 945 | 2,185 | 425 | 140 | 1,050 | 1.2 | 525 | 1,235 | 425 | 140 |
| V3 | 2,045 | 1.6 | 1,155 | 2,755 | 550 | 180 | 1,205 | 1.4 | 680 | 1,565 | 550 | 180 |

For SI: 1 psi = 6.895 kPa

[a] The characteristic values may be obtained from the published allowable design values for lumber in the United States as follows:

$f_{b,0}$ = 2.1 x published allowable bending stress ($F_b$), $f_{t,0}$ = 2.1 x published allowable tensile stress ($F_t$), $f_{c,0}$ = 1.9 x published allowable compressive stress parallel to grain ($F_c$), $f_{v,0}$ = 3.15 x published allowable shear stress ($F_v$), and $f_{s,0}$ = 1/3 x calculated $f_{v,0}$.

Image Source: CLT Handbook

***DOUGLAS-FIR* GLUED LAMINATED BEAM SECTION PROPERTIES AND CAPACITIES**

**$F_b$ = 2,400 psi, E = 1.80 x $10^6$ psi, $F_v$ = 265 psi**

**3-1/8-INCH WIDTH**

| Depth (in.) | 6 | 7-1/2 | 9 | 10-1/2 | 12 | 13-1/2 | 15 | 16-1/2 | 18 | 19-1/2 | 21 | 22-1/2 | 24 | 25-1/2 | 27 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Beam Weight (lb/ft) | 4.6 | 5.7 | 6.8 | 8.0 | 9.1 | 10.3 | 11.4 | 12.5 | 13.7 | 14.8 | 16.0 | 17.1 | 18.2 | 19.4 | 20.5 |
| A (in.²) | 18.75 | 23.44 | 28.13 | 32.81 | 37.50 | 42.19 | 46.88 | 51.56 | 56.25 | 60.94 | 65.63 | 70.31 | 75.00 | 79.69 | 84.38 |
| S (in.³) | 18.75 | 29.30 | 42.19 | 57.42 | 75.00 | 94.92 | 117.2 | 141.8 | 168.8 | 198.0 | 229.7 | 263.7 | 300.0 | 338.7 | 379.7 |
| I (in.⁴) | 56.25 | 109.9 | 189.8 | 301.5 | 450.0 | 640.7 | 878.9 | 1170 | 1519 | 1931 | 2412 | 2966 | 3600 | 4318 | 5126 |
| EI ($10^6$ lb-in.²) | 101.3 | 197.8 | 341.7 | 542.6 | 810.0 | 1153 | 1582 | 2106 | 2734 | 3476 | 4341 | 5339 | 6480 | 7773 | 9226 |
| Moment Capacity (lb-ft) | 3750 | 5859 | 8438 | 11480 | 15000 | 18980 | 23440 | 28360 | 33750 | 39610 | 45940 | 52730 | 60000 | 67730 | 75940 |
| Shear Capacity (lb) | 3313 | 4141 | 4969 | 5797 | 6625 | 7453 | 8281 | 9109 | 9938 | 10770 | 11590 | 12420 | 13250 | 14080 | 14910 |

**3-1/2-INCH WIDTH**

| Depth (in.) | 6 | 7-1/2 | 9 | 10-1/2 | 12 | 13-1/2 | 15 | 16-1/2 | 18 | 19-1/2 | 21 | 22-1/2 | 24 | 25-1/2 | 27 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Beam Weight (lb/ft) | 5.1 | 6.4 | 7.7 | 8.9 | 10.2 | 11.5 | 12.8 | 14.0 | 15.3 | 16.6 | 17.9 | 19.1 | 20.4 | 21.7 | 23.0 |
| A (in.²) | 21.00 | 26.25 | 31.50 | 36.75 | 42.00 | 47.25 | 52.50 | 57.75 | 63.00 | 68.25 | 73.50 | 78.75 | 84.00 | 89.25 | 94.50 |
| S (in.³) | 21.00 | 32.81 | 47.25 | 64.31 | 84.00 | 106.3 | 131.3 | 158.8 | 189.0 | 221.8 | 257.3 | 295.3 | 336.0 | 379.3 | 425.3 |
| I (in.⁴) | 63.00 | 123.0 | 212.6 | 337.6 | 504.0 | 717.6 | 984.4 | 1310 | 1701 | 2163 | 2701 | 3322 | 4032 | 4836 | 5741 |
| EI ($10^6$ lb-in.²) | 113.4 | 221.5 | 382.7 | 607.8 | 907.2 | 1292 | 1772 | 2358 | 3062 | 3893 | 4862 | 5980 | 7258 | 8705 | 10330 |
| Moment Capacity (lb-ft) | 4200 | 6563 | 9450 | 12860 | 16800 | 21260 | 26250 | 31760 | 37800 | 44360 | 51450 | 59060 | 67200 | 75860 | 85050 |
| Shear Capacity (lb) | 3710 | 4638 | 5565 | 6493 | 7420 | 8348 | 9275 | 10200 | 11130 | 12060 | 12990 | 13910 | 14840 | 15770 | 16700 |

**5-1/8-INCH WIDTH**

| Depth (in.) | 12 | 13-1/2 | 15 | 16-1/2 | 18 | 19-1/2 | 21 | 22-1/2 | 24 | 25-1/2 | 27 | 28-1/2 | 30 | 31-1/2 | 33 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Beam Weight (lb/ft) | 14.9 | 16.8 | 18.7 | 20.6 | 22.4 | 24.3 | 26.2 | 28.0 | 29.9 | 31.8 | 33.6 | 35.5 | 37.4 | 39.2 | 41.1 |
| A (in.²) | 61.50 | 69.19 | 76.88 | 84.56 | 92.25 | 99.94 | 107.6 | 115.3 | 123.0 | 130.7 | 138.4 | 146.1 | 153.8 | 161.4 | 169.1 |
| S (in.³) | 123.0 | 155.7 | 192.2 | 232.5 | 276.8 | 324.8 | 376.7 | 432.4 | 492.0 | 555.4 | 622.7 | 693.8 | 768.8 | 847.5 | 930.2 |
| I (in.⁴) | 738.0 | 1051 | 1441 | 1919 | 2491 | 3167 | 3955 | 4865 | 5904 | 7082 | 8406 | 9887 | 11530 | 13350 | 15350 |
| EI ($10^6$ lb-in.²) | 1328 | 1891 | 2595 | 3453 | 4483 | 5700 | 7119 | 8757 | 10630 | 12750 | 15130 | 17800 | 20760 | 24030 | 27630 |
| Moment Capacity (lb-ft) | 24600 | 31130 | 38440 | 46510 | 55350 | 64960 | 75340 | 86480 | 98400 | 111100 | 124500 | 138800 | 153800 | 169500 | 186000 |
| Shear Capacity (lb) | 10870 | 12220 | 13580 | 14940 | 16300 | 17660 | 19010 | 20370 | 21730 | 23090 | 24450 | 25800 | 27160 | 28520 | 29880 |

**5-1/2-INCH WIDTH**

| Depth (in.) | 12 | 13-1/2 | 15 | 16-1/2 | 18 | 19-1/2 | 21 | 22-1/2 | 24 | 25-1/2 | 27 | 28-1/2 | 30 | 31-1/2 | 33 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Beam Weight (lb/ft) | 16.0 | 18.0 | 20.1 | 22.1 | 24.1 | 26.1 | 28.1 | 30.1 | 32.1 | 34.1 | 36.1 | 38.1 | 40.1 | 42.1 | 44.1 |

Image Source: Eng. Wood Assoc.

