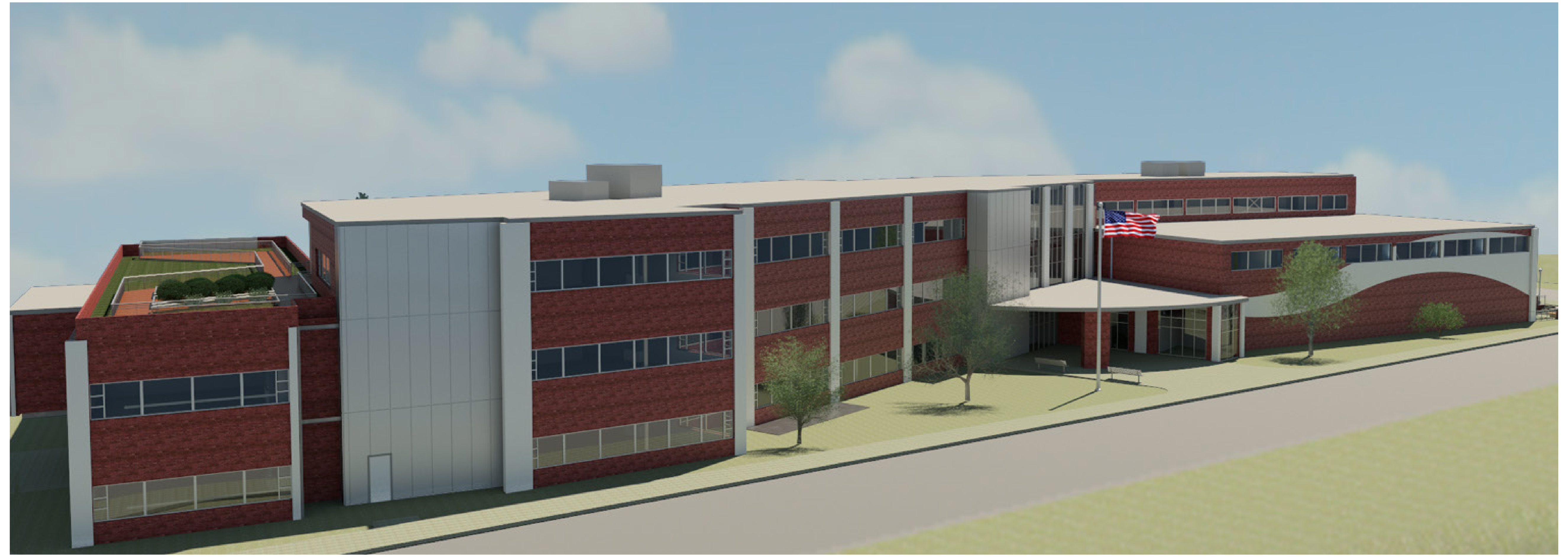
UNITUS
designing for people
enhancing environments
BUILDING TO UNITE US

High-Performance Reading Elementary School
Reading, Pennsylvania



Team Mission Statement

"Building to Unite Us"

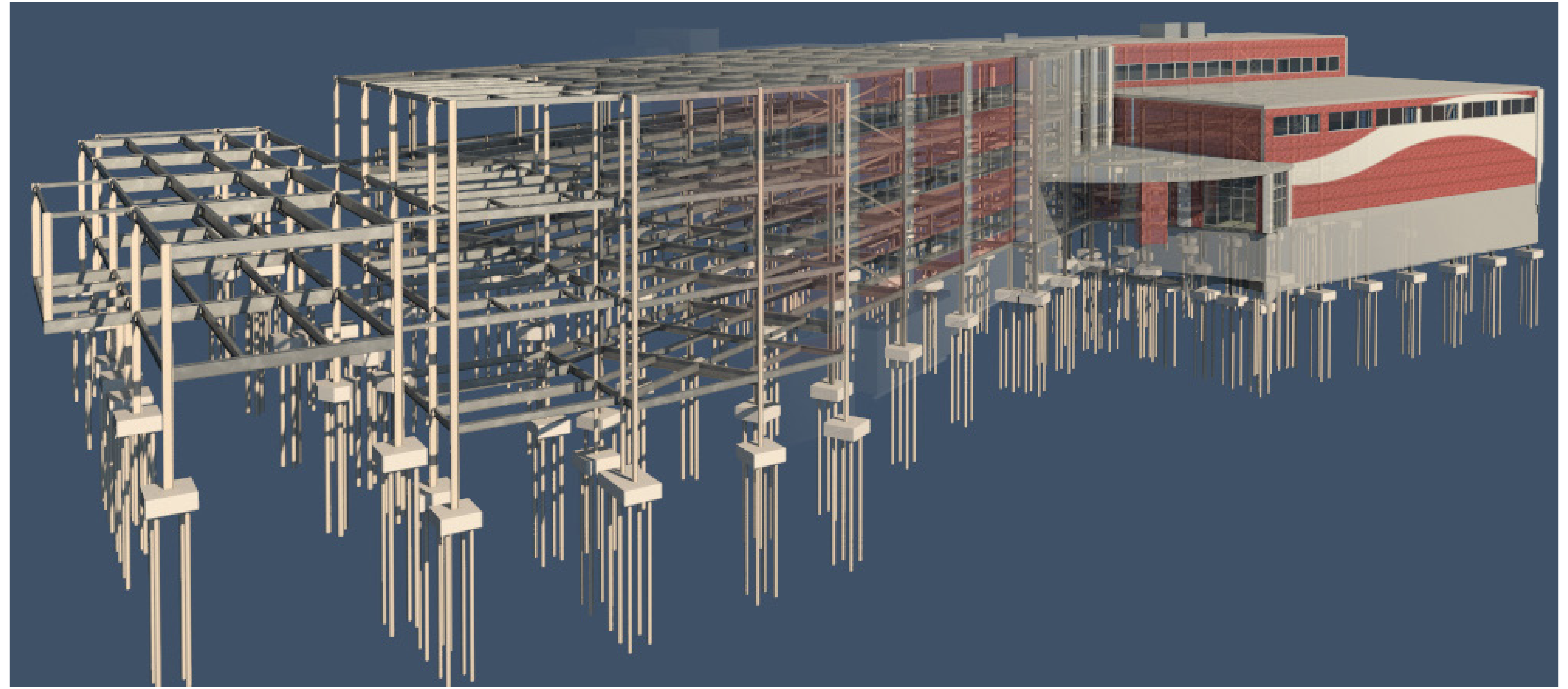
Project Mission Statement

"To build a stronger sense of community"

ASCE Charles Pankow Foundation Student Competition - Structural Systems
The Pennsylvania State University Senior BIM Thesis 2013 - Structural Option
Design Team - Eric Cook and Devon Saunders

Presentation Outline

- Project Overview
- Virtual Modeling & Analysis
- Code and Load Considerations
- Substructure
- Superstructure
- Areas of Interest



Presentation Outline

Project Overview
- Competition Guidelines
- Building Overview

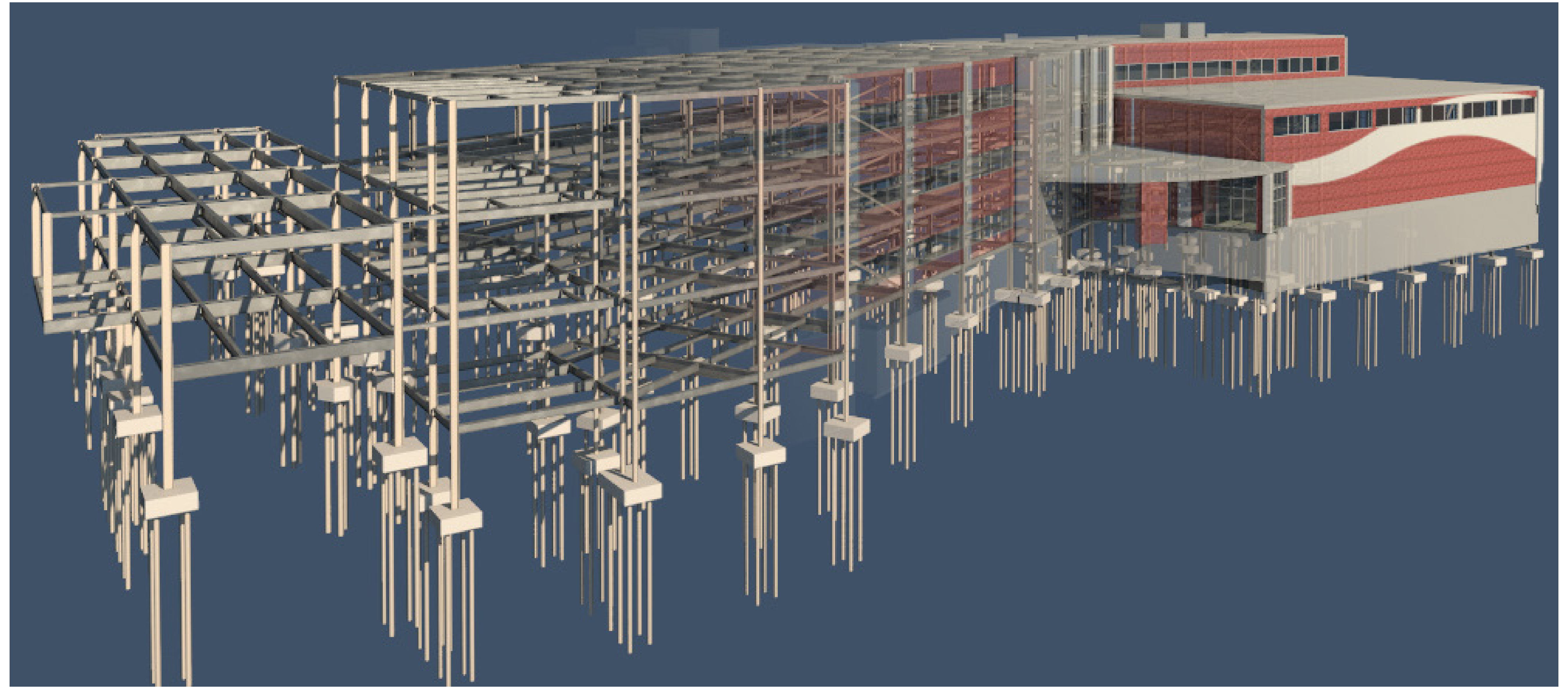
Virtual Modeling & Analysis
- Coordination Modeling and BIM

Code and Load Considerations

Substructure
- Grade Beams, Piles, and Pile Caps

Superstructure
- Gravity Framing
- Lateral Framing

Areas of Interest
- Building Envelope
- Multi Purpose Room
- Natatorium



CONSTRUCTION
Brian Blenner
Matthew Hoerner

LIGHTING / ELECTRICAL
Kyle Houser
Keith McMullen

STRUCTURAL
Eric Cook
Devon Saunders

MECHANICAL
Daniel McGee
Brittany Notor

Competition Guidelines

Teams should address:

“Construction and design issues related to a high performance building that meets the needs of both the school district and community”

“Innovation in the performance of building design and construction by advancing integration, collaboration, communication, and efficiency through new tools and technologies”

Structural Competition Guidelines

The design team shall:

“Consider the given Geotechnical Report and existing conditions ”

“Create a design development submittal of the structural systems (foundation and wall, floor, and roof framing systems)”

Building Overview

Project Owner: Reading School District
Project Name: High-Performance Elementary School
Project Location: Intersection of 13th Street and Union Street
Reading, Pennsylvania
Delivery Method: Integrated Project Delivery

Square Footage: 108,000 SF

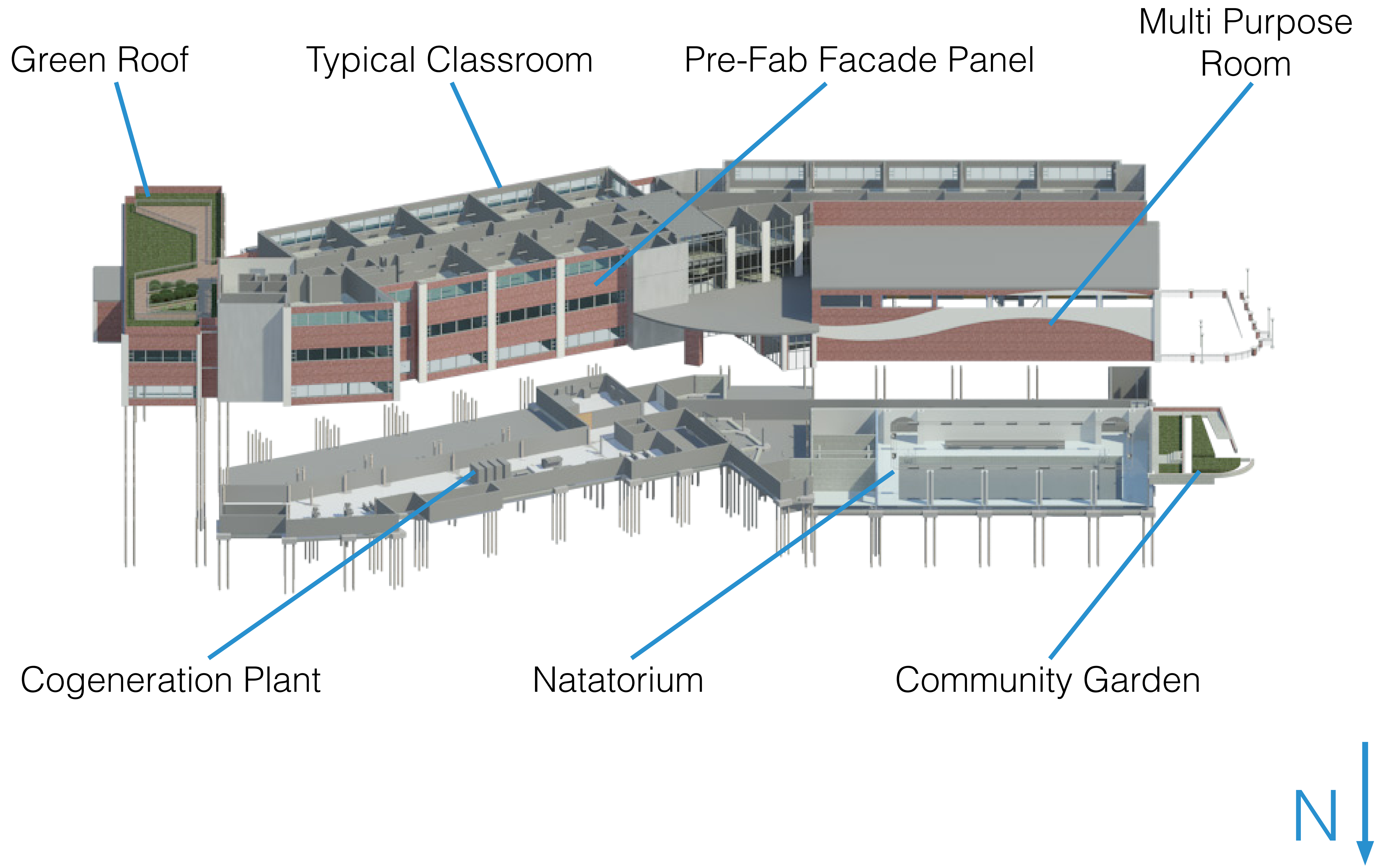
Overall Cost: $21,344,312
Cost per SF: $203.15

3 stories above grade, half-footprint basement level open to public

Multi Purpose Room, Community Health Clinic

6-lane, competition size swimming pool on the lower level

Applying for LEED GOLD certification



Building Overview

Project Owner: Reading School District
Project Name: High-Performance Elementary School
Project Location: Intersection of 13th Street and Union Street
Reading, Pennsylvania
Delivery Method: Integrated Project Delivery