# Appendix

- Wind Drift Check

**1604.3 Serviceability.**
Structural systems and members thereof shall be designed to have adequate stiffness to limit deflections and lateral drift.

| CONSTRUCTION | *L* | *S* or $W^f$ | *D* + $L^{d, g}$ |
|---|---|---|---|
| Roof members:[e] | | | |
| Supporting plaster ceiling | l/360 | l/360 | l/240 |
| Supporting nonplaster ceiling | l/240 | l/240 | l/180 |
| Not supporting ceiling | l/180 | l/180 | l/120 |
| Floor members | l/360 | - | l/240 |
| Exterior walls and interior partitions: | | | |
| With brittle finishes | - | l/240 | - |
| With flexible finishes | - | l/120 | - |
| Farm buildings | - | - | l/180 |
| Greenhouses | - | - | l/120 |

f. The wind load is permitted to be taken as 0.7 times the "component and cladding" loads for the purpose of determining deflection limits herein.

**CC.1.2 Drift of Walls and Frames.** Drifts (lateral deflections) of concern in serviceability checking arise primarily from the effects of wind. Drift limits in common usage for building design are on the order of 1/600 to 1/400 of the building or story height [Ref. CC-7]. These limits generally are sufficient to minimize damage to cladding and nonstructural walls and partitions. Smaller drift limits may be appropriate if the cladding is brittle. An absolute limit on interstory drift may also need to be imposed in light of evidence that damage to non-structural partitions, cladding and glazing may occur if the interstory drift exceeds about 10 mm (3/8 in.) unless special detailing practices are made to tolerate movement [Refs. CC-6, CC-8]. Many components can accept deformations that are significantly larger.

Use of the factored wind load in checking serviceability is excessively conservative. The load combination with an annual probability of 0.05 of being exceeded, which can be used for checking short-term effects, is

$$D + 0.5L + 0.7W \qquad \text{(CC-3)}$$

obtained using a procedure similar to that used to derive Eqs. CC-1a and CC-1b. Wind load, *W*, is defined in Chapter 6. Due to its transient nature, wind load need not be considered in analyzing the effects of creep or other long-term actions.

Deformation limits should apply to the structural assembly as a whole. The stiffening effect of nonstructural walls and partitions may be taken into account in the analysis of drift if substantiating information regarding their effect is available. Where load cycling occurs, consideration should be given to the possibility that increases in residual deformations may lead to incremental structural collapse.

# Appendix

- In-Plane Deflection

$$\delta_{dia} = \frac{5vL^3}{8EAW} + \frac{0.25vL}{1000G_a} + \frac{\sum(x\Delta_c)}{2W}$$

$G_a$ = apparent stiffness from nail slip
glued product, ∴ does not apply

$\Delta_c$ = diaphragm chord splice slip, DNA

$$\therefore \delta_{dia} = \frac{5vL^3}{8EAW}$$

$v$ = 4.8 klf = 4800 plf

L = 26'

E = $1.5 \times 10^6$ psi

A = 3000 $in^2$

W = 30' (Bay act individually)

$$\delta_{dia} = \frac{5(4800)(26)^3(1728)}{8(1.5E6)(3000)(30)} = \underline{0.675 \text{ in}}$$

From ETABS: $\delta_{dia}$ = 0.823

calculated $l/360$ limit = 0.877, ∴ acceptable

The hand calc is just a bit lower, most likely b/c the equation couldn't account for shear controlled deflection. ∴ hand calc may be low, ETABS may be conservative.

# Appendix

- Shear Wall Reinforcement

| Typical Required Reinforcement in Wall Ends or Corners* | | | | | |
|---|---|---|---|---|---|
| Level | Grid 10 | Elev Stair Core | Stair Core | Grid 3, Wall AB | Grid 3, Wall CD |
| PH | (4) #4 | (4) #4 | (6) #6 | - | - |
| 12 | (4) #6 | (4) #4 | (6) #6 | (4) #6 | (4) #6 |
| 11 | (4) #6 | (4) #4 | (6) #6 | (4) #6 | (6) #6 |
| 10 | (4) #6 | (4) #4 | (6) #6 | (4) #6 | (8) #6 |
| 9 | (6) #6 | (4) #4 | (6) #6 | (4) #6 | (8) #6 |
| 8 | (6) #6 | (4) #4 | (6) #6 | (4) #6 | (8) #6 |
| 7 | (8) #6 | (4) #4 | (6) #6 | (4) #6 | (10) #6 |
| *All walls typically have 2 curtains of #4's at 18" o.c. vertical and 10" o.c. horizontal in the field of the wall | | | | | |

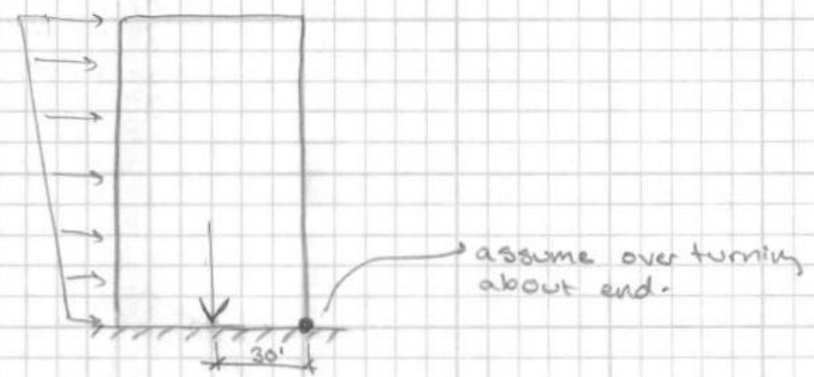
## Modeling Assumptions Using ETABS:

- All bases pinned
- Only lateral system and loads modeled
- 4000 psi NW concrete
- Concrete cracking modifier of 0.7 for walls
- CLT floor modeled as orthotropic
- Only addition modeled
- Actual elevations above ground level used
- Automatic ASCE 7-05 wind loads used and verified

# Appendix

- Overturning Moment

From Wind Analysis in ETABS, overturning Moment = 34,000 ft·kip




Dead Load of Building =

110 psf (7 floors)(12,800 sf)
+ 36 psf (7 floors)(12,800 sf) = 13,080 kips

Resisting w/ moment arm of half building width = 30'