Square Footage: 108,000 SF

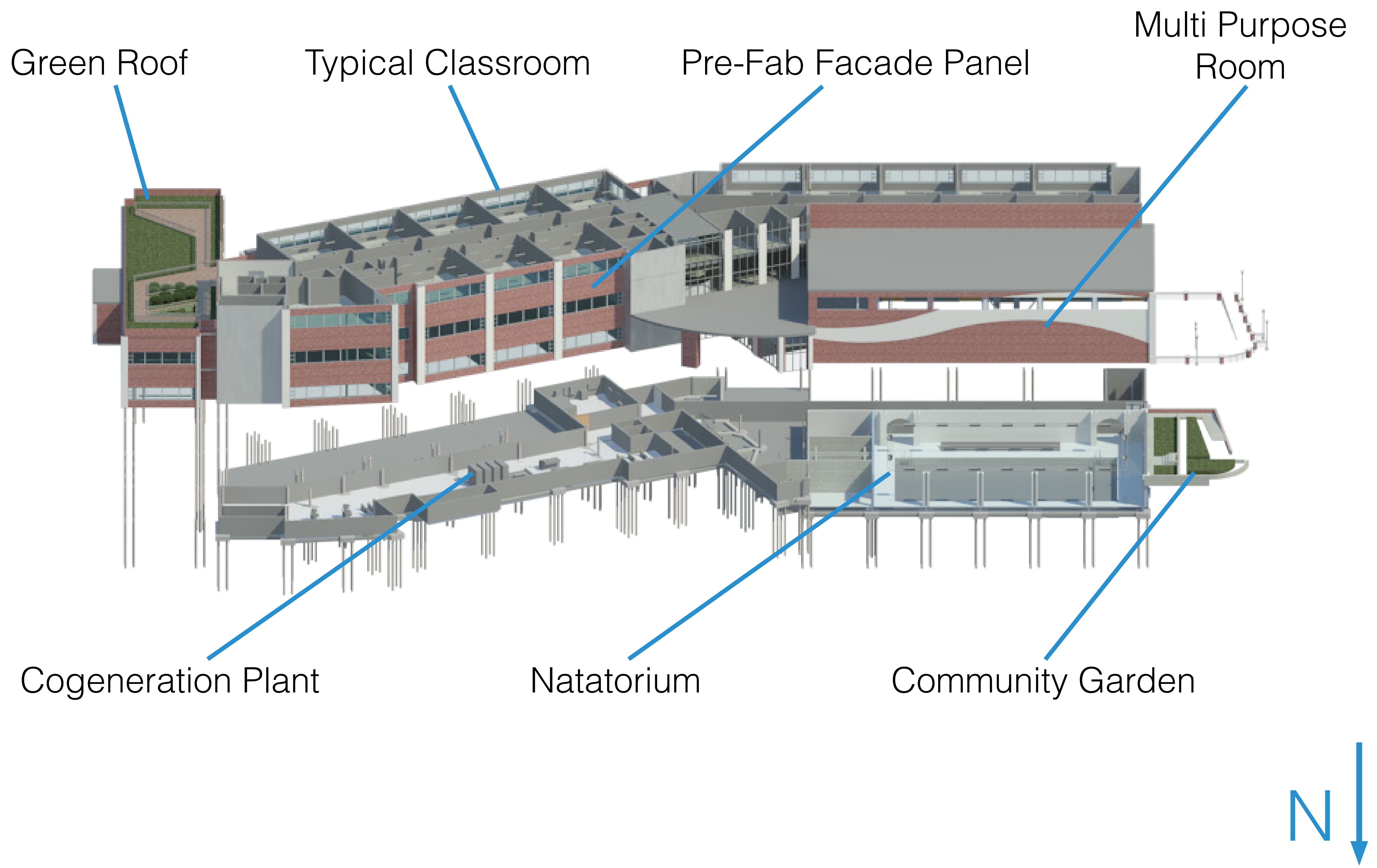
Overall Cost: $21,344,312
Cost per SF: $203.15

3 stories above grade, half-footprint basement level open to public

Multi Purpose Room, Community Health Clinic

6-lane, competition size swimming pool on the lower level

Applying for LEED GOLD certification



Community Based Criteria

- Transparent and open spaces that induce productivity in learning and allows for a crime-free environment
- A structural frame that defines educational spaces from community spaces

Building Overview

Project Owner: Reading School District
Project Name: High-Performance Elementary School
Project Location: Intersection of 13th Street and Union Street
Reading, Pennsylvania
Delivery Method: Integrated Project Delivery

Square Footage: 108,000 SF

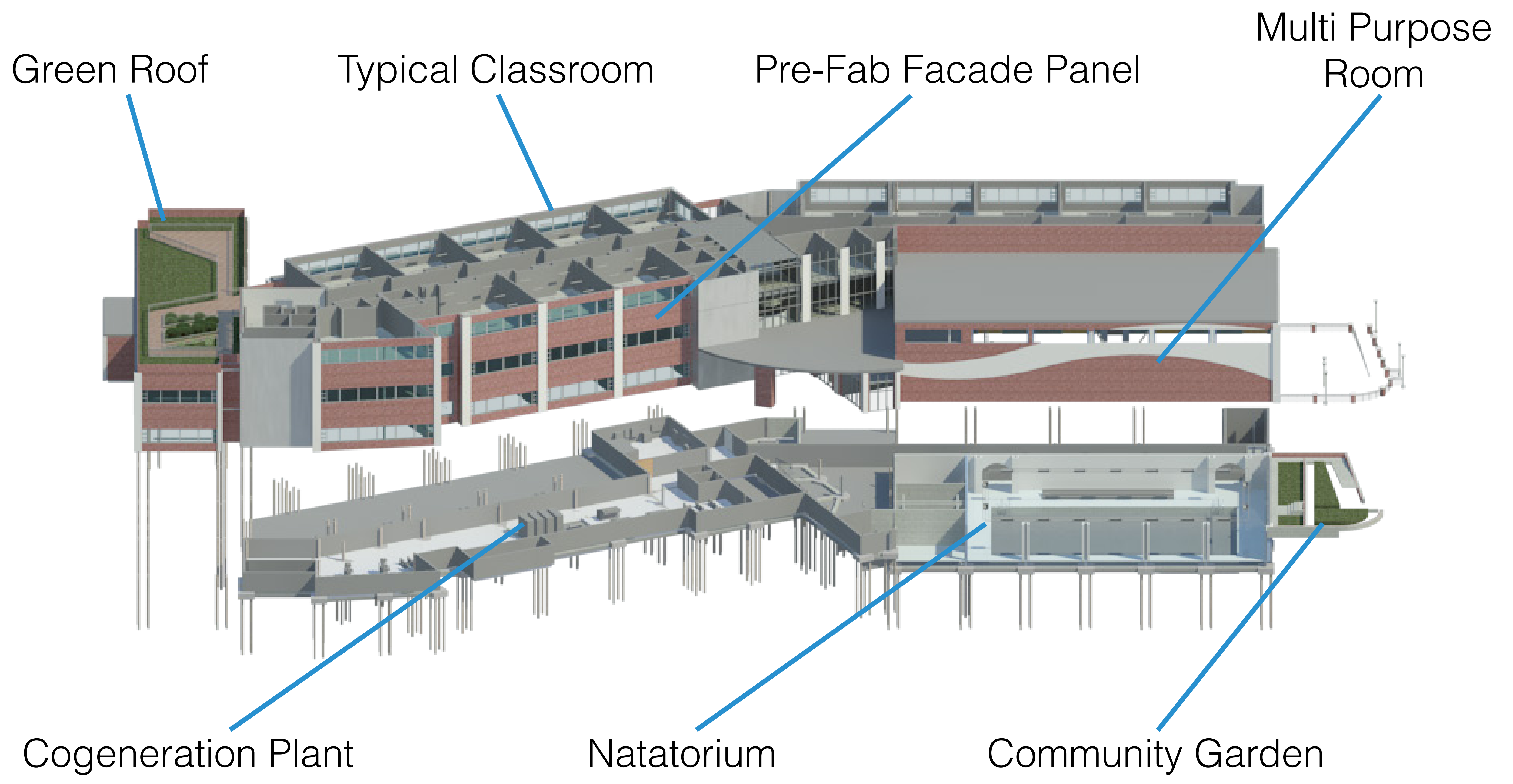
Overall Cost: $21,344,312
Cost per SF: $203.15

3 stories above grade, half-footprint basement level open to public

Multi Purpose Room, Community Health Clinic

6-lane, competition size swimming pool on the lower level

Applying for LEED GOLD certification



N

Community Based Criteria

- Transparent and open spaces that induce productivity in learning and allows for a crime-free environment
- A structural frame that defines educational spaces from community spaces

Design Based Criteria

- Capability of the frame integration with other engineering disciplines
- A design process and modeling techniques that allow for virtual and BIM based analyses

UNITUS
designing for people
enhancing environments
BUILDING TO UNITE US

OUTLINE

Project Overview
- Competition Guidelines
- Building Overview

Virtual Modeling and Analyses

Code and Load Considerations

Substructure

Superstructure

Areas of Interest

CONSTRUCTION
Brian Blenner
Matthew Hoerner

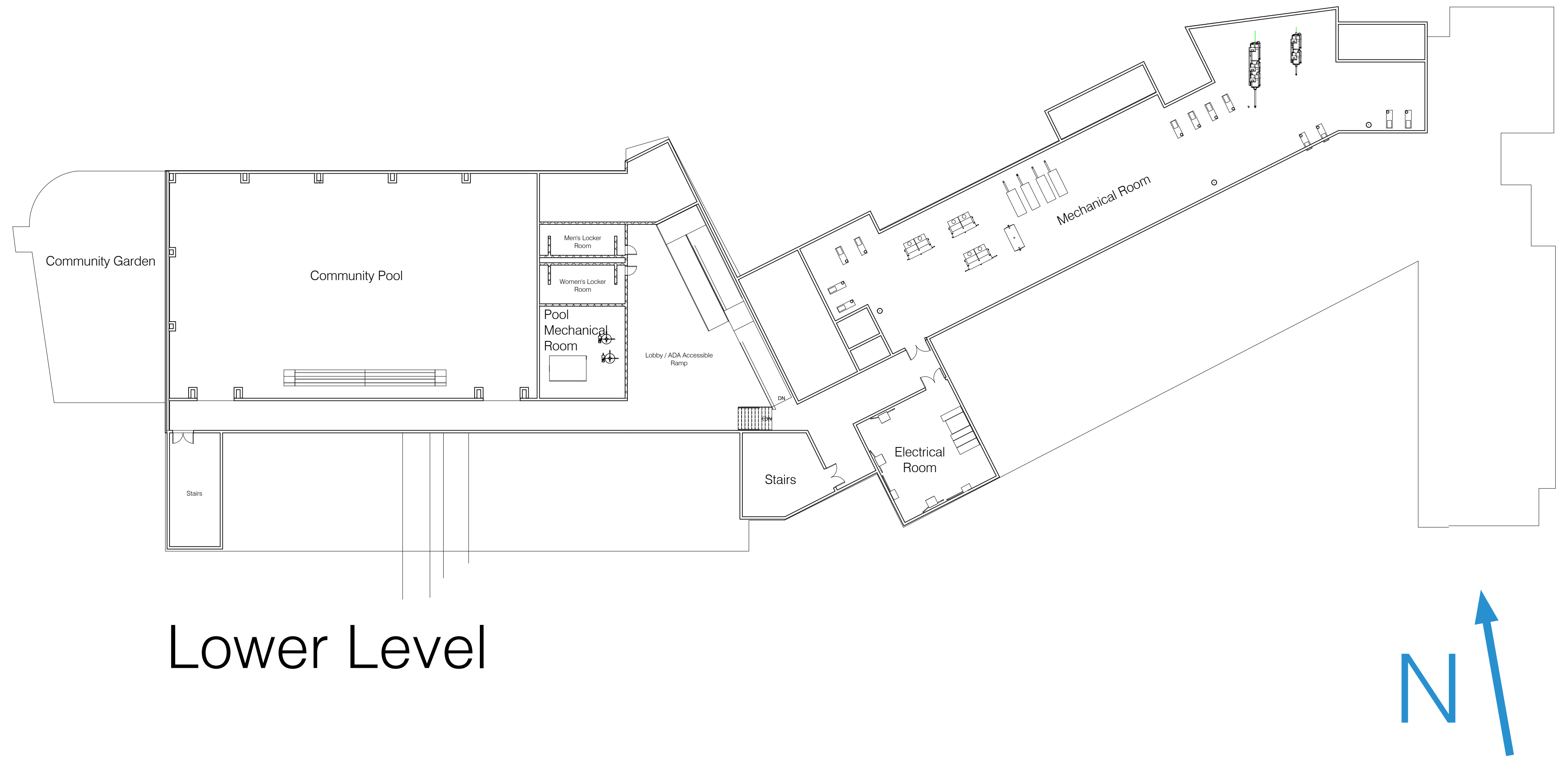
LIGHTING / ELECTRICAL
Kyle Houser
Keith McMullen

STRUCTURAL
Eric Cook
Devon Saunders

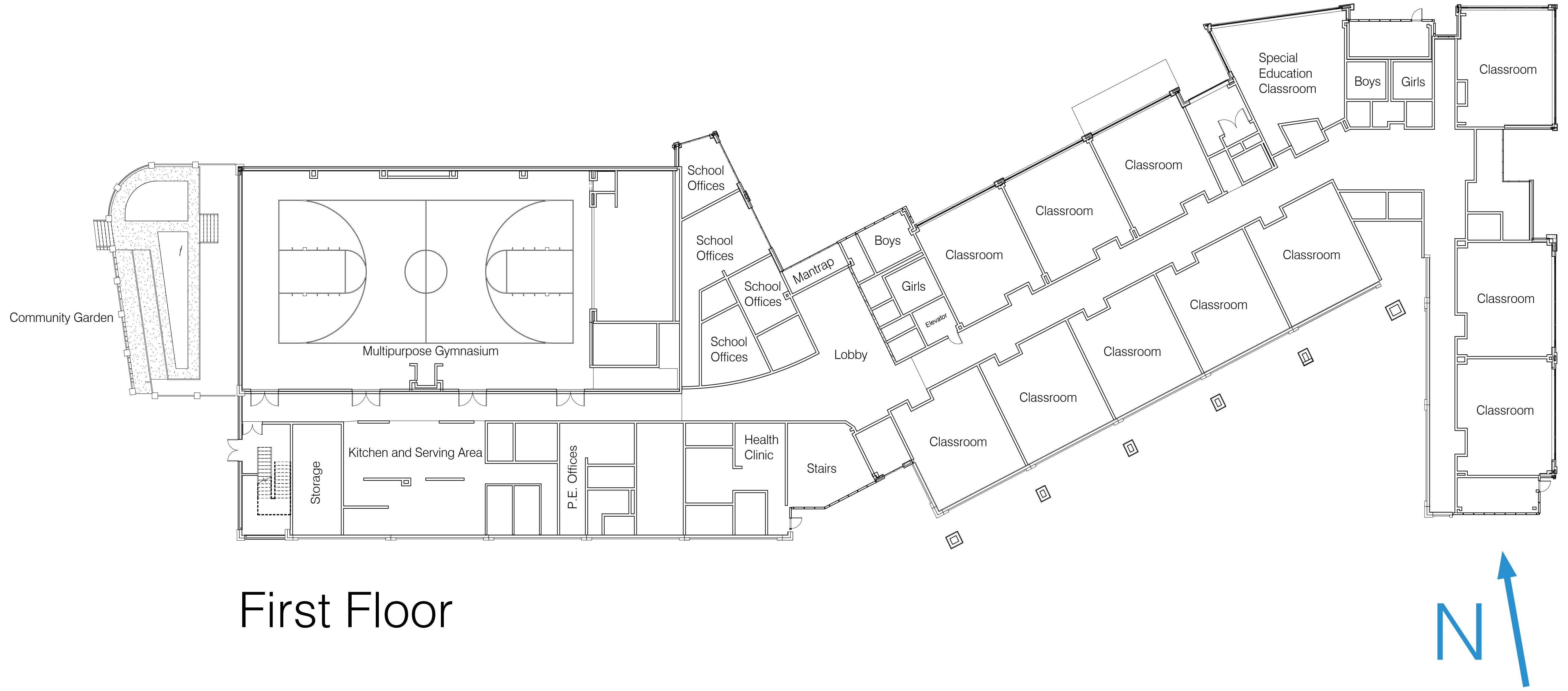
MECHANICAL
Daniel McGee
Brittany Notor

High Performance Elementary School
Reading, Pennsylvania

Building Overview - Floor Plans

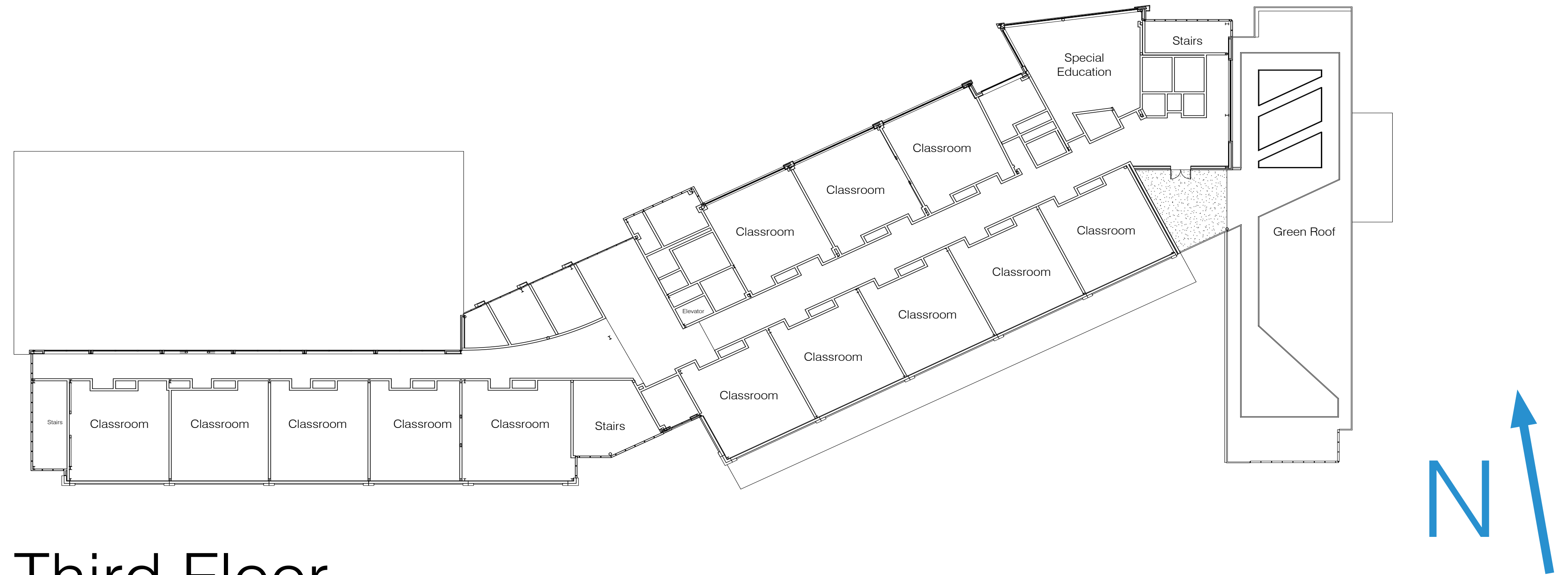


Lower Level



First Floor

Second Floor



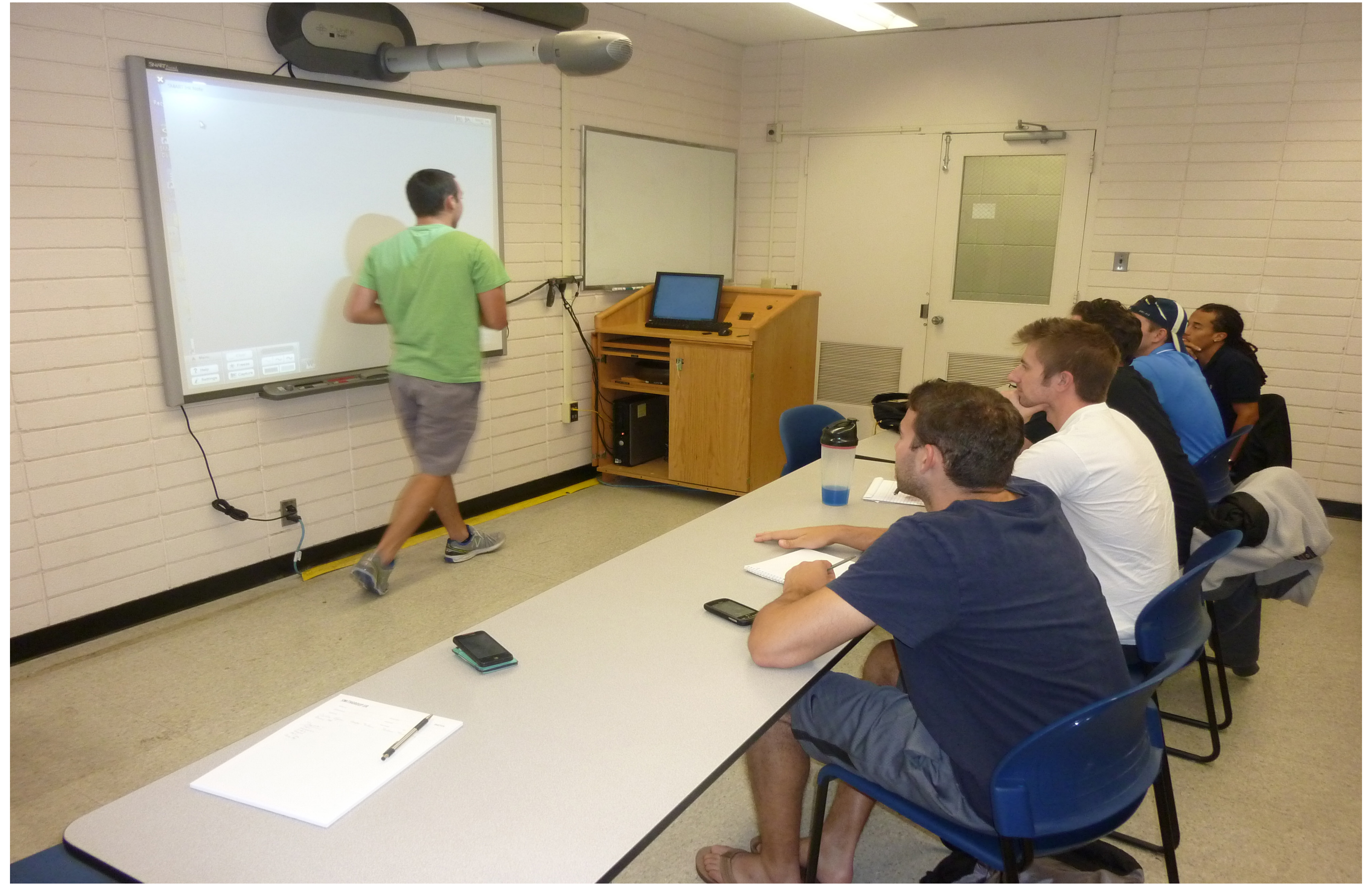
Third Floor

ASCE Charles Pankow Foundation Student Competition
The Pennsylvania State University Department of Architectural Engineering