13,080 kips (30') = 392,000 ft·k

$M_R > M_{ov}$

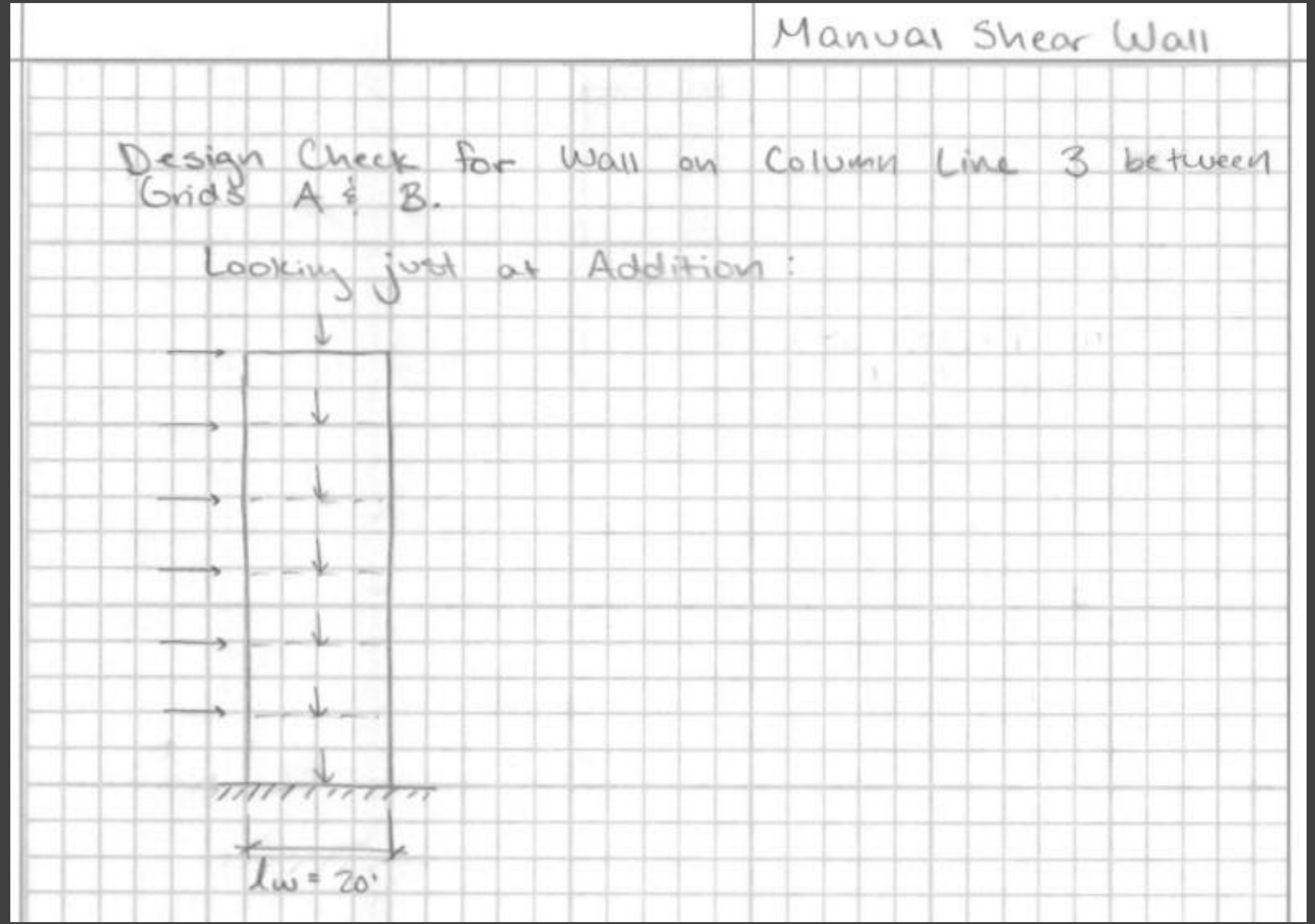
392,000 >> 34,000

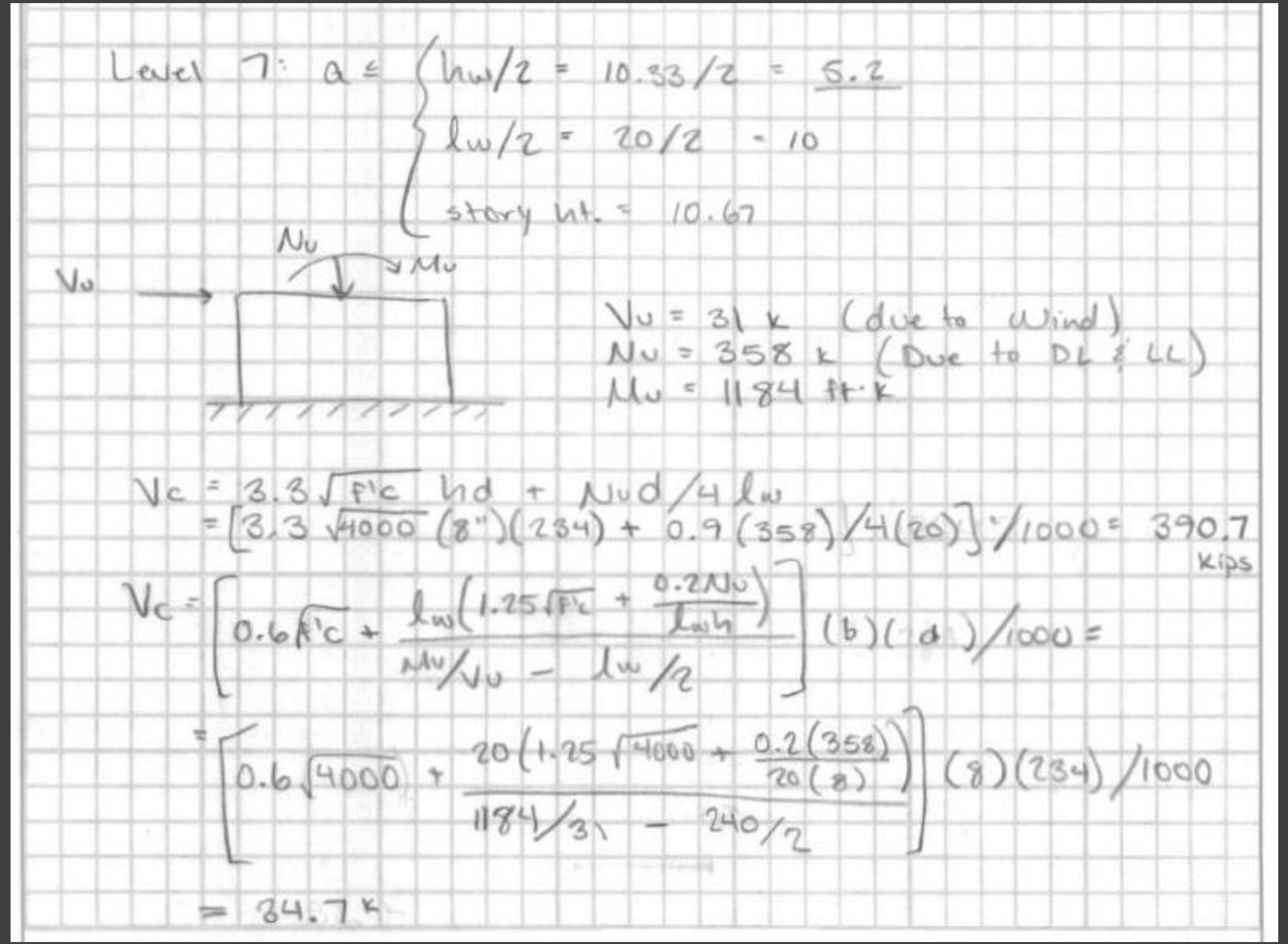
∴ building can resist overturning moment due to wind

Other direction has much lower overturning moment due to significantly less surface area ∴ will not control.

# Appendix

- Shear Wall Hand Check at Critical Section



# Appendix

- Shear Wall Hand Check at Critical Section

or $V_c = 2\sqrt{f'_c}\,hd = 2\sqrt{4000}\,(8)(234)/1000 = 237^k$

$V_u > 0.5\,\phi V_c = 0.5(0.75)(237) = 88.9$

$34.7 < 88.9$, ∴ no shear reinf. req.

Include to meet min reinf. req's

Horizontal : $\rho_t \geq 0.0025 =$ $8''(240'')(0.0025) = 4.8\,in^2$

$S \leq$ (min of)
- $l_w/5 = 20/5 = 4' = 48''$
- $3h = 3(8) = 24''$
- $18''$ → controls

#4 bar → $A = 0.2\,in^2/bar$ 24 bars

2 curtains, 12 #4's each side @ 10" O.C.

Vertical :

$\rho_\ell \geq$ (min of) $0.0025 + 0.5\left(2.5 - \frac{h_w}{l_w}\right)(\rho_t - 0.0025)$

$= 0.0025 + 0.5(2.5 - (10.33/20))(0.0025 - 0.0025)$

$= 0.0025$

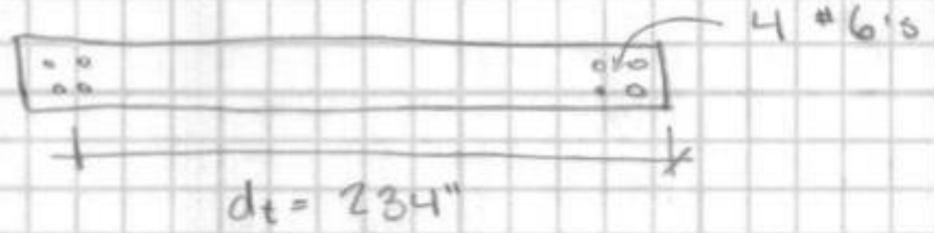
$8''(240'')(0.0025) = 4.8\,in^2$ → 24 bars

2 curtains, 12 #4's each side @ 18" O.C.