Coordination Modeling and BIM

"Big Room" design approach

Team Collaboration

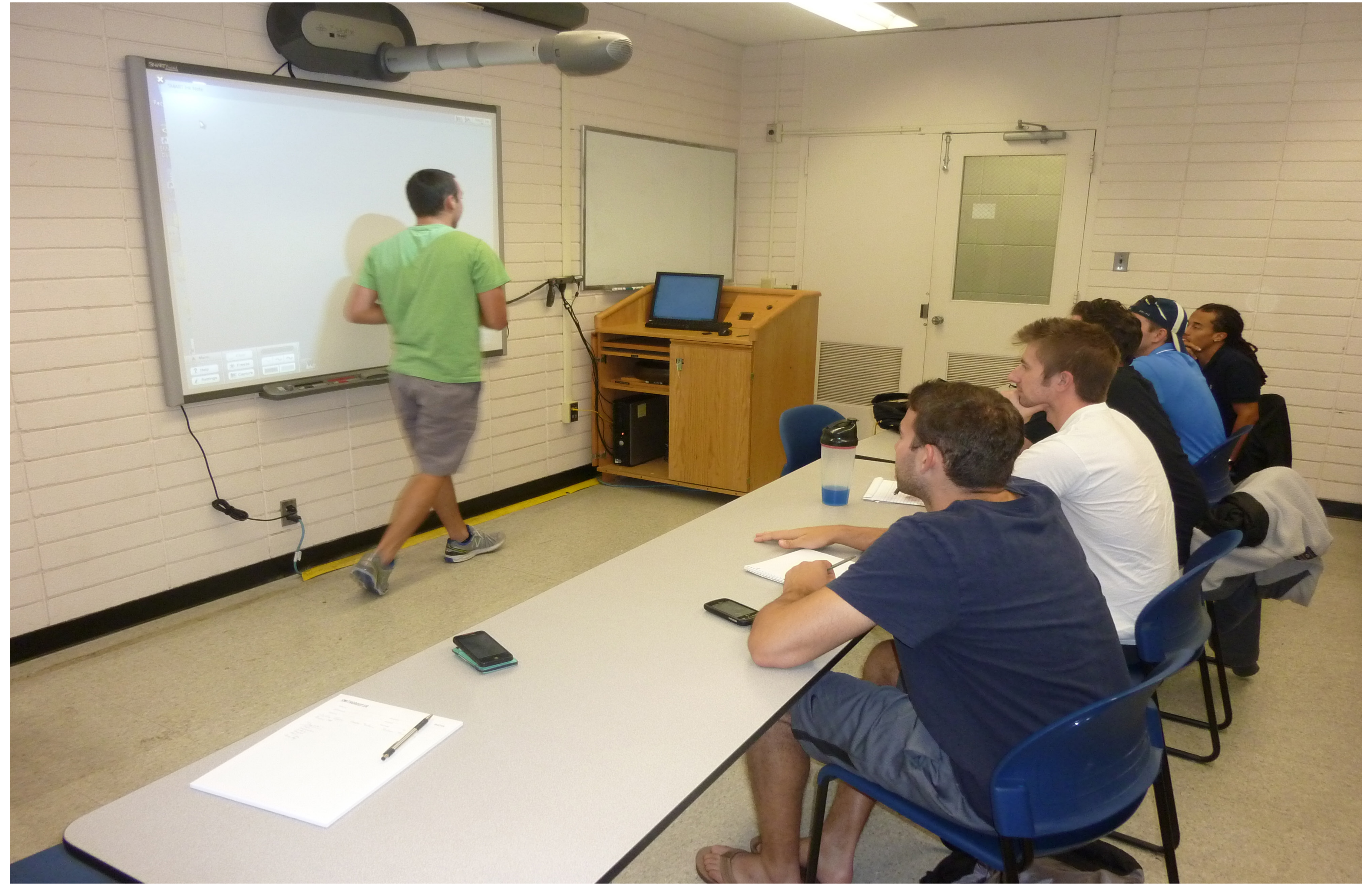


Coordination Modeling and BIM

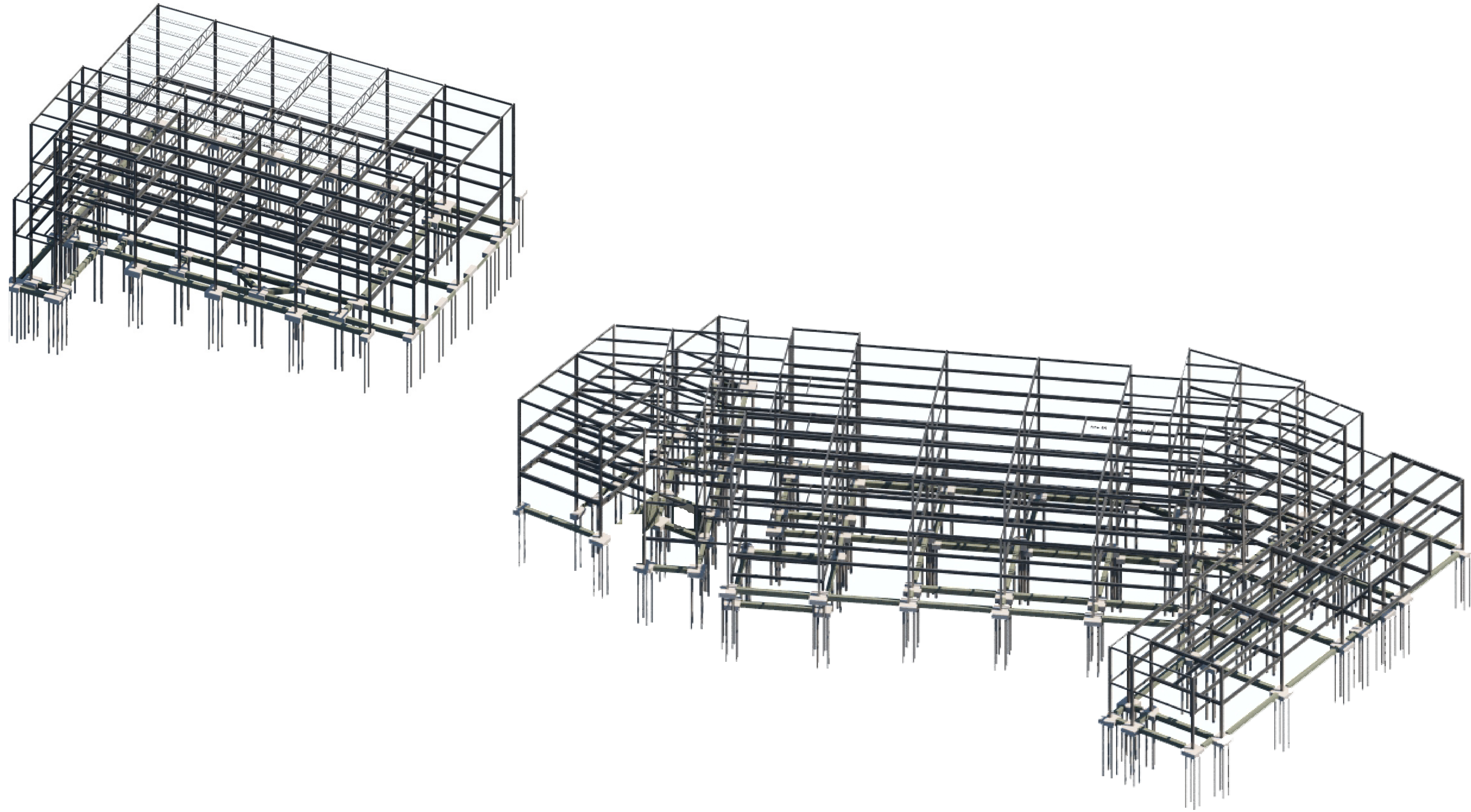
"Big Room" design approach

Structural layout with Revit

Team Collaboration



Structural Layout Using Revit



UNITUS
designing for people
enhancing environments
BUILDING TO UNITE US

OUTLINE

Project Overview

Virtual Modeling and Analyses

Coordinaton Modeling and BIM

Code and Load Considerations

Substructure

Superstructure

Areas of Interest

CONSTRUCTION
Brian Blenner
Matthew Hoerner

LIGHTING / ELECTRICAL
Kyle Houser
Keith McMullen

STRUCTURAL
Eric Cook
Devon Saunders

MECHANICAL
Daniel McGee
Brittany Notor

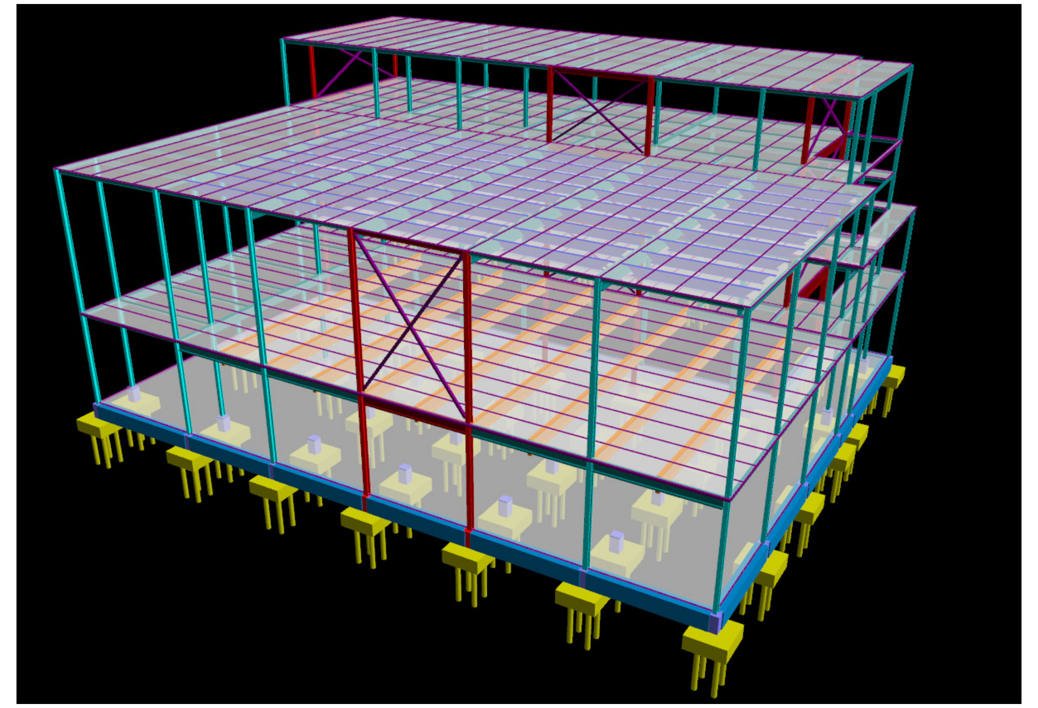
Coordination Modeling and BIM

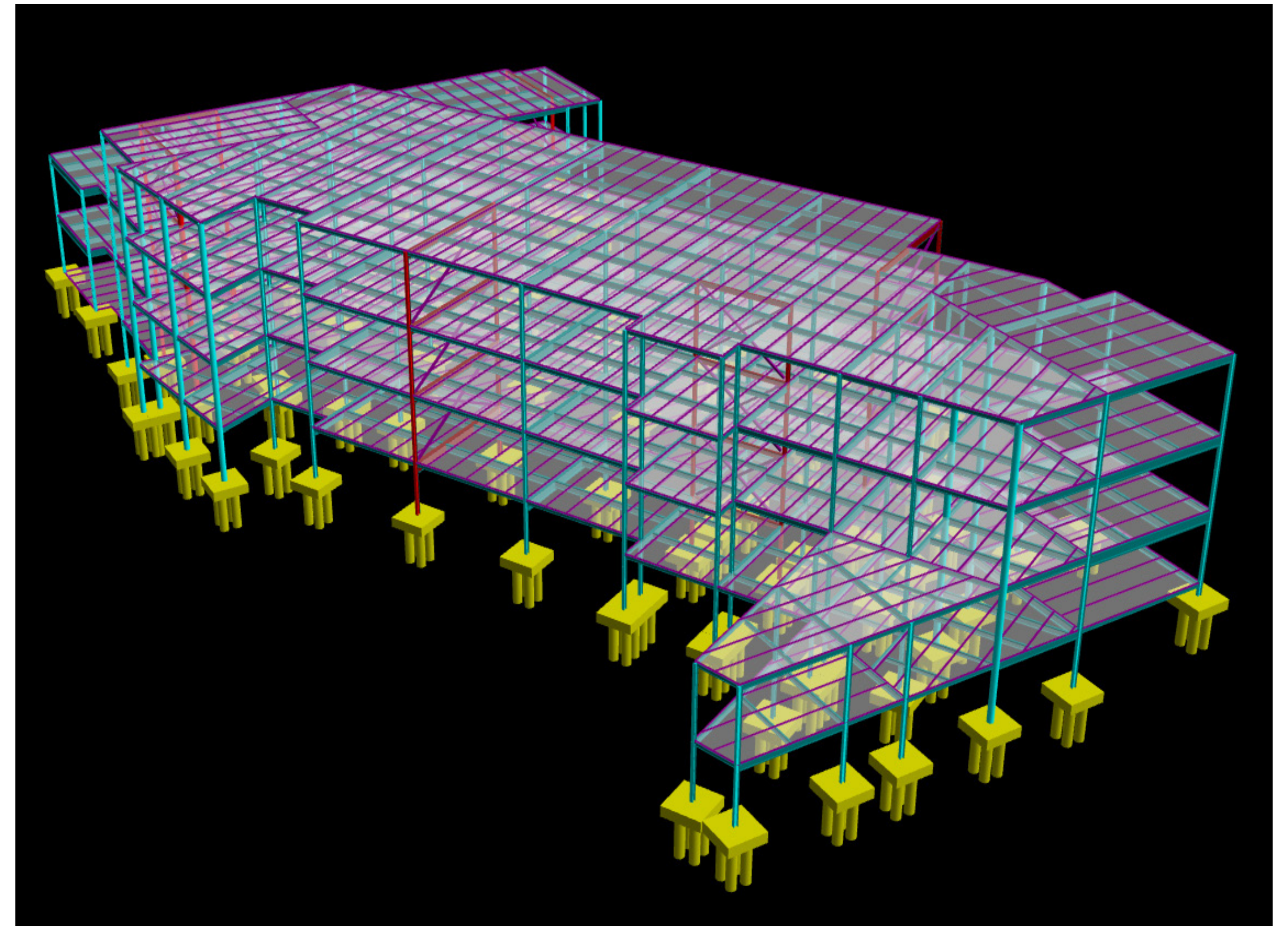
“Big Room” design approach

Structural layout with Revit

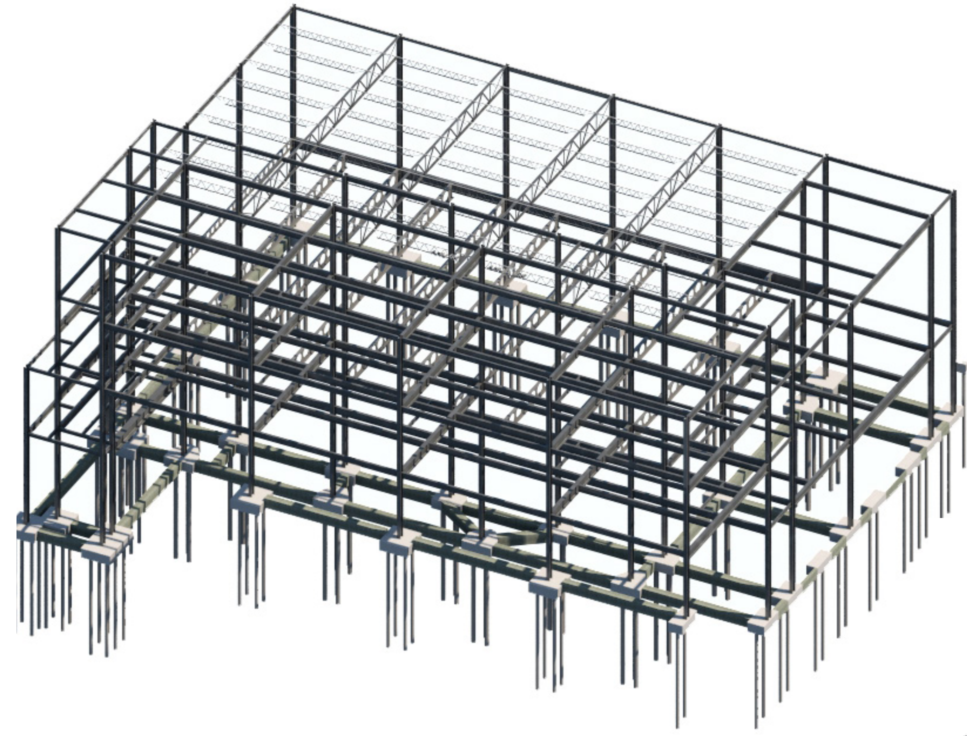
Analysis in RAM Structural Systems

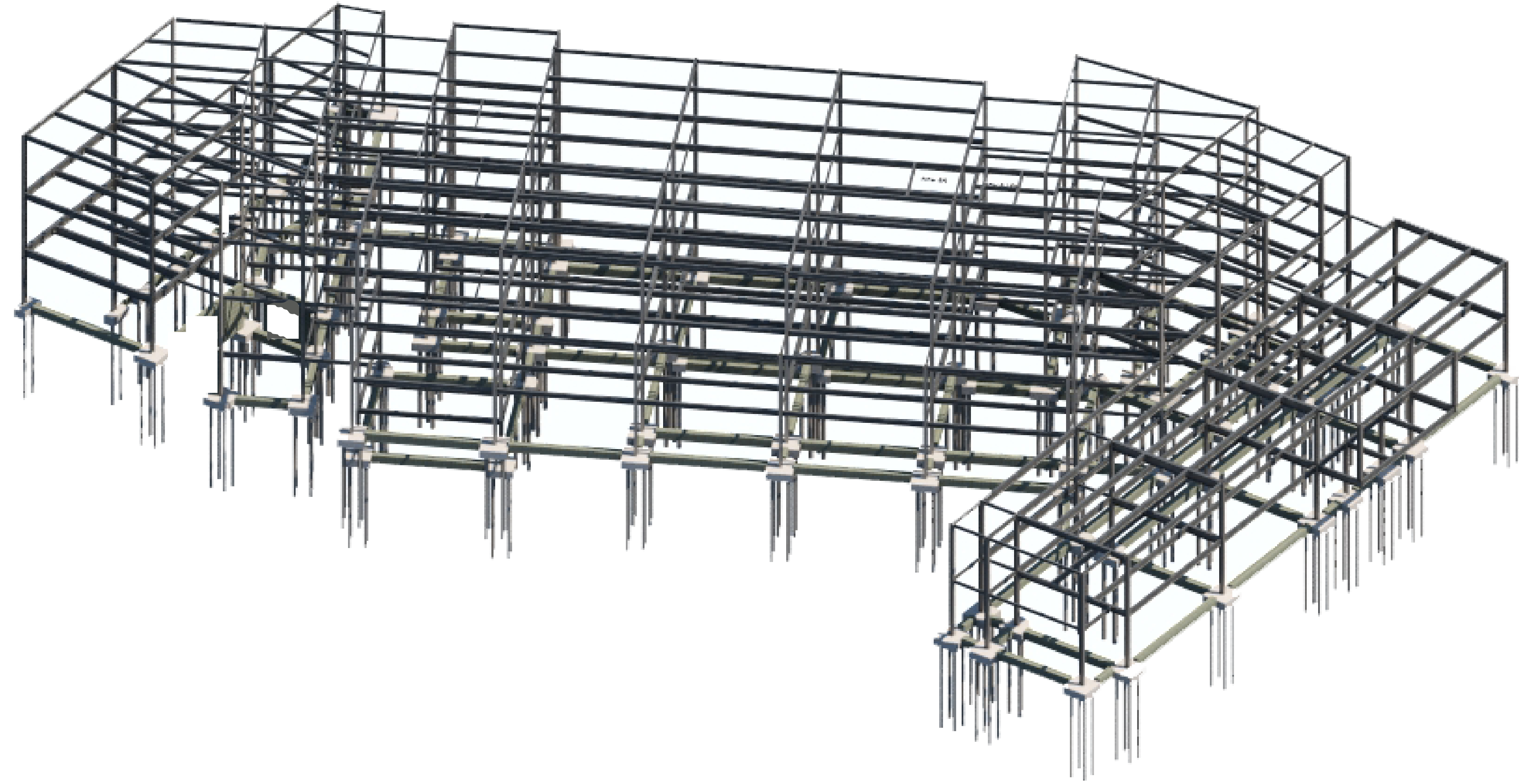
Structural Analysis Using RAM





Structural Layout Using Revit





Coordination Modeling and BIM

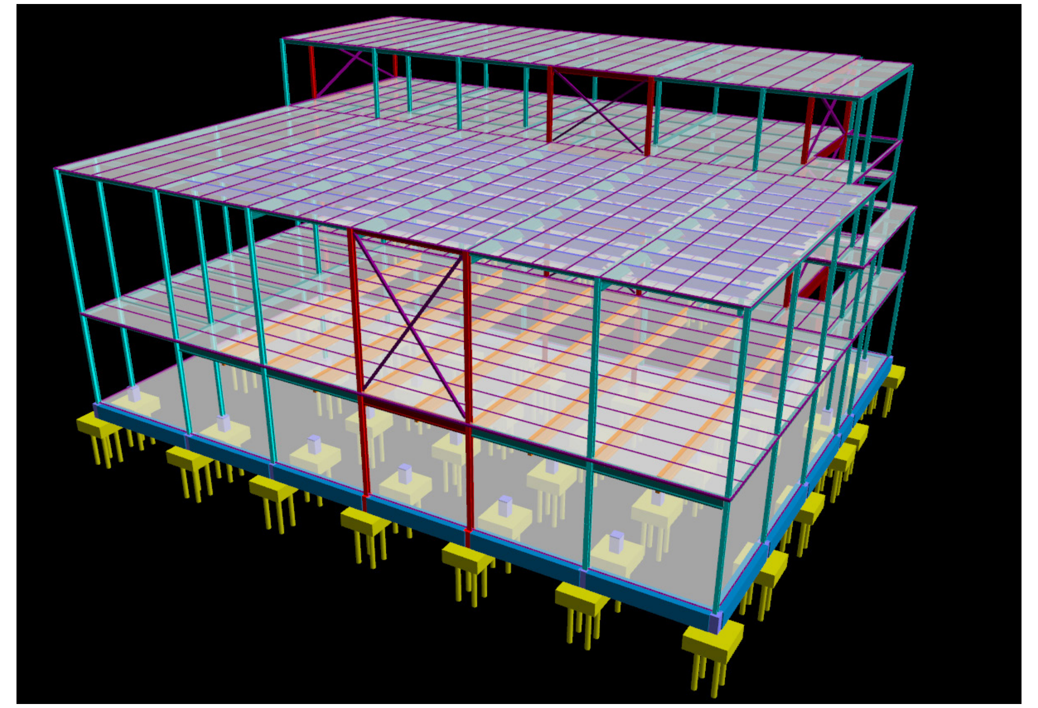
“Big Room” design approach

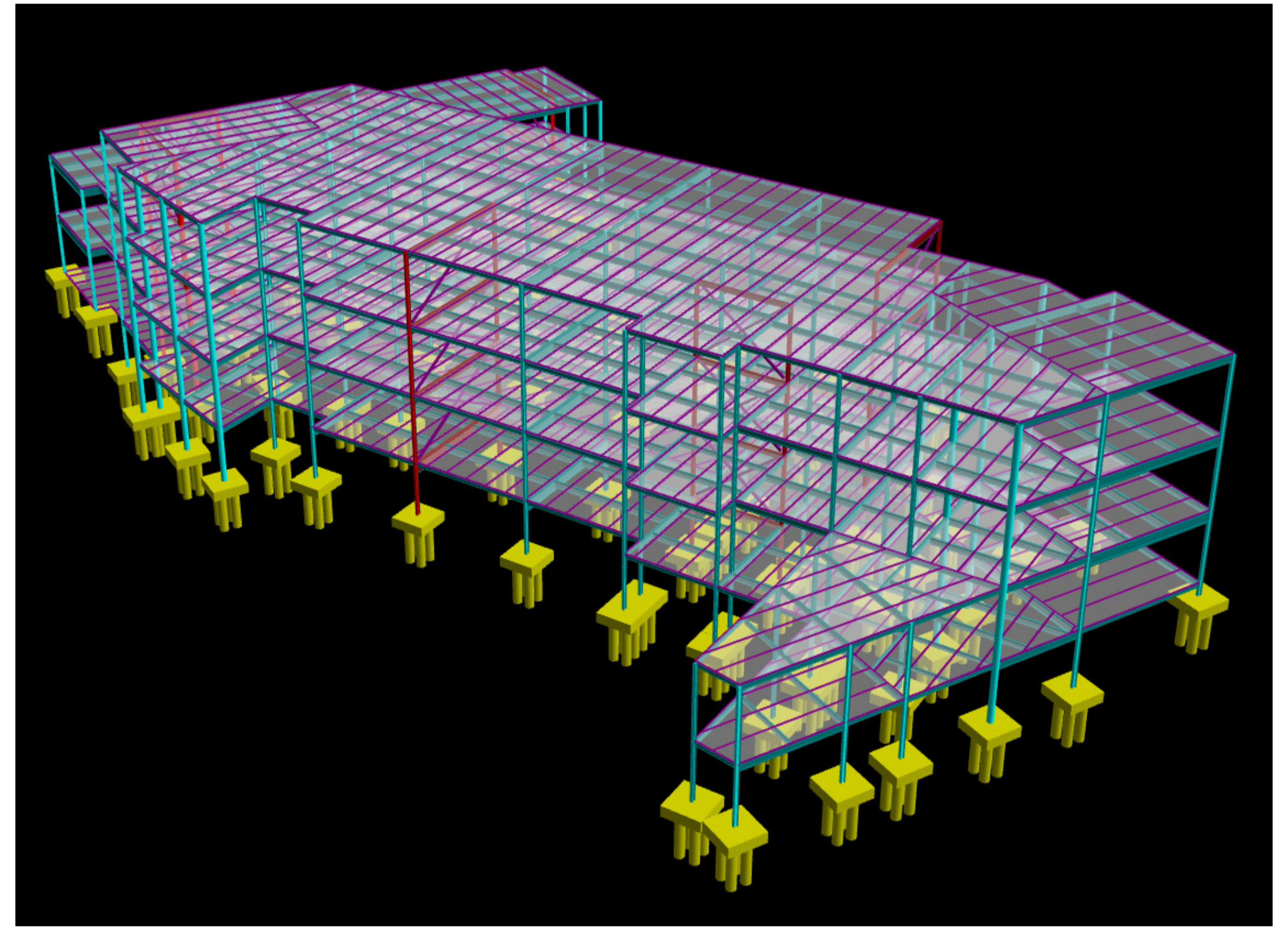
Structural layout with Revit

Analysis in RAM Structural Systems

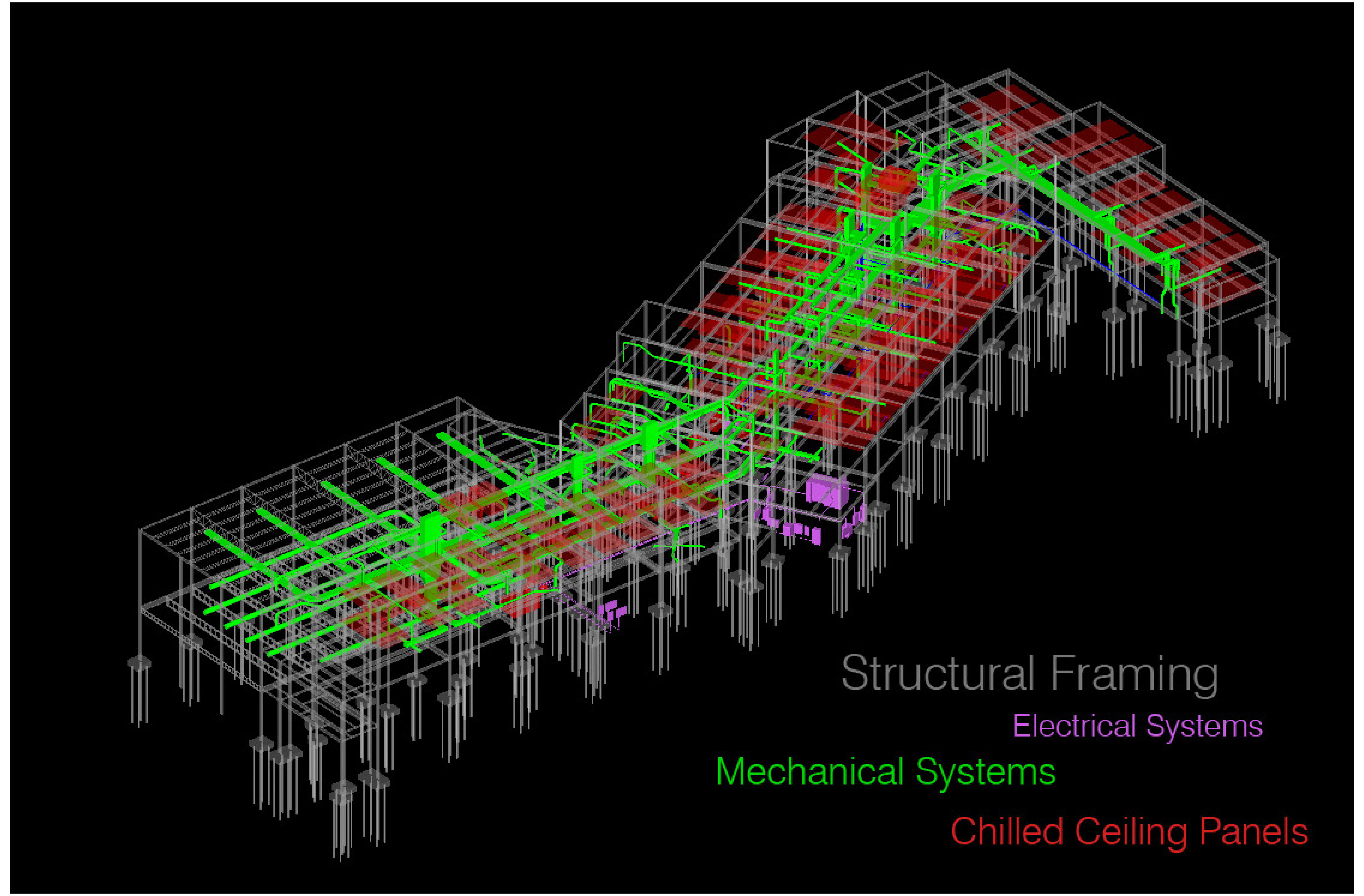
Virtual modeling work sessions

Structural Analysis Using RAM

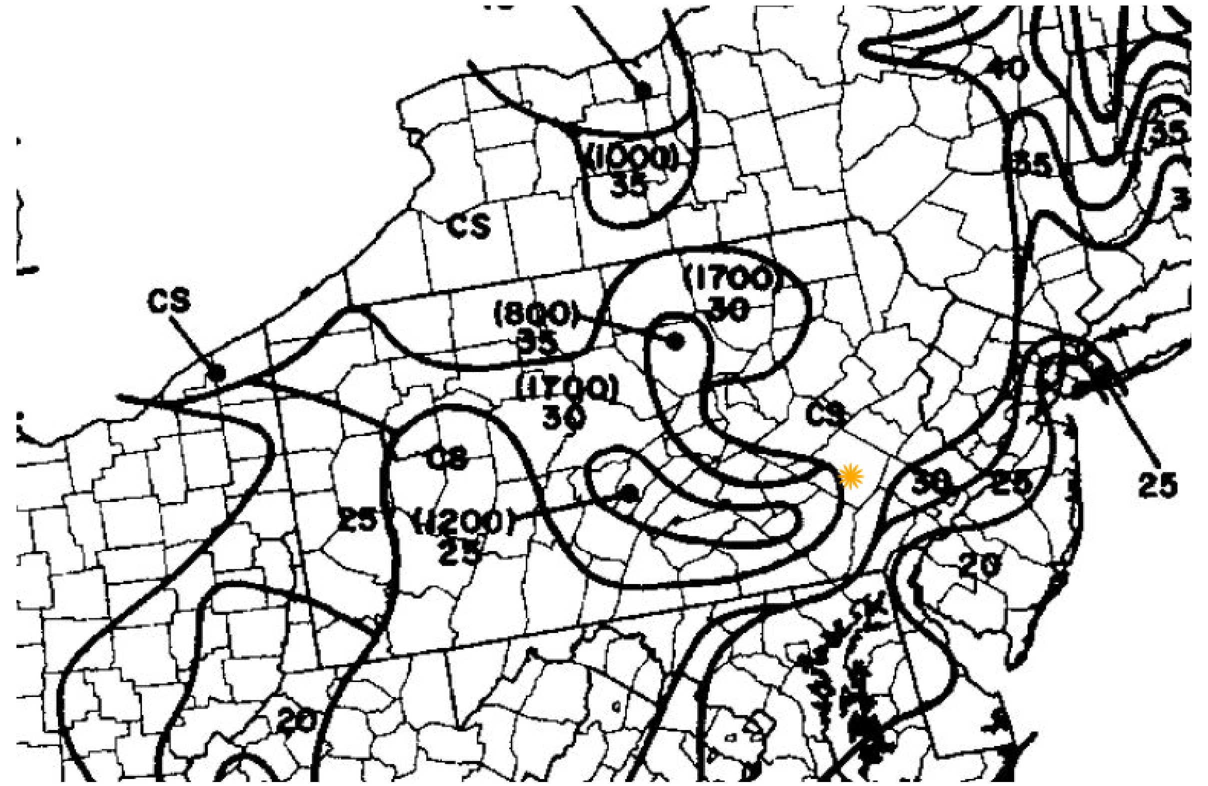




Virtual Coordination Model



Code and Load Considerations



Local Reading Building Codes

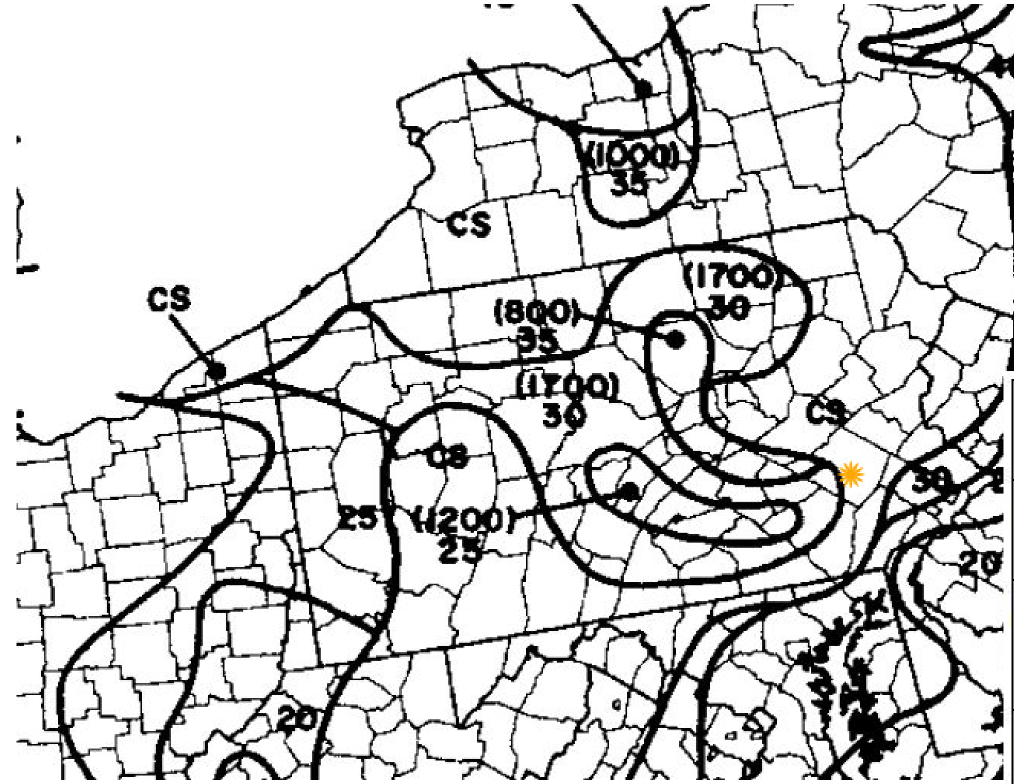
Ground snow load case study region

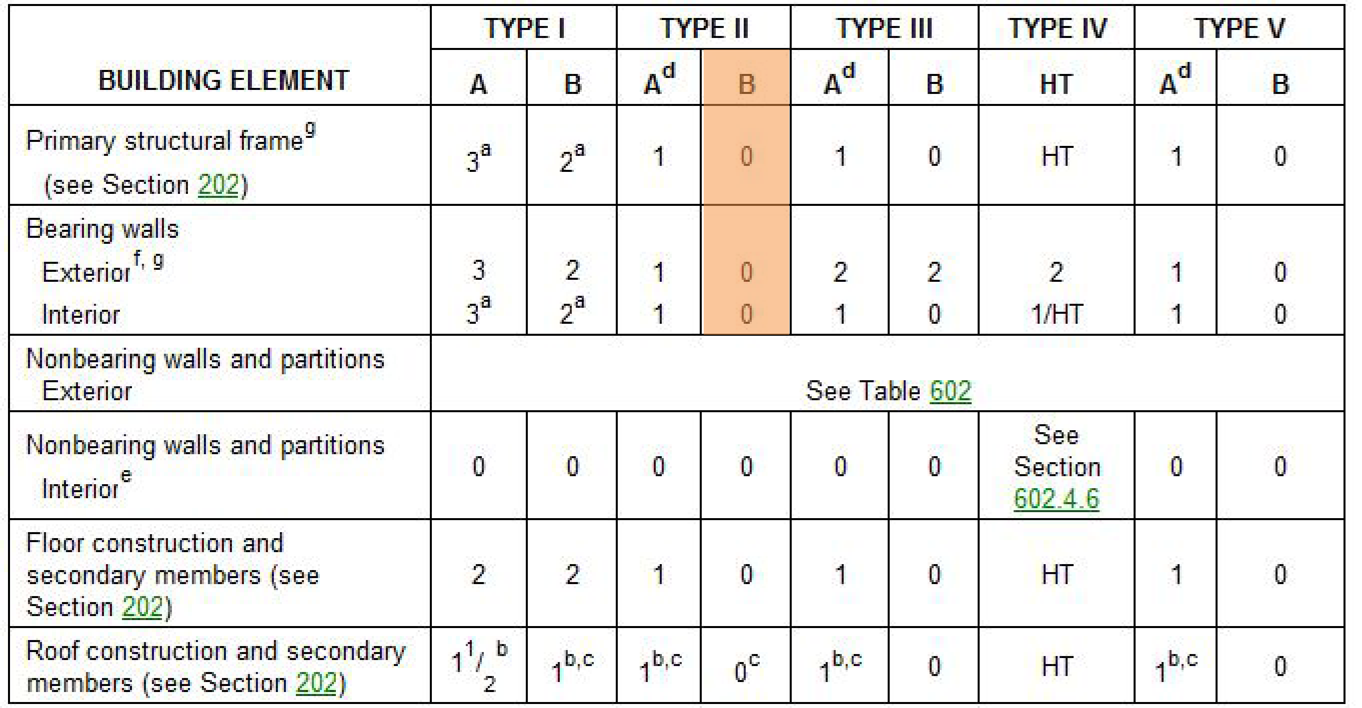
Code and Load Considerations

Local Reading Building Codes

Ground snow load case study region

IBC classification B type II Construction





BUILDING ELEMENT	TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
	A	B	A^d	B	A^d	B	HT	A^d	B
Primary structural frame^g (see Section 202)	3^a	2^a	1	0	1	0	HT	1	0
Bearing walls									
Exterior$^{f, g}$	3	2	1	0	2	2	2	1	0
Interior	3^a	2^a	1	0	1	0	1/HT	1	0
Nonbearing walls and partitions Exterior	See Table 602								
Nonbearing walls and partitions Interior^e	0	0	0	0	0	0	See Section 602.4.6	0	0
Floor construction and secondary members (see Section 202)	2	2	1	0	1	0	HT	1	0
Roof construction and secondary members (see Section 202)	$1\frac{1}{2}^b$	1^{b,c}	1^{b,c}	0^c	1^{b,c}	0	HT	1^{b,c}	0

Code and Load Considerations

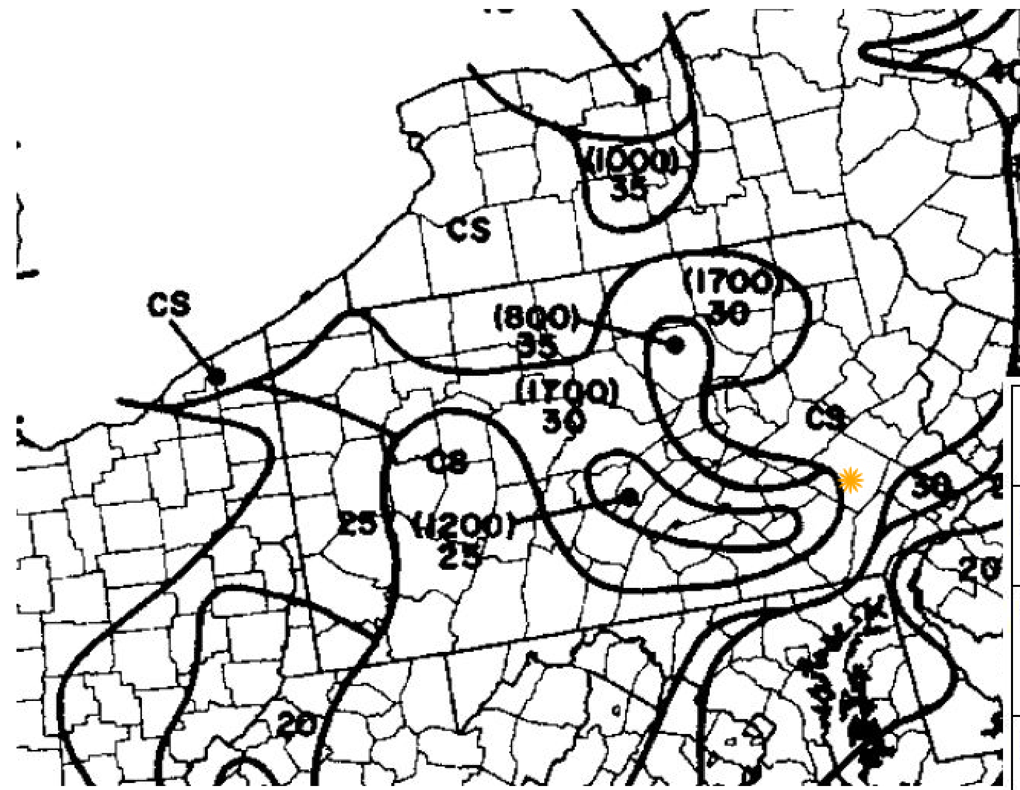
Local Reading Building Codes

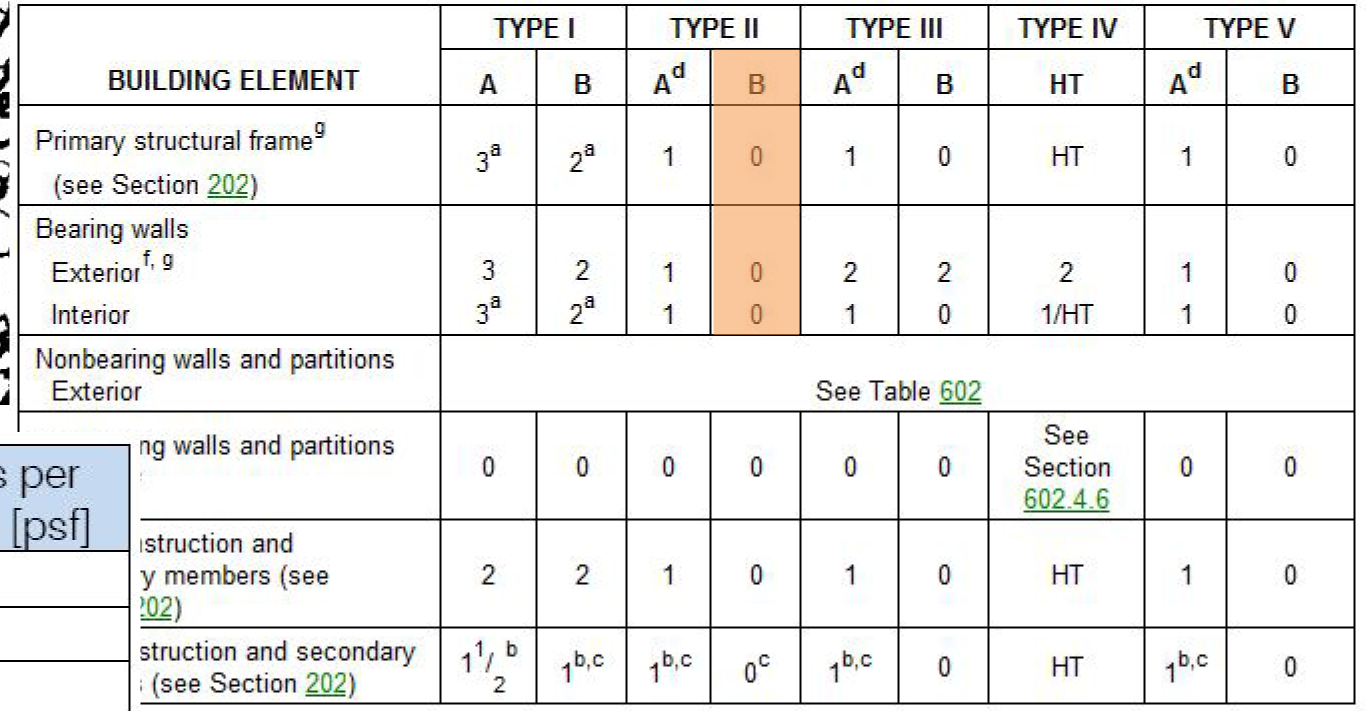
Ground snow load case study region

IBC classification B type II Construction

Design Loads

Live and snow loads





BUILDING ELEMENT	TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
	A	B	A^d	B	A^d	B	HT	A^d	B
Primary structural frame^g (see Section 202)	3^a	2^a	1	0	1	0	HT	1	0
Bearing walls Exterior^{f,g} Interior	 3 3^a	 2 2^a	 1 1	 0 0	 2 1	 2 0	 2 1/HT	 1 1	 0 0
Nonbearing walls and partitions Exterior	See Table 602								
ng walls and partitions	0	0	0	0	0	0	See Section 602.4.6	0	0
istruction and y members (see 02)	2	2	1	0	1	0	HT	1	0
struction and secondary (see Section 202)	1 1/2^b	1^{b,c}	1^{b,c}	0^c	1^{b,c}	0	HT	1^{b,c}	0

Space	Live Loads per ASCE 7-05 [psf]
Flat Roof	20
Green Roof	100
Classroom	40
Corridor on 1st Flr	100
Corridors above 1st Flr	80
Gymnasium	100
Stairs/Exits	100

Note: Live Loads subject to reduction except for Roof Live Load

Level	Snow Loads [psf]
Ground (Local Code)	35
Roof (east wing / west wing)	27 / 29.4