$S \leq$ (min of)
- $l_w/3 = 20'/3 = 6.67'$
- $3h = 24''$
- $18''$ → controls

<u>Flexural Design</u> (Level 7 : Base Level)

$M_u = 1184$ ft·k check Etabs design




assume case 1:

$M_n = A_s f_y jd = 4(0.44)(60)(0.9)(19.5) = 1853$ ft·k

$M_u \geq \phi M_n$ → $1184 \leq 1667$ ft·k ✓ ok

Could go to #5's, but should be 2 sizes up from #4's

# Appendix

- CM Cost Analysis

**Structurlam Products Ltd Budget Pricing for CrossLam (Cross Laminated Timber Panels) CDN$**

| | | | 1 | 2 | 3 | | | |
|---|---|---|---|---|---|---|---|---|
| Panel Type | # of Laminations | Panel Thickness | Blank Panel $/Sq. Ft | Hand Framing (Floor/Roof) $/Sq. Ft | 5 Axis Robotic Framing (Walls) $/Sq. Ft | Fasterner, Hardware, Shop Drawings Floor/Roof $/Sq. Ft. | Walls $/Sq. Ft. | Visual Grade $/Sq. Ft |
| SLT3 | 3 | 99mm | 5.80 | 6.05 | 7.02 | 2.50 | 3.00 | 1.00 |
| SLT5 | 5 | 169mm | 9.68 | 9.93 | 11.21 | 2.50 | 3.00 | 1.00 |
| SLT7 | 7 | 239mm | 13.77 | 14.02 | 15.93 | 3.00 | 3.50 | 1.00 |
| SLT9 | 9 | 309mm | 17.53 | 17.97 | 19.90 | 3.00 | 3.50 | 1.00 |

**Note: it's columns 1 or 2 or 3... not 1 + 2 or 1 +3 or 1 + 2 + 3**

# Appendix

- CM Cost Analysis

**Item Quantities**

| Gravity System Items | Unit | Quantity Per Level | | | Total |
|---|---|---|---|---|---|
| | | Typ. Level | 12th Level | Penthouse | |
| 5-ply CLT Panels (including visual grading) | S.F. | 10780 | 0 | 5500 | 59400 |
| 7-ply CLT Panels (including visual grading) | S.F. | 1560 | 10780 | 0 | 18580 |
| 9-ply CLT Panels (including visual grading) | S.F. | 0 | 1560 | 0 | 1560 |
| Double 3-ply Partitions | S.F. | 6600 | 7400 | 1990 | 42390 |
| Wall Insulation | S.F. | 5980 | 6704 | 1803 | 38405 |
| Studs 2" x 3", pneumatic nailed | MBF | 9 | 10 | 3 | 56 |
| Sound Attenuation for Floor | S.F. | 12340 | 12340 | 5500 | 79540 |
| Glulam Typ Beams | Ea | 27 | 27 | 18 | 180 |
| Glulam Perimeter Beams | Ea | 20 | 20 | 12 | 132 |
| Glulam Columns | MBF | 3640 | 4110 | 3760 | 26070 |
| **Shear Wall System Items** | **Unit** | **Quantity Per Level** | | | **Total** |
| | | **Existing Typ.** | **Addition Typ.** | **Penthouse** | |
| Cast in Place Concrete | C.Y. | 50 | 50 | 64 | 714 |
| Rebar (#4's @ 18" O.C.) | Ton | 0.51 | 0.51 | 0.705 | 7.335 |

**Item Quantities**

| Gravity System Items | Unit | Quantity Per Level | | | Total |
|---|---|---|---|---|---|
| | | Typ. Level | 12th Level | Penthouse | |
| Steel Columns | L.F. | 455 | 513 | 270 | 3058 |
| Steel Columns | Ton | 10.9 | 12.34 | 11.43 | 78.27 |
| W 12x22 | L.F. | 336 | 336 | 0 | 2016 |
| W10x33 | L.F. | 798 | 798 | 0 | 4788 |
| W16x26 | L.F. | 0 | 0 | 625 | 625 |
| W14x22 | L.F. | 0 | 0 | 310 | 310 |
| W12x30 | L.F. | 105 | 105 | 0 | 630 |
| Open Web Joist 12K3 | L.F. | 2700 | 2700 | 0 | 16200 |
| Open Web Joist 16K3 | L.F. | 0 | 0 | 1100 | 1100 |
| Floor Deck | S.F. | 12840 | 12840 | 0 | 77040 |
| Roof Deck | S.F. | 0 | 0 | 4300 | 4300 |
| Moment Connection Weld | L.F. | 82 | 82 | 30 | 522 |
| Shear Connection Weld | L.F. | 207 | 207 | 138 | 1380 |
| Bolts | Ea | 1250 | 1250 | 830 | 8330 |
| Connection Angle | L.F. | 294 | 294 | 196 | 1960 |
| Welded Wire Fabric | C.S.F. | 12840 | 12840 | 4300 | 813.4 |
| Concrete deck topping | CY | 12840 | 12840 | 4300 | 81340 |
| Partitions | L.F. | 750 | 750 | 130 | 4630 |
| **Shear Wall System Items** | **Unit** | **Quantity Per Level** | | | **Total** |
| | | **B2** | **B1** | **Typ** | |
| CMU | S.F. | 1650 | 1510 | 1140 | 8860 |
| Rebar (#5's @ 24" O.C.) | Ton | 0.51 | 0.47 | 0.36 | 2.78 |

# Appendix

- CM Cost Analysis

**Project Name: 11141 Georgia Ave Wood Addition**

| Location: | Wheaton Ave, Maryland | | | | | | |
|---|---|---|---|---|---|---|---|
| Line Number | Description | Qty | Unit | Material | Labor | Estimate Total | |
| From Structurlam | 5-ply CLT Panels (including visual grading) | 59400 | S.F. | $ 571,558.68 | $ 11,731.50 | | |
| Products Budget | 7-ply CLT Panels (including visual grading) | 18580 | S.F. | $ 246,153.41 | $ 3,669.55 | | |
| Pricing Provided in a | 9-ply CLT Panels (including visual grading) | 1560 | S.F. | $ 25,301.17 | $ 542.26 | | |
| CLT Presentation | 3-ply Partitions | 42390 | S.F. | $ 261,207.18 | $ 8,372.03 | | |
| 07 21 16.20 1320 | Blanket Insulation, mineral wool batts 3.5" thick | 38405 | S.F. | $ 23,043.20 | $ 8,833.23 | | |
| 06 11 10.40 6125 | Studs 2" x 3", pneumatic nailed | 56 | MBF | $ 42,367.50 | $ 57,902.25 | | |
| 09 81 16.10 4200 | Sound Attenuation for Floor | 79540 | S.F. | $ 132,036.40 | $ 192,486.80 | | |
| 06 18 13.20 8138 | Straight Glulam Beam, 20' span, 6.75" x 15" (Typ.) | 180 | Ea | $ 86,400.00 | $ 11,610.00 | | |
| 06 18 13.20 8142 | Straight Glulam Beam, 20' span, 6.75" x 18" (Perim.) | 132 | Ea | $ 75,900.00 | $ 8,844.00 | | |
| 06 18 13.20 4400 | Alternate Pricing, columns including hardware | 26.07 | MBF | $ 79,513.50 | $ 24,375.45 | | |
| Division 06 | Subtotal | | | $ 1,543,481.05 | $ 328,367.06 | $ 1,871,848.11 | Division 06 |
| 03 30 53.40 4200 | Wall, free-standing, 8" thick | 714 | C.Y. | $ 108,528.00 | $ 138,516.00 | | |
| 03 21 11.60 0700 | Reinforcing in place, walls, #3 to #7 | 7.335 | Ton | $ 7,335.00 | $ 3,960.90 | | |
| Division 03/04 | Subtotal | | | $ 115,863.00 | $ 142,476.90 | $ 258,339.90 | Division 03/04 |
| | | Subtotal | | $ 1,659,344.05 | $ 470,843.96 | $ 2,130,188.01 | Subtotal |
| Division 01 | General Requirements @5% | | | $ 82,967.20 | $ 23,542.20 | | Gen. Requirements |
| | | Estimate Subtotal | | $ 1,742,311.25 | $ 494,386.16 | $ 2,236,697.41 | Estimate Subtotal |
| | | Sales Tax @ 5.75% | | $ 100,182.90 | | | Sales Tax |
| | | Subtotal A | | $ 1,842,494.15 | $ 494,386.16 | | Subtotal |
| | | GC O & P | | $ 92,124.71 | $ 271,418.00 | | GC O&P |
| | | Subtotal B | | $ 1,934,618.86 | $ 765,804.16 | $ 2,700,423.01 | Subtotal |
| | | Contingency @5% | | | | $ 135,021.15 | Contingency |
| | | Sutotal C | | | | $ 2,835,444.17 | Subtotal |
| | | Location Adjustment Factor | | 97.2 | | -$ 79,392.44 | Location Adjustment |
| | | Grand Total | | | | $ 2,756,051.73 | Grand Total |