Note: Roof Snow Load found using ASCE 7-05 Eqn. 7-1

Code and Load Considerations

Local Reading Building Codes

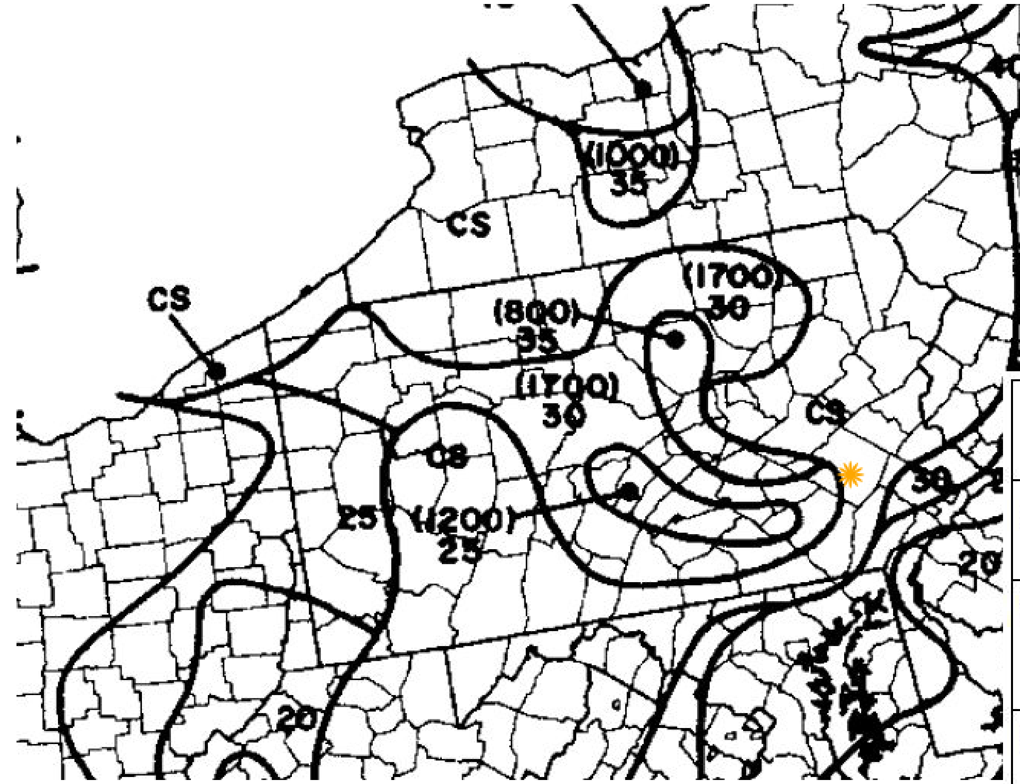
Ground snow load case study region

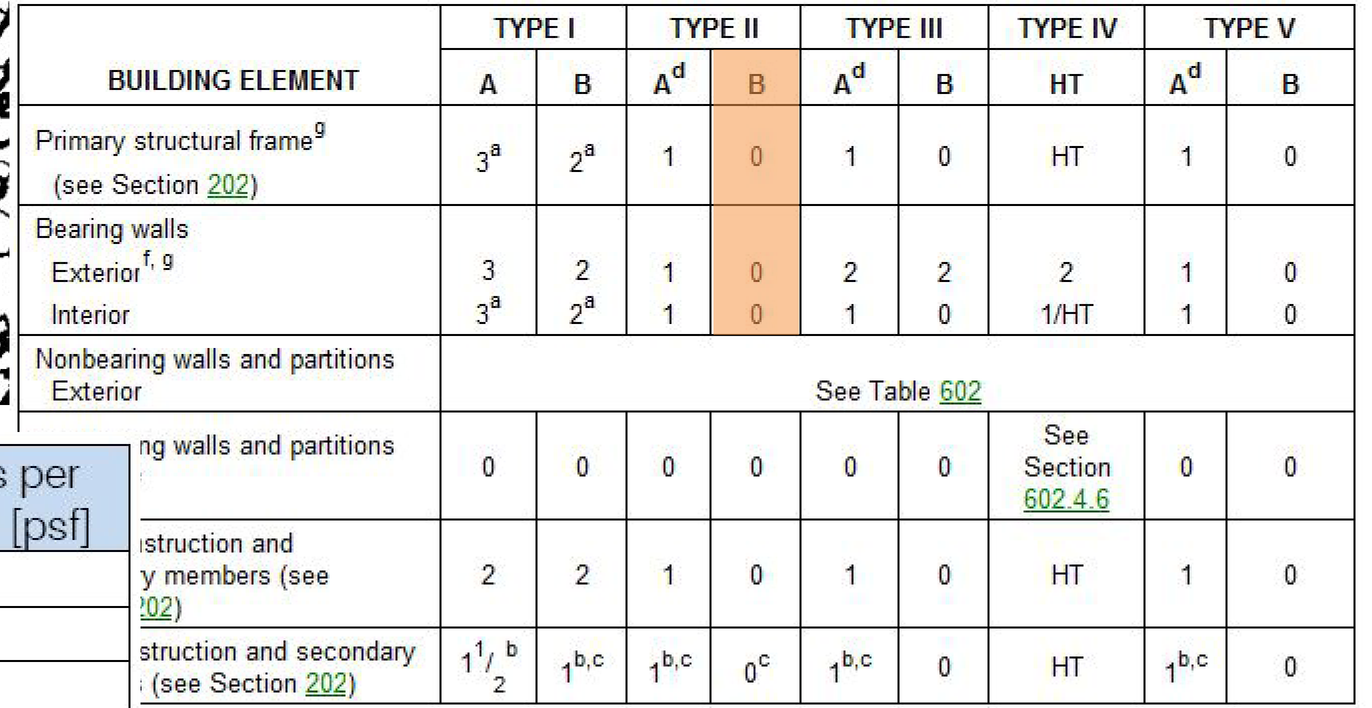
IBC classification B type II Construction

Design Loads

Live and snow loads

Dead loads





BUILDING ELEMENT	TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
	A	B	A[d]	B	A[d]	B	HT	A[d]	B
Primary structural frame[g] (see Section 202)	3[a]	2[a]	1	0	1	0	HT	1	0
Bearing walls Exterior[f, g] Interior	 3 3[a]	 2 2[a]	 1 1	 0 0	 2 1	 2 0	 2 1/HT	 1 1	 0 0
Nonbearing walls and partitions Exterior	See Table 602								
ng walls and partitions	0	0	0	0	0	0	See Section 602.4.6	0	0
struction and y members (see 202)	2	2	1	0	1	0	HT	1	0
struction and secondary (see Section 202)	$1\frac{1}{2}$[b]	1[b,c]	1[b,c]	0[c]	1[b,c]	0	HT	1[b,c]	0

Space	Live Loads per ASCE 7-05 [psf]
Flat Roof	20
Green Roof	100
Classroom	40
Corridor on 1st Flr	100
Corridors above 1st Flr	80
Gymnasium	100
Stairs/Exits	100

Note: Live Loads subject to reduction except for Roof Live Load

Level	Snow Loads [psf]
Ground (Local Code)	35
Roof (east wing / west wing)	27 / 29.4

Note: Roof Snow Load found using ASCE 7-05 Eqn. 7-1

Material	Dead Loads [psf]
Built-up Roof	20
Misc. (ducts, fixtures, etc.)	10
3 VLI Deck w/ 3.5" Concrete	63
3" Gypcrete [a]	30

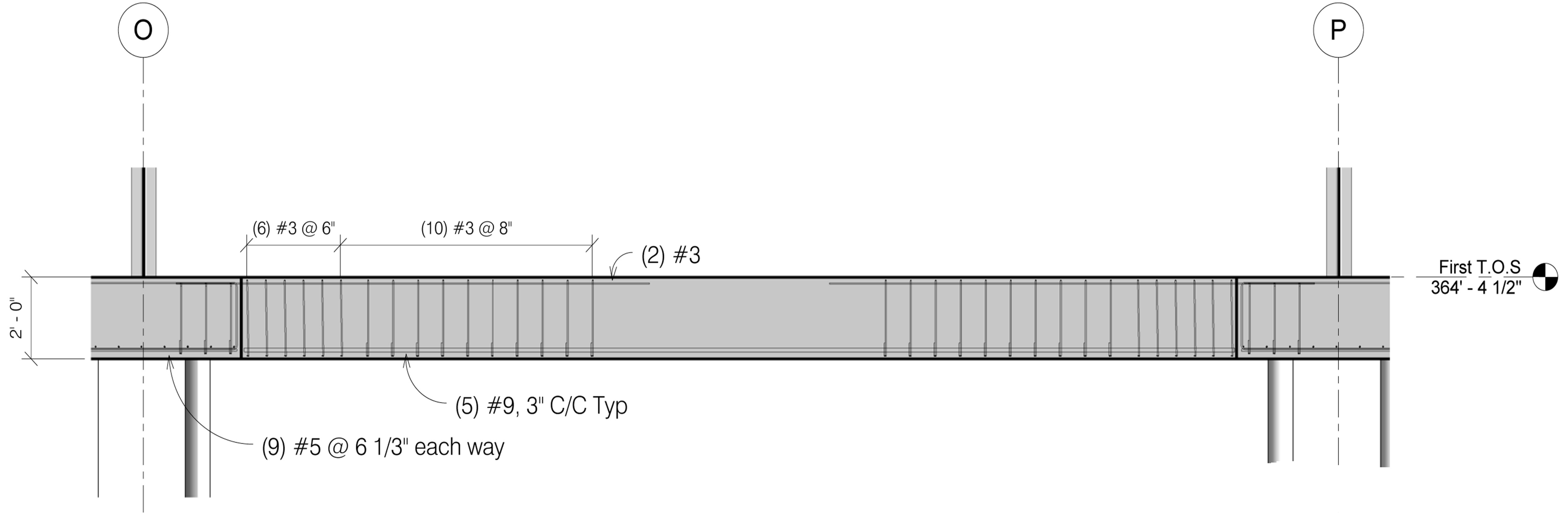
[a] 3" Gypcrete only applies to classroom spaces for the radiant flooring

Grade Beams

Design Governed by:

Smallest x-sect dim shall be $\geq \dfrac{\text{smallest clear span between columns}}{20}$

Closed ties shall be provided at spacing $\leq \dfrac{\text{smallest cross sectional dimension}}{2}$



UNITUS
designing for people
enhancing environments
BUILDING TO UNITE US

OUTLINE

Project Overview

Virtual Modeling and Analyses

Code and Load Considerations

Substructure

Grade Beams, Piles, and Pile Caps

Superstructure

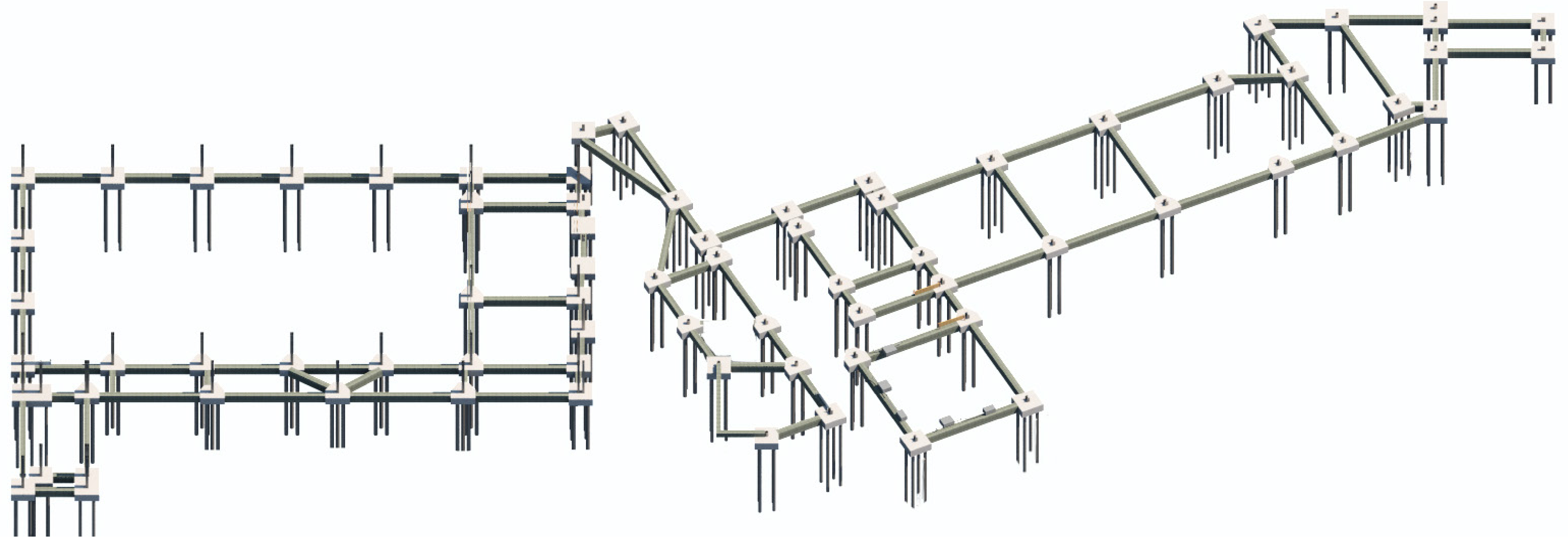
Areas of Interest

CONSTRUCTION
Brian Blenner
Matthew Hoerner

LIGHTING / ELECTRICAL
Kyle Houser
Keith McMullen

STRUCTURAL
Eric Cook
Devon Saunders

MECHANICAL
Daniel McGee
Brittany Notor

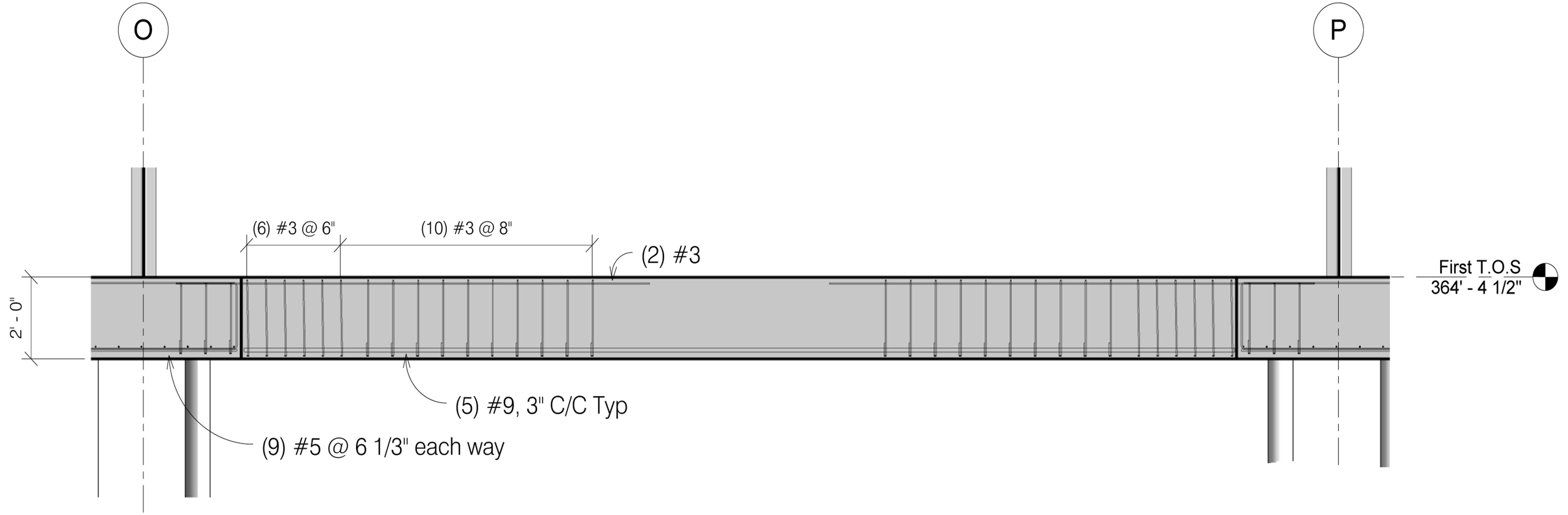


Grade Beams

Design Governed by:

$$\text{Smallest x-sect dim shall be} \geq \frac{\text{smallest clear span between columns}}{20}$$

$$\text{Closed ties shall be provided at spacing} \leq \frac{\text{smallest cross sectional dimension}}{2}$$



Piles and Pile Caps

Pile and Pile Cap Design Criteria:

Embed piles into caps by 6"

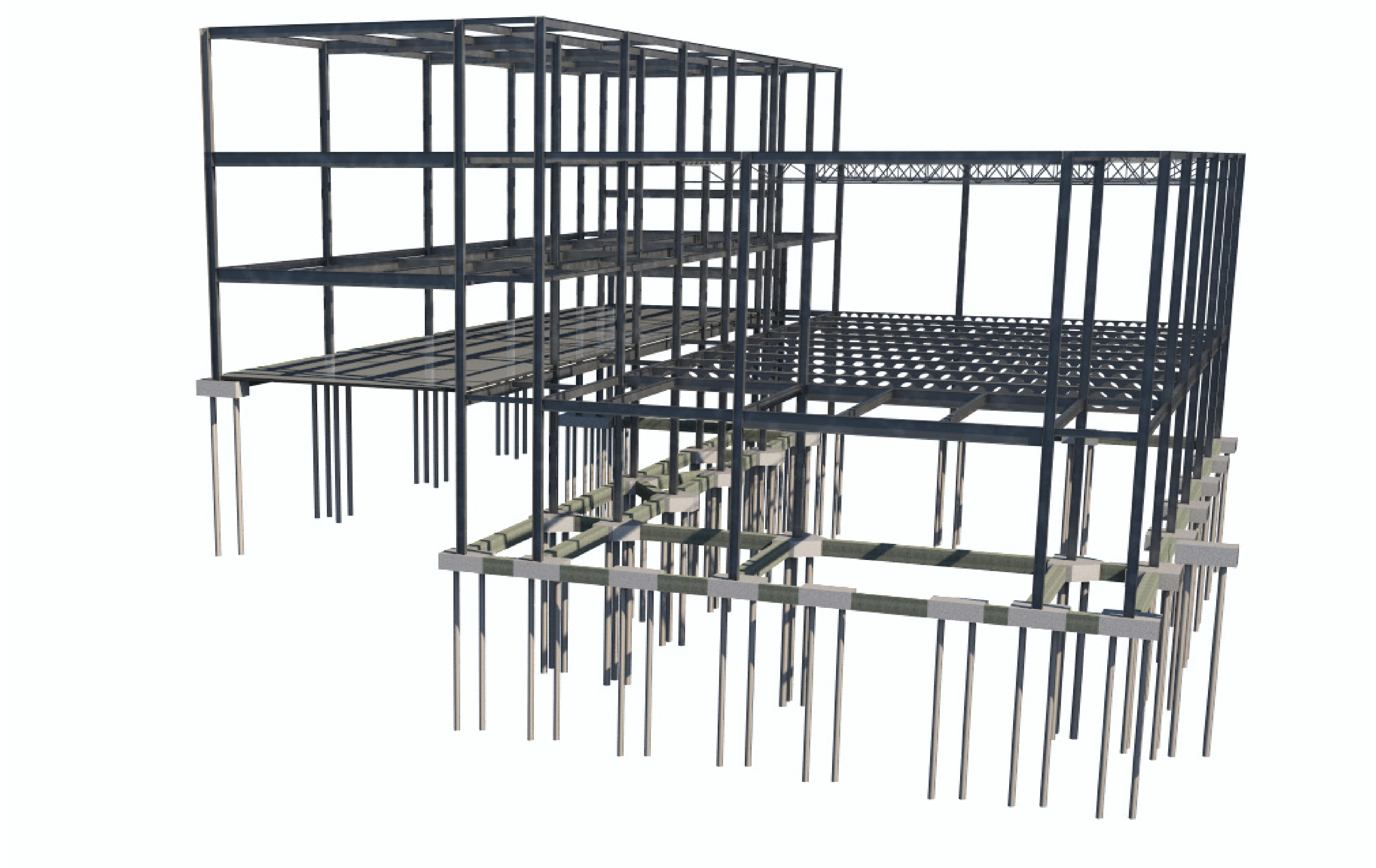
Rebar clear cover is 3" minimum

Spacing between piles must be 3' minimum for diameters ≤ 12"

Designed per CRSI Templates

Steel Frame

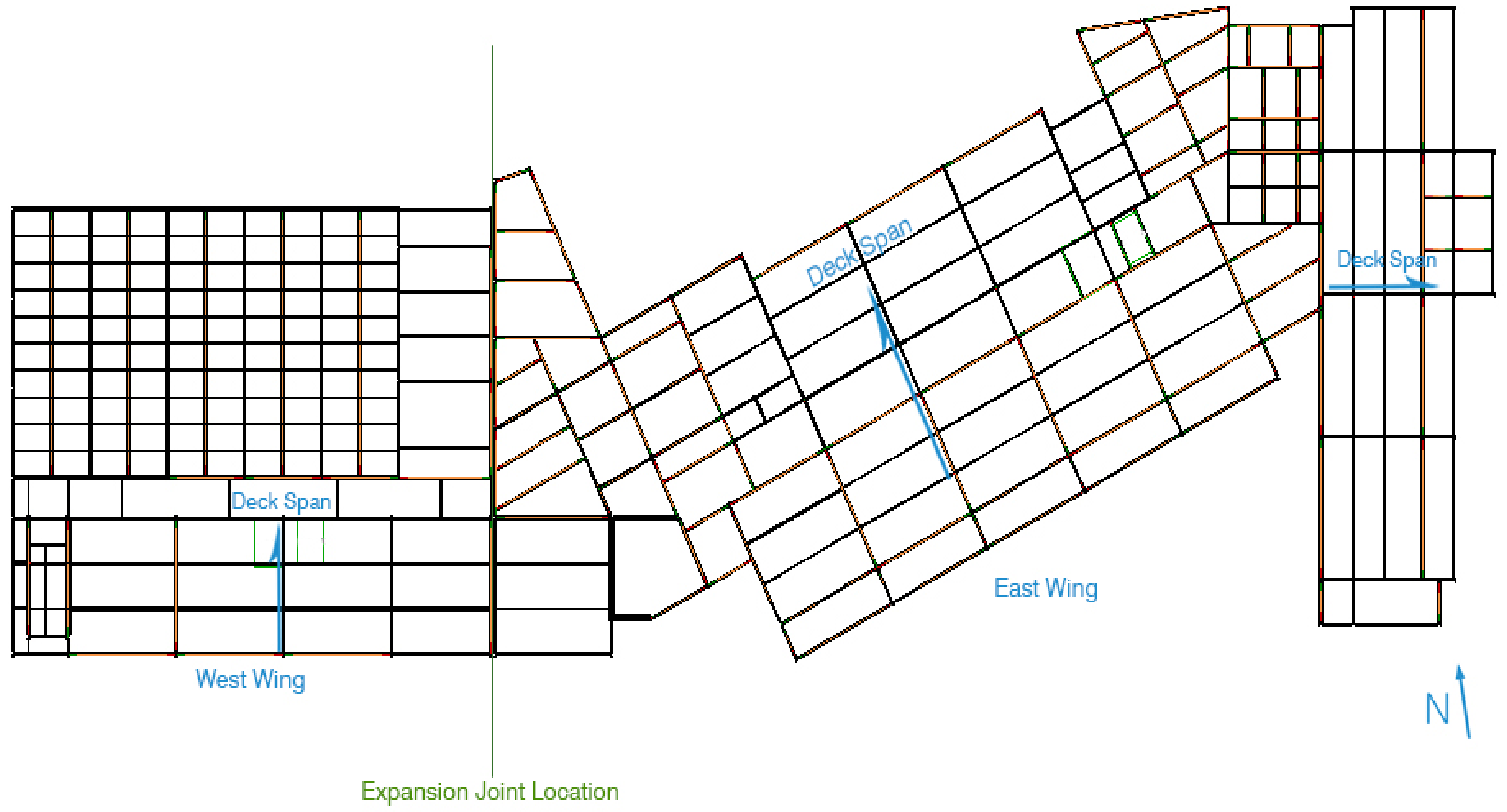
- Caters to assumptions made by geotechnical report
  - Ability to create open spaces



Steel Frame

Caters to assumptions made by geotechnical report

Ability to create open spaces



Building Seperation

Achieved using a 1.5" building expansion joint

Accounts for abrupt changes in building orientation

West Wing [shelter] seismic importance factor = 1.5

East Wing seismc importance factor = 1.25

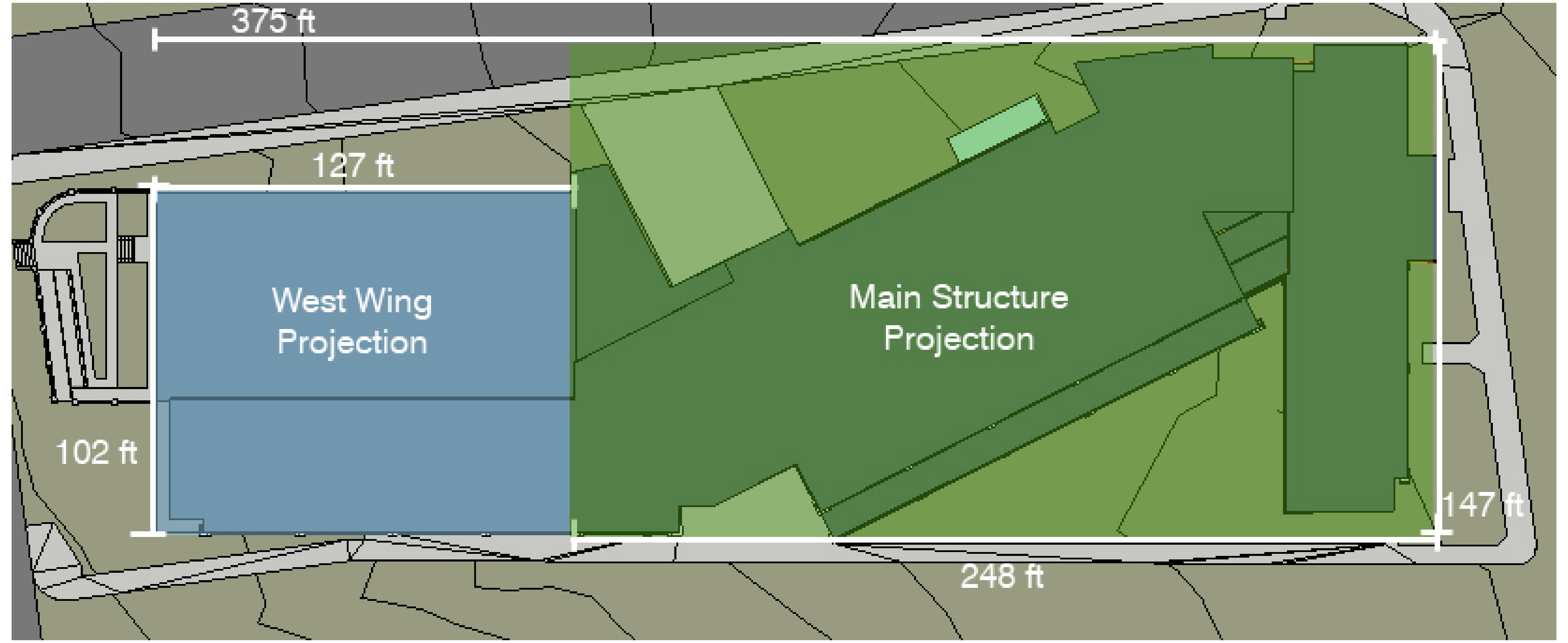
Wind importance factor = 1.15 for both buildings

Lateral Analysis and Design

Main Wind-Force Resisting System

Orhtogonal projected area optimized for calculations

Wind load forces control in the N-S direction for both structures and controls in the E-W direction for the West Wing



<u>West Wing Wind Base Shear</u>
N-S = 245 kips
E-W = 199 kips

<u>Main Structure Wind Base Shear</u>
N-S = 476 kips
E-W = 287 kips

Lateral Analysis and Design

Seismic Force Resisting System

Seismic Importance Factor for shelter

Equivalent Lateral Force Method analysis

	West Wing	East Wing
Risk Category	IV	III
I_e	1.5	1.25
Site Class	C	C
R Factor[a]	3.25	3.25
SDC	B	B
Building Weight	2033 kip	5727 kip
Base Shear Coefficient, C_s	0.0738	0.0615
Base Shear	153 kip	318 kip

[a] Ordinary Steel Concentrically Braced Frames are used in both directions of analysis

West Wing Seismic Story Forces
Roof = 49 kips
Story 3 = 84 kips
Story 2 = 20 kips

East Wing Seismic Story Forces
Roof = 115 kips
Story 3 = 140 kips
Story 2 = 63 kips

UNITUS
designing for people
enhancing environments
BUILDING TO UNITE US

OUTLINE

- Project Overview
- Virtual Modeling and Analyses
- Code and Load Considerations
- Substructure
- Superstructure
  - Gravity Faming
  - Lateral Framing
- Areas of Interest

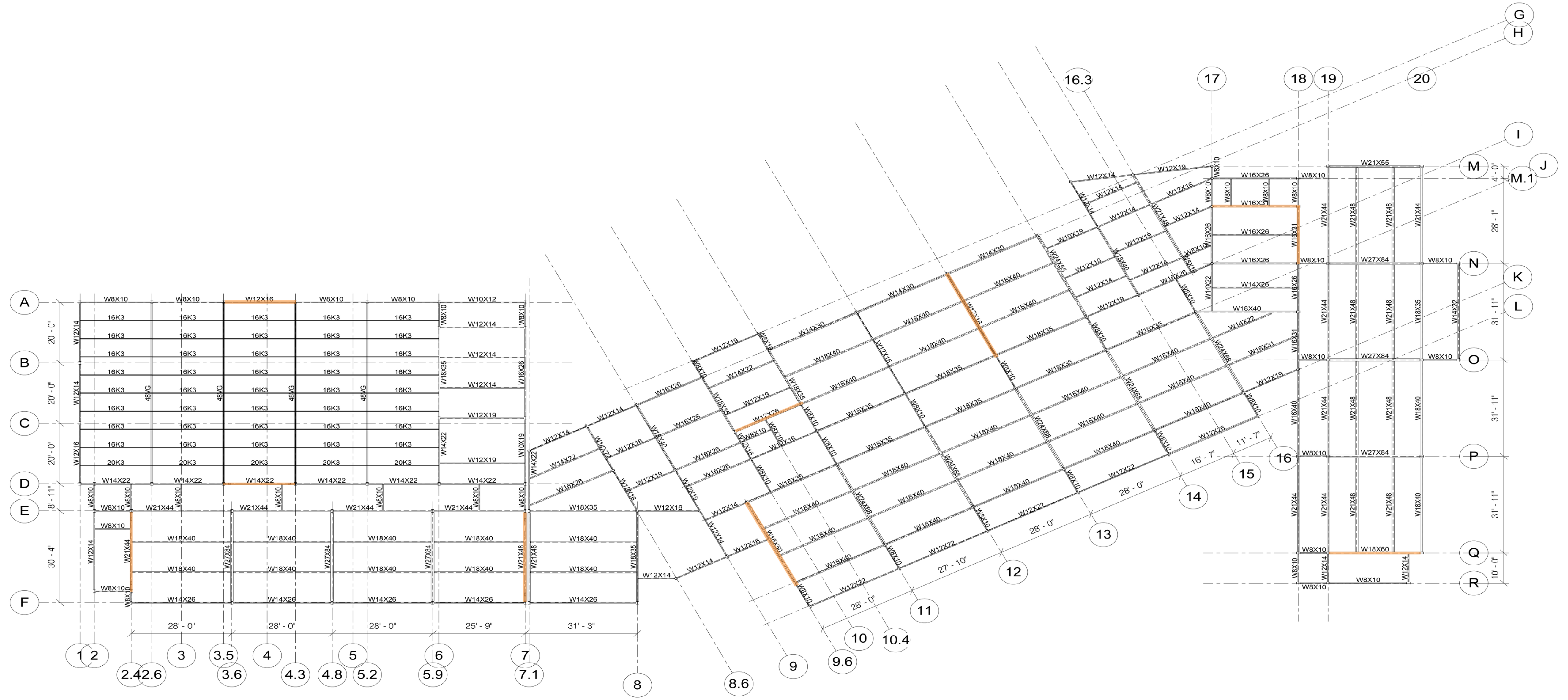
CONSTRUCTION
Brian Blenner
Matthew Hoerner

LIGHTING / ELECTRICAL
Kyle Houser
Keith McMullen

STRUCTURAL
Eric Cook
Devon Saunders

MECHANICAL
Daniel McGee
Brittany Notor

Lateral Force Resisting System

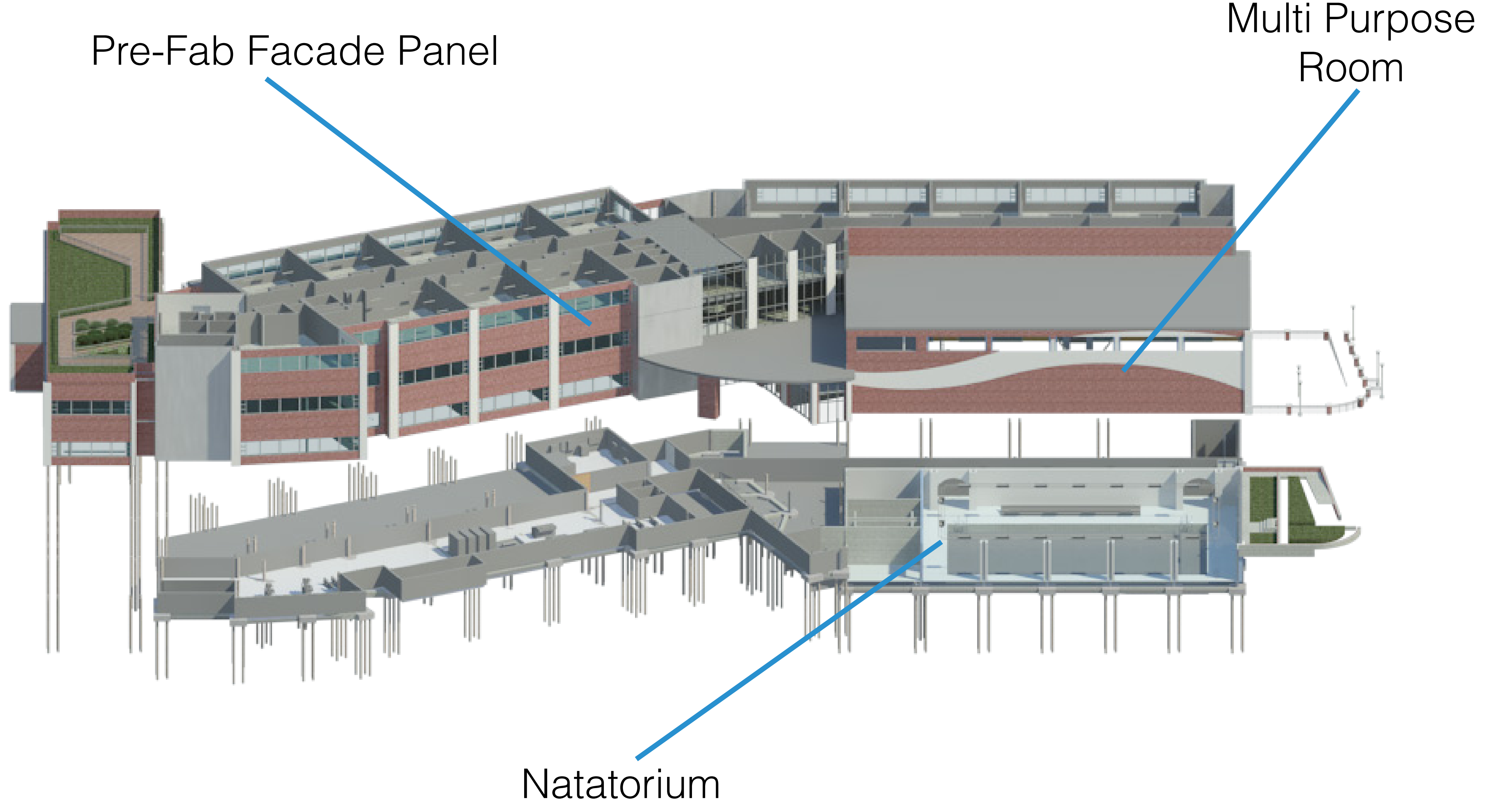


Rectangular HSS members used for lateral cross bracing

Member sizes range from: 4.5 x 4.5 x 3/8 to 6 x 6 x 5/8

Brace sizes were controlled by compression with a KL/r < 200 from column to column