**Project Name: 11141 Georgia Ave Existing Addition**

| Location: | Wheaton Ave, Maryland | | | | | | |
|---|---|---|---|---|---|---|---|
| Line Number | Description | Qty | Unit | Material | Labor | Estimate Total | |
| 05 12 23.75 0900 | W 10x49 | 3058 | L.F. | $ 218,922.22 | $ 15,595.80 | | |
| 05 12 23.75 1300 | W 12x22 | 2016 | L.F. | $ 64,512.00 | $ 6,431.04 | | |
| 05 12 23.75 0740 | W10x33 | 4788 | L.F. | $ 229,824.00 | $ 24,418.80 | | |
| 05 12 23.75 1520 | W12x35 | 625 | L.F. | $ 31,875.00 | $ 2,168.75 | | |
| 05 12 23.75 2700 | W16x26 | 310 | L.F. | $ 11,780.00 | $ 871.10 | | |
| 05 12 23.75 1520 | W14x22 | 630 | L.F. | $ 23,940.00 | $ 1,789.20 | | |
| 05 21 19 10 0160 | Open Web Joist 12K3 | 16200 | L.F. | $ 76,464.00 | $ 63,342.00 | | |
| 05 21 19 10 0200 | Open Web Joist 16K3 | 1100 | L.F. | $ 5,720.00 | $ 2,475.00 | | |
| 05 31 13.50 5140 | Floor Decking, Composite decking, 1.5" deep, 20 ga. | 77040 | S.F. | $ 180,504.72 | $ 36,208.80 | | |
| 05 31 13.50 2100 | Roof Decking, under 50 squares, 1.5" deep, 22 ga. | 4300 | S.F. | $ 9,318.10 | $ 1,720.00 | | |
| 05 05 21.90 2010 | Weld, 4 passes, 1/2" thick plus avg 150% (half over head) | 522 | L.F. | $ 872.78 | $ 15,111.90 | | |
| 05 05 21.90 2010 | Weld, 4 passes, 1/2" thick + 20% for vertical | 1380 | L.F. | $ 2,307.36 | $ 31,960.80 | | |
| 05 05 23.10 2200 | 3/4" diameter bolts 2" long | 8330 | Ea | $ 13,119.75 | $ 28,405.30 | | |
| 05 12 23.78 0320 | Angles, 3"x3" | 1960 | L.F. | $ 3,743.60 | $ 3,214.40 | | |
| 03 22 11.10 0200 | Welded Wire Fabric 6x6 W2.1xW2.1 | 813.4 | C.S.F | $ 15,389.53 | $ 21,148.40 | | |
| 03 30 53.40 3250 | Elevated Slab, regular 4000 psi conc., 2-1/2" floor fill | 81340 | S.F. | $ 81,421.34 | $ 69,139.00 | | |
| 05 41 13.30 5190 | Framing, stud walls, 10' high, 6" wide, studs 12" O.C. | 4630 | L.F. | $ 74,080.00 | $ 66,672.00 | | |
| Division 05 | Subtotal | | | $ 1,043,794.40 | $ 390,672.29 | $ 1,434,466.69 | Division 05 |
| 04 22 10.34 5600 | 8" CMU solid grouted reinforced altenate cources | 8860 | S.F. | $ 33,579.40 | $ 42,085.00 | | |
| 03 21 11.60 0700 | Reinforcing in place, walls, #3 to #7 | 2.78 | Ton | $ 2,780.00 | $ 1,501.20 | | |
| Division 03/04 | Subtotal | | | $ 36,359.40 | $ 43,586.20 | $ 79,945.60 | Division 03/04 |
| | | Subtotal | | $ 1,080,153.80 | $ 434,258.49 | $ 1,514,412.29 | Subtotal |
| Division 01 | General Requirements @10% | | | $ 108,015.38 | $ 43,425.85 | | Gen. Requirements |
| | | Estimate Subtotal | | $ 1,188,169.18 | $ 477,684.34 | $ 1,665,853.52 | Estimate Subtotal |
| | | Sales Tax @ 5.75% | | $ 68,319.73 | | | Sales Tax |
| | | Subtotal A | | $ 1,256,488.91 | $ 477,684.34 | | Subtotal |
| | | GC O & P | | $ 125,648.89 | $ 262,248.70 | | GC O&P |
| | | Subtotal B | | $ 1,382,137.80 | $ 739,933.04 | $ 2,122,070.84 | Subtotal |
| | | Contingency @5% | | | | $ 106,103.54 | Contingency |
| | | Sutotal C | | | | $ 2,228,174.38 | Subtotal |
| | | Location Adjustment Factor | | 97.2 | | -$ 62,388.88 | Location Adjustment |
| | | Grand Total | | | | $ 2,165,785.50 | Grand Total |

# Appendix

- CM Schedule Analysis

**Schedule Analysis: 11141 Georgia Ave Wood Addition Redesign**

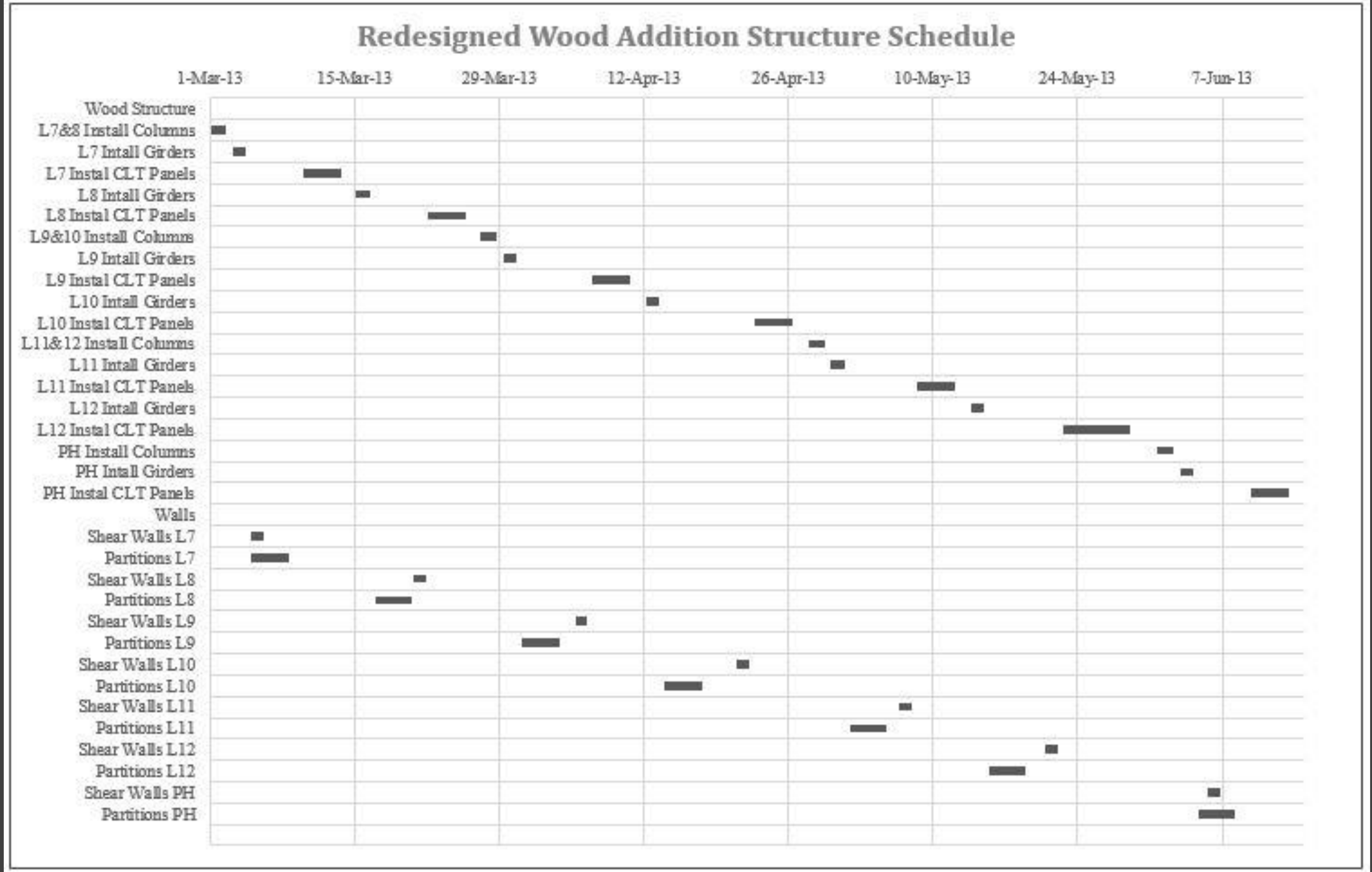
| Item | Qty | Crew Type | # on Crew | Daily Output | Labor Hours | Hrs per item |
|---|---|---|---|---|---|---|
| 03 41 13.50 Precaset Slab Planks (5-ply CLT) | 59400 | C-11 | 10 | 2400 | 0.03 | 178.2 |
| 03 41 13.50 Precaset Slab Planks (7-ply CLT) | 18580 | C-11 | 10 | 2800 | 0.026 | 48.3 |
| 03 41 13.50 Precaset Slab Planks (9-ply CLT) | 1560 | C-11 | 10 | 3200 | 0.023 | 3.6 |
| 03 47 13.40 Tilt-up walls (Double 3-ply Partitions) | 42390 | C-14 | 19 | 1600 | 0.09 | 200.8 |
| Mineral Wool Wall Insulation | 38405 | 1 Carp | 1 | 1600 | 0.005 | 192.0 |
| 2x3 Studs in wall | 56 | 2 Carp | 2 | 22.222 | 0.72 | 20.3 |
| Sound Attenuation for Floor | 79540 | 1 Caro | 2 | 1600 | 0.0005 | 19.9 |
| Straight Glulam Beam, 20' span, 6.75" x 15" (Typ Beams) | 180 | F-3 | 6 | 29 | 1.379 | 41.4 |
| Straight Glulam Beam, 20' span, 6.75" x 18" (Perim. Beams) | 132 | F-3 | 6 | 28 | 1.429 | 31.4 |
| Alternate Pricing, columns including hardware | 26.07 | F-3 | 6 | 2 | 20 | 86.9 |
| Wall, free-standing, 8" thick | 714 | C-14D | 27 | 45.83 | 4.364 | 115.4 |
| Reinforcing in place, walls, #3 to #7 | 7.335 | 4 Rodm | 4 | 3 | 10.667 | 19.6 |
| | | | | | Total (days) | 119.7 |
| | | | | | Weeks (5 d/wk) | 23.9 |
| | | | | | Months (4 wk/m) | 6.0 |

**Schedule Analysis: 11141 Georgia Ave Existing Addition**

| Item | Qty | Crew Type | # on Crew | Daily Output | Labor Hours | Hrs per item |
|---|---|---|---|---|---|---|
| W10x49 | 3058 | E-2 | 8 | 550 | 0.102 | 39.0 |
| W12x22 | 2016 | E-2 | 8 | 880 | 0.064 | 16.1 |
| W10x33 | 4788 | E-2 | 8 | 550 | 0.102 | 61.0 |
| W12x35 | 625 | E-2 | 8 | 810 | 0.069 | 5.4 |
| W16x26 | 310 | E-2 | 8 | 1000 | 0.056 | 2.2 |
| W14x22 | 630 | E-2 | 8 | 990 | 0.057 | 4.5 |
| Open Web Joist 12K3 | 16200 | E-7 | 13 | 1500 | 0.053 | 66.0 |
| Open Web Joist 16K3 | 1100 | E-7 | 13 | 1800 | 0.044 | 3.7 |
| Floor Decking, Composite decking, 1.5" deep, 20 ga. | 77040 | E-4 | 8 | 3800 | 0.008 | 77.0 |
| Roof Decking, under 50 squares, 1.5" deep, 22 ga. | 4300 | E-4 | 8 | 4500 | 0.007 | 3.8 |
| Weld, 4 passes, 1/2" thick plus avg 150% for half overhead | 522 | E-14 | 2 | 22 | 0.364 | 95.0 |
| Weld, 4 passes, 1/2" thick + 20% for vertical | 1380 | E-14 | 2 | 22 | 0.364 | 251.2 |
| 3/4" diameter bolts 2" long | 8330 | 1 Sswk | 1 | 120 | 0.067 | 558.1 |
| Angles, 3"x3" | 1960 | 2 Sswk | 2 | 500 | 0.032 | 31.4 |
| Welded Wire Fabric 6x6 W2.1xW2.1 | 813.4 | 2 Rodm | 2 | 31 | 0.516 | 209.9 |
| Elevated Slab, regular 4000 psi conc., 2-1/2" thick floor fill | 81340 | C-8 | 8 | 2685 | 0.022 | 223.7 |
| Framing, stud walls, 10' high, 6" wide, studs 12" O.C. | 4630 | 2 Carp | 2 | 51 | 0.314 | 726.9 |
| 8" CMU solid grouted reinforced altenate cources | 8860 | D-8 | 5 | 355 | 0.113 | 200.2 |
| Reinforcing in place, walls, #3 to #7 | 2.78 | 4 Rodm | 4 | 3 | 10.667 | 7.4 |
| | | | | | Total (days) | 322.8 |
| | | | | | Weeks (5 d/wk) | 64.6 |
| | | | | | Months (4 wk/m) | 16.1 |

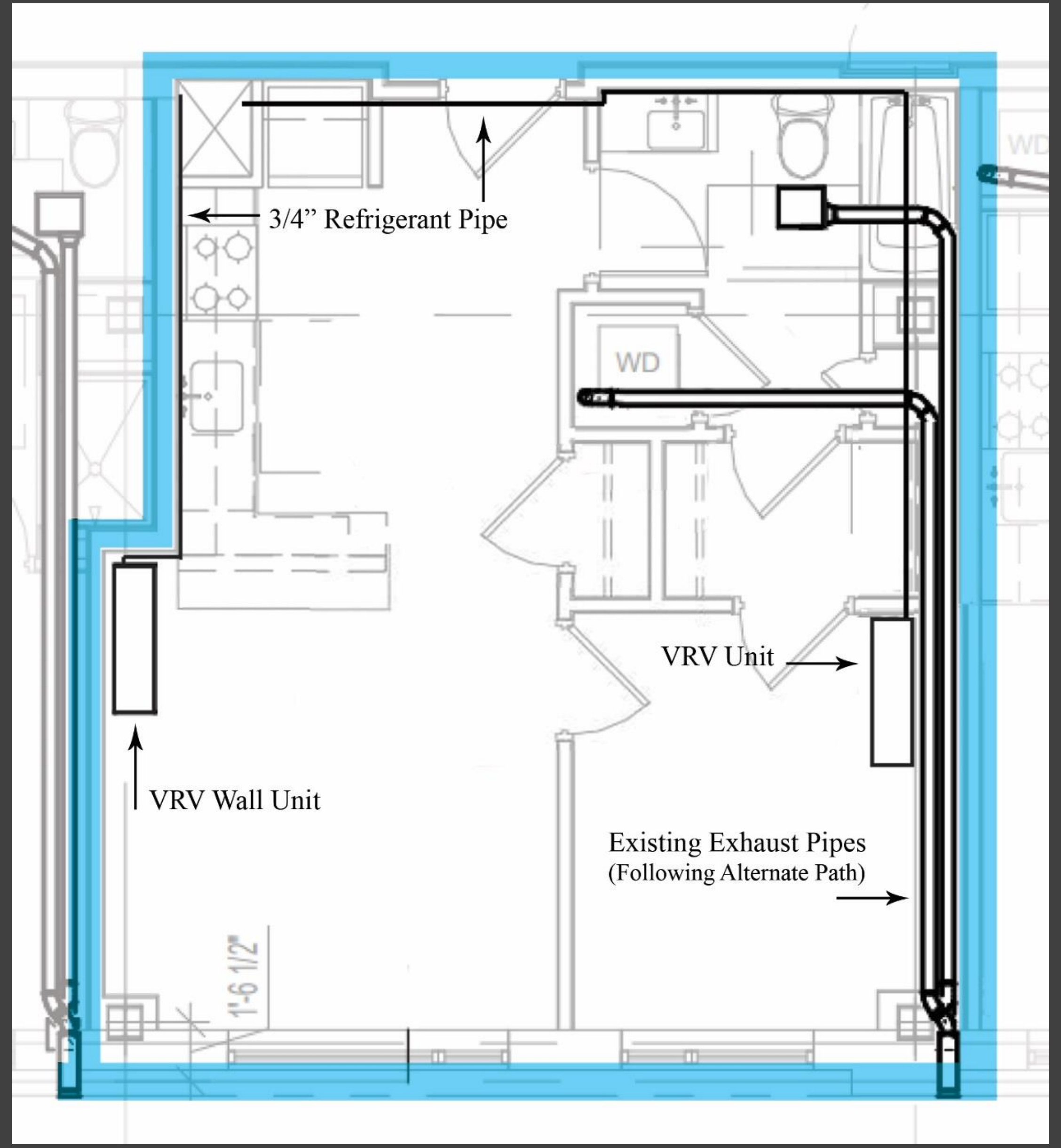
# Appendix

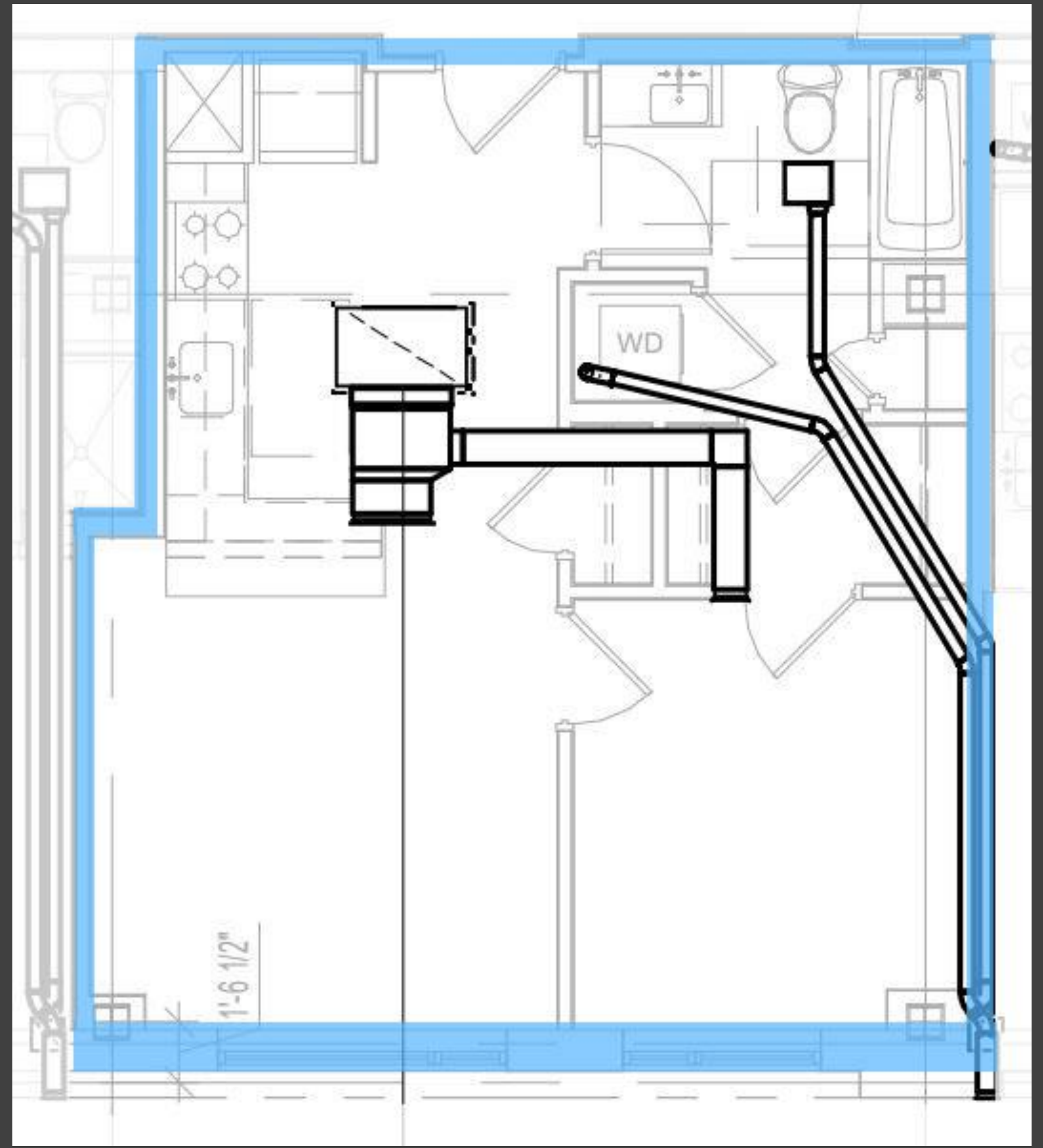
- CM Schedule Analysis




# Appendix

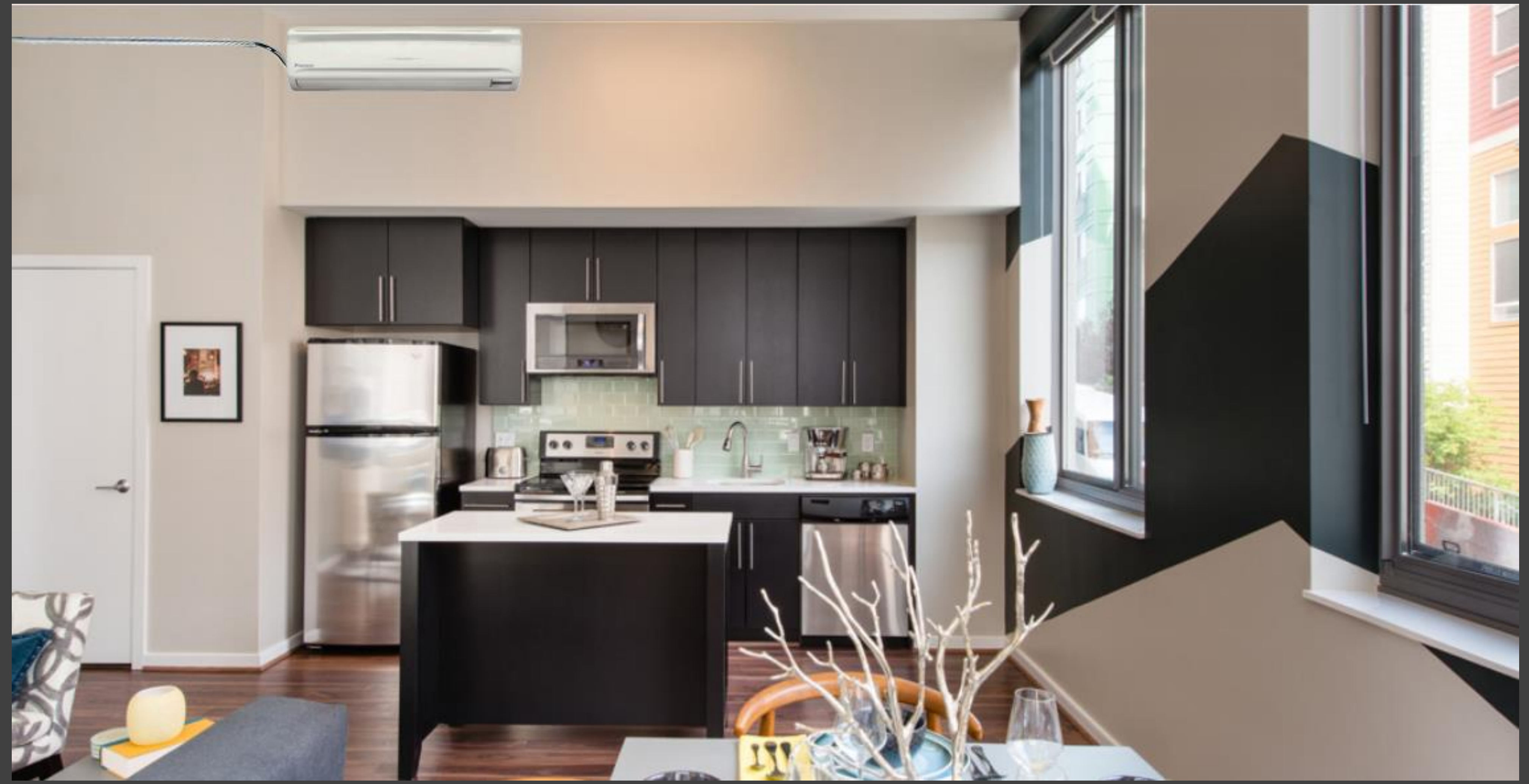
- Mechanical Plans



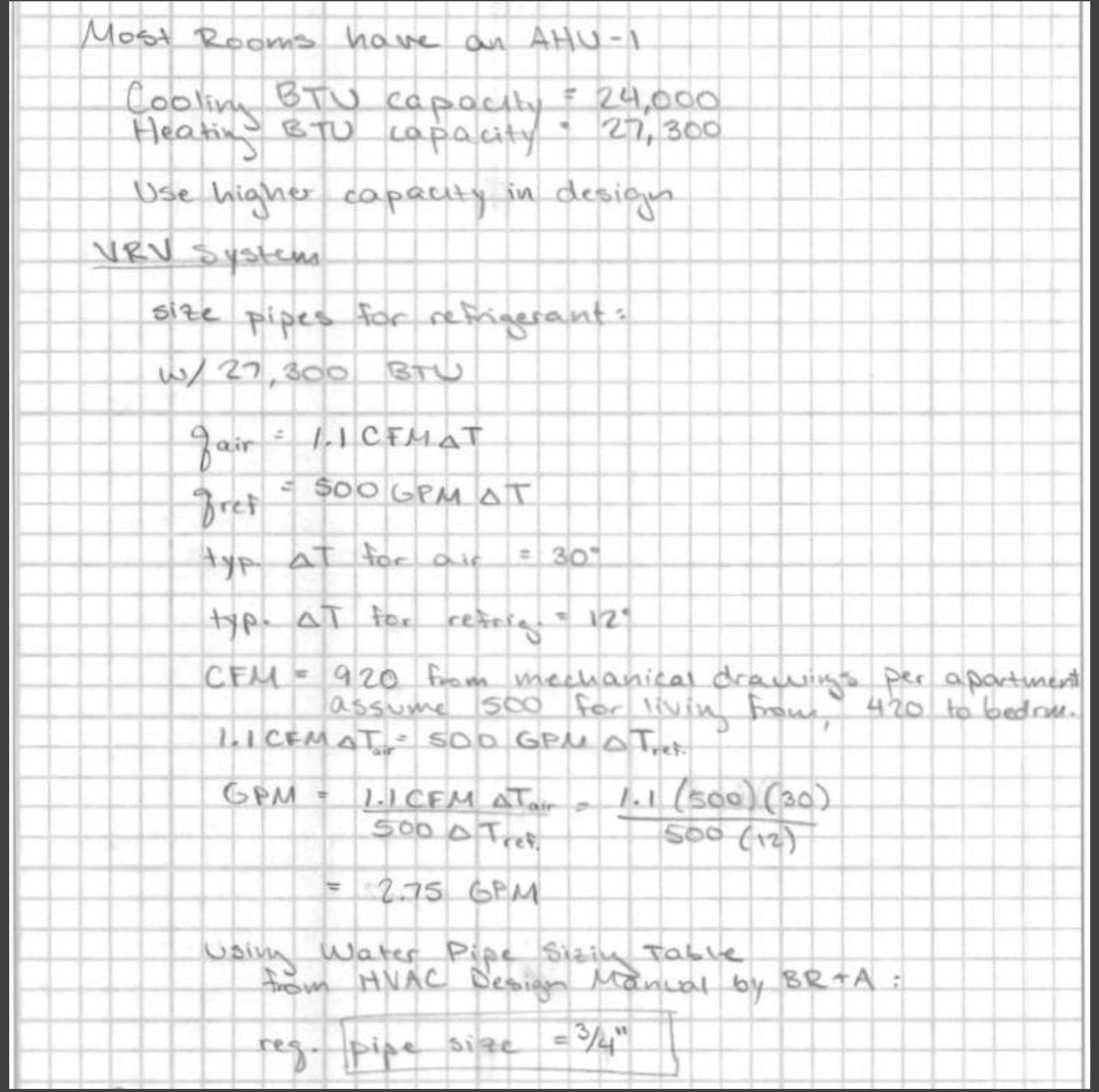
# Appendix

- Mechanical Sample Apartment



# Appendix

- Mechanical Calcs



Most Rooms have an AHU-1

Cooling BTU capacity = 24,000
Heating BTU capacity = 27,300

Use higher capacity in design

<u>VRV System</u>

size pipes for refrigerant:

w/ 27,300 BTU

$q_{air} = 1.1\ CFM\ \Delta T$

$q_{ref} = 500\ GPM\ \Delta T$

typ. $\Delta T$ for air = 30°

typ. $\Delta T$ for refrig. = 12°

CFM = 920 from mechanical drawings per apartment
assume 500 for living room, 420 to bedrm.

$1.1\ CFM\ \Delta T_{air} = 500\ GPM\ \Delta T_{ref.}$

$GPM = \frac{1.1\ CFM\ \Delta T_{air}}{500\ \Delta T_{ref.}} = \frac{1.1(500)(30)}{500(12)}$

$= 2.75$ GPM

Using Water Pipe Sizing Table
from HVAC Design Manual by BR+A:

req. pipe size = 3/4"