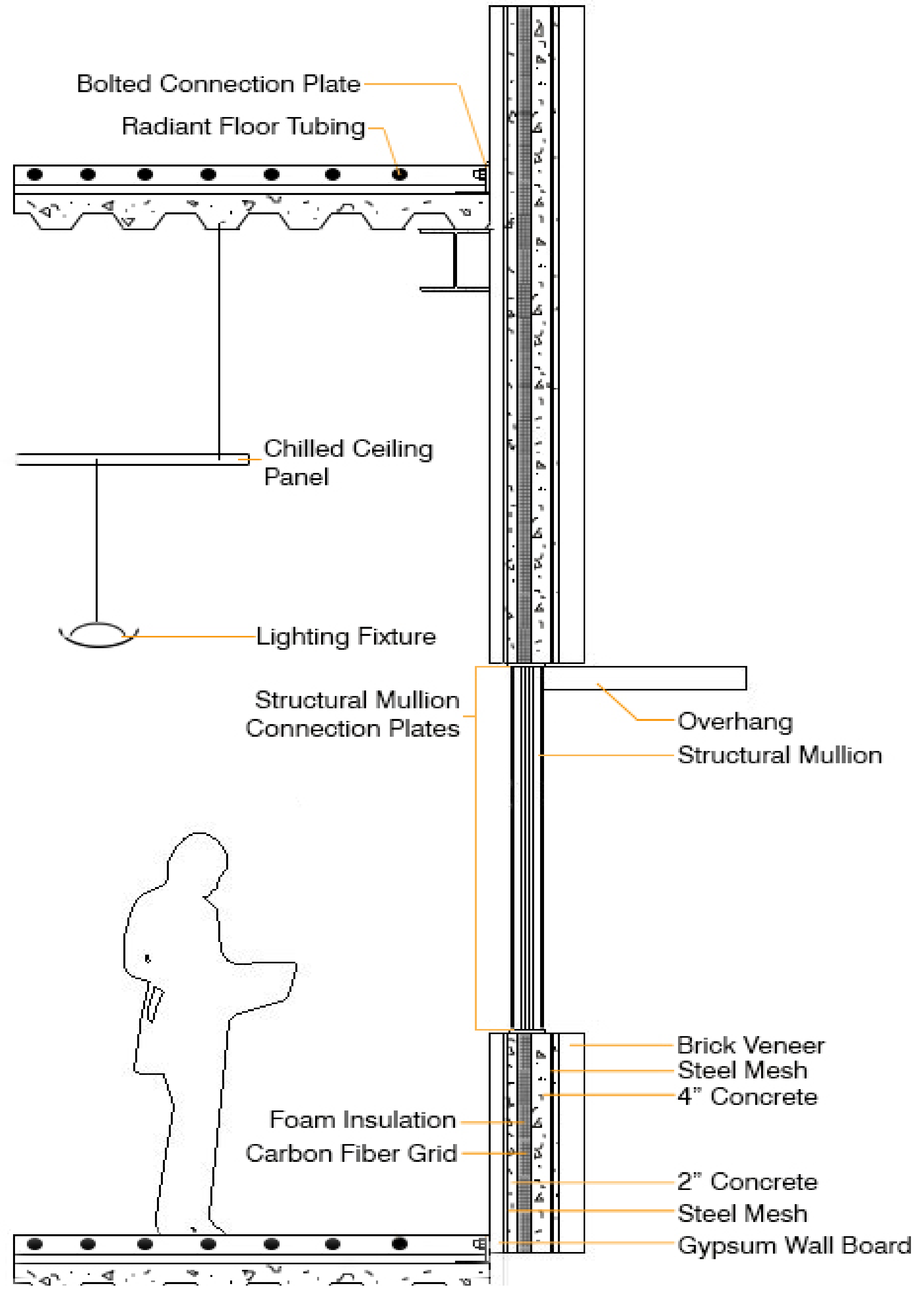
Areas of Interest



Prefabricated Facade Panels

Panel design coordination

- Panel assembly designed based off of “Big Room” meetings with the CM and Mechanical disciplines



UNITUS
designing for people
enhancing environments
BUILDING TO UNITE US

OUTLINE

- Project Overview
- Virtual Modeling and Analyses
- Code and Load Considerations
- Substructure
- Superstructure
- Areas of Interest
  - Building Envelope
  - Multi Purpose Room
  - Natatorium

CONSTRUCTION
Brian Blenner
Matthew Hoerner

LIGHTING / ELECTRICAL
Kyle Houser
Keith McMullen

STRUCTURAL
Eric Cook
Devon Saunders

MECHANICAL
Daniel McGee
Brittany Notor

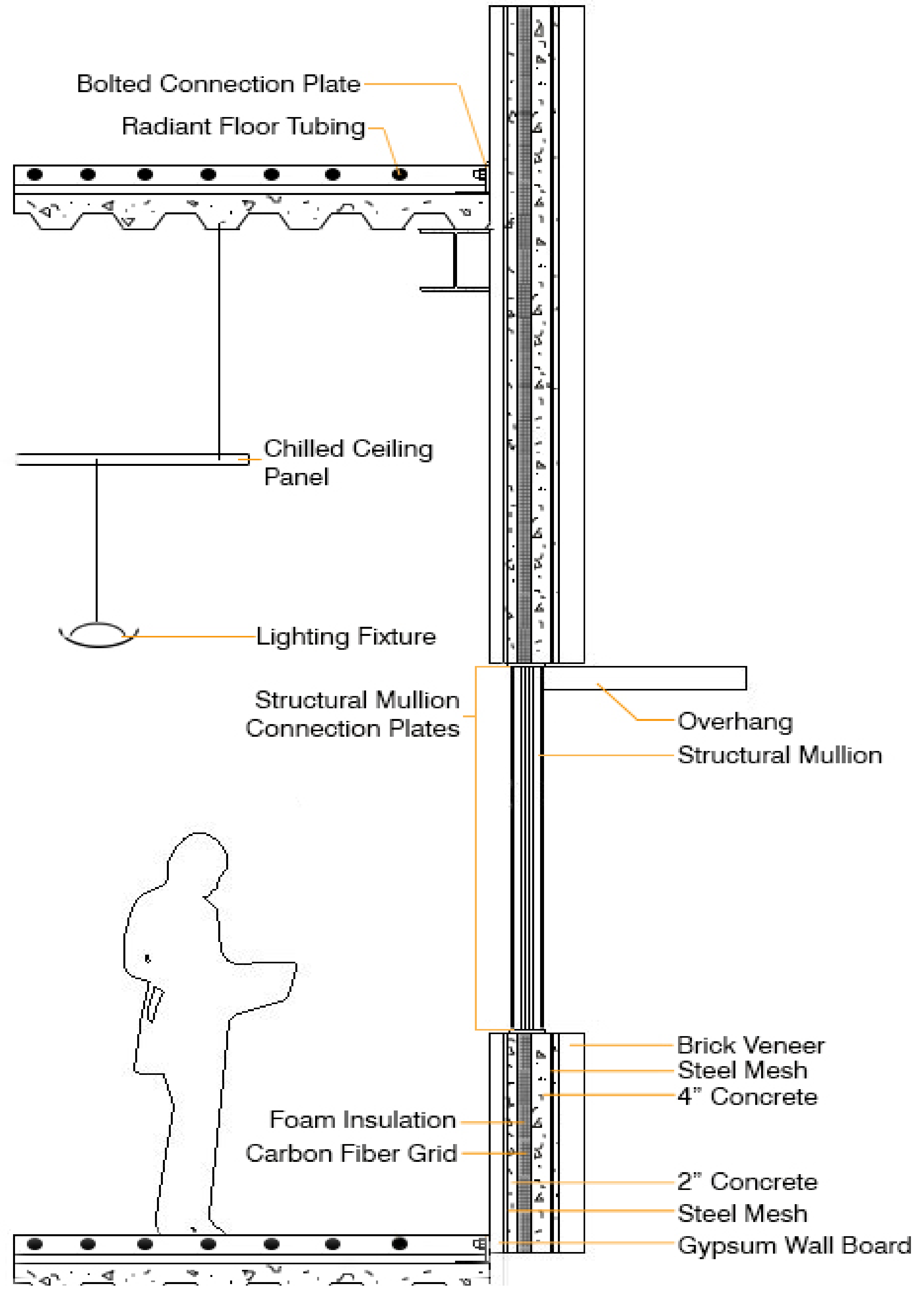
Prefabricated Facade Panels

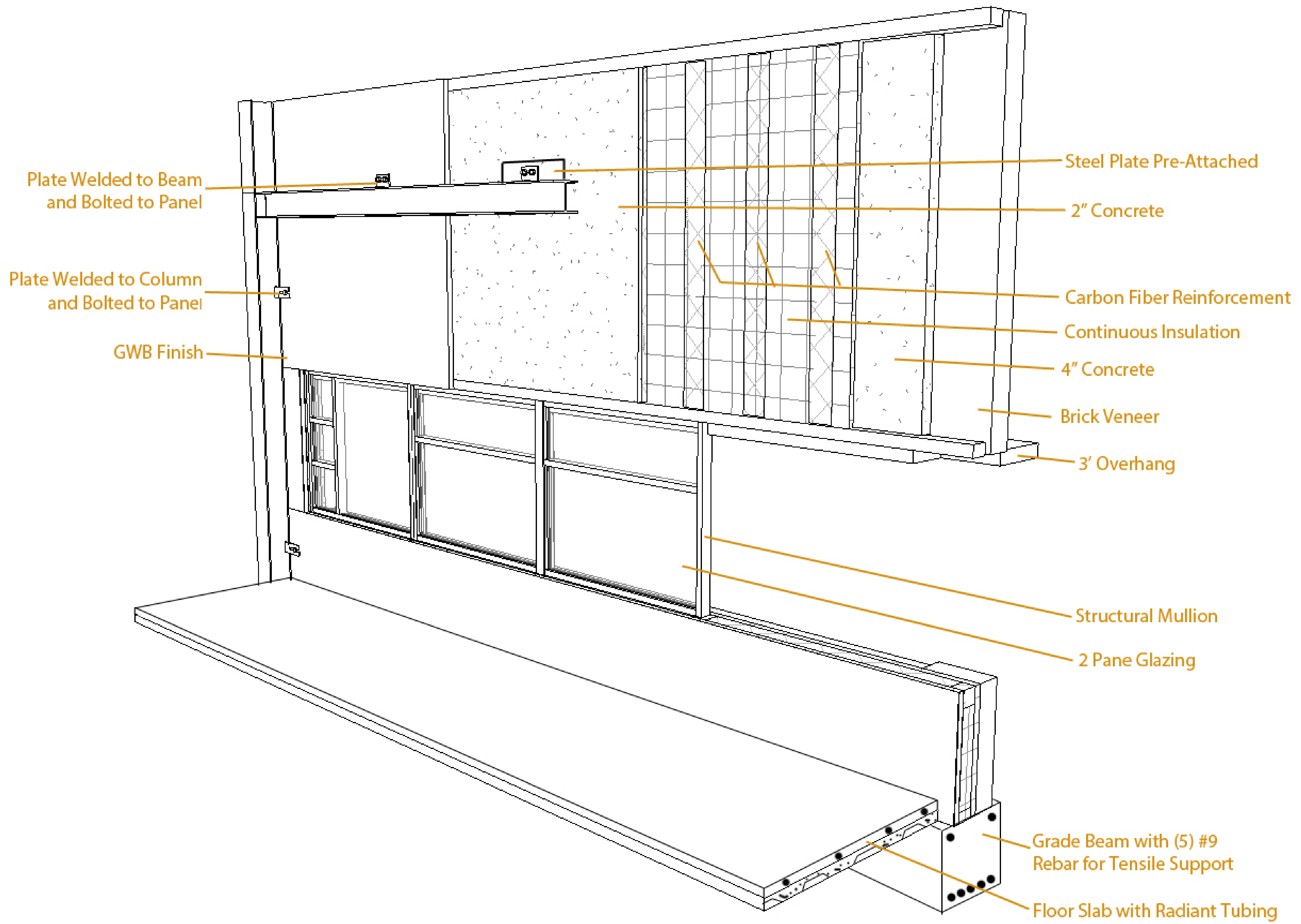
Panel design coordination

- Panel assembly designed based off of "Big Room" meetings with the CM and Mechanical disciplines

Panel structural design

- Layout and simplified design of connections to structural frame
  - Reinforced concrete wythes
    - Composite section created using carbon fiber reinforcement





Multi Purpose Room [Hurricane Shelter]

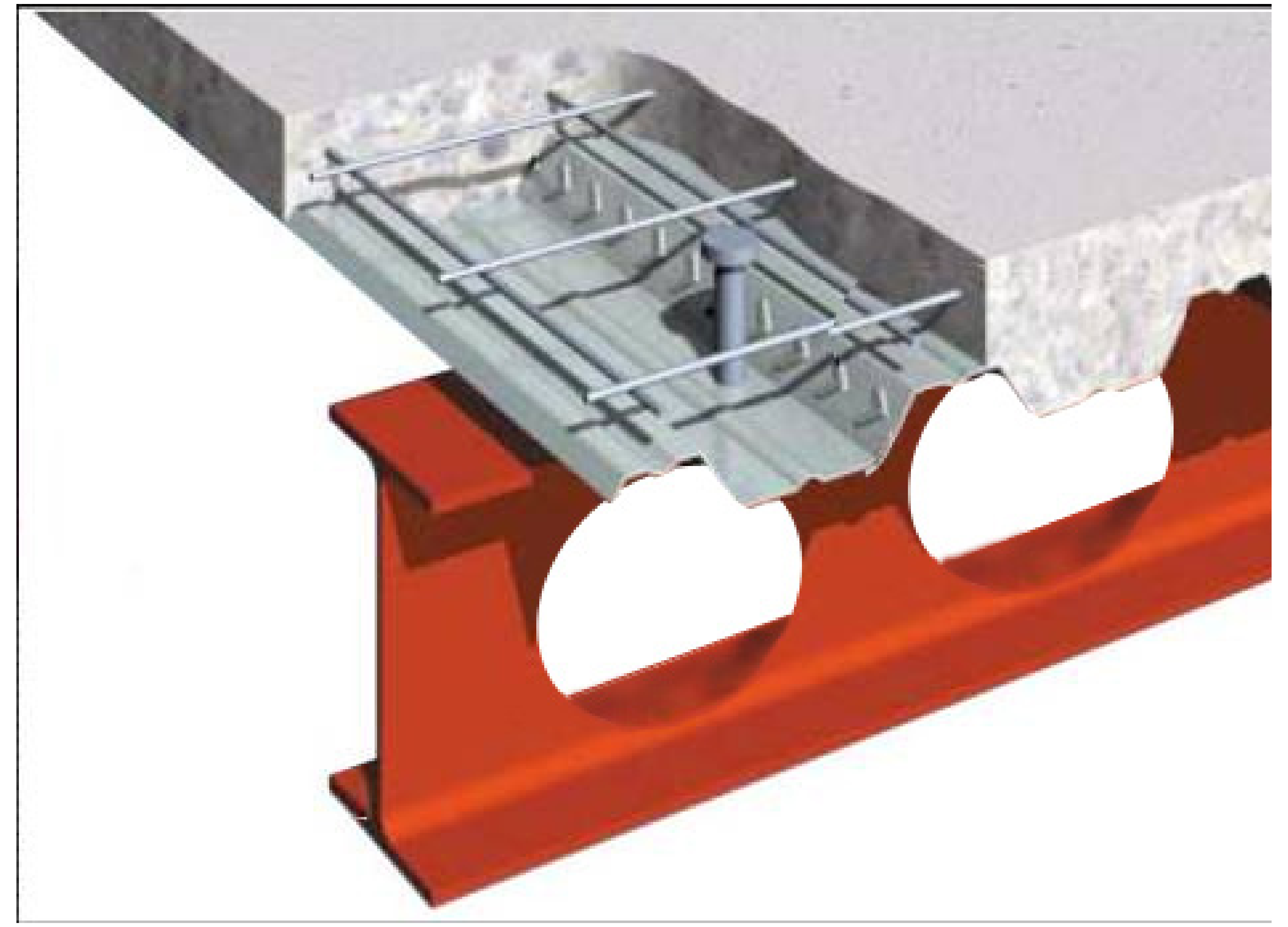
Designed to Fema 320 / FEMA 361 Windborne Debris Standards

- Polycarbonate glazing
  - Roof system designed to resist 26 psf due to wind uplift

Long Span Joist Girders

- 3NA22 accoustical steel deck supported by Vulcraft 48G10N10F joist girders
  - 20' Spaced joist girders braced with 16K2 bar joists spaced at 6'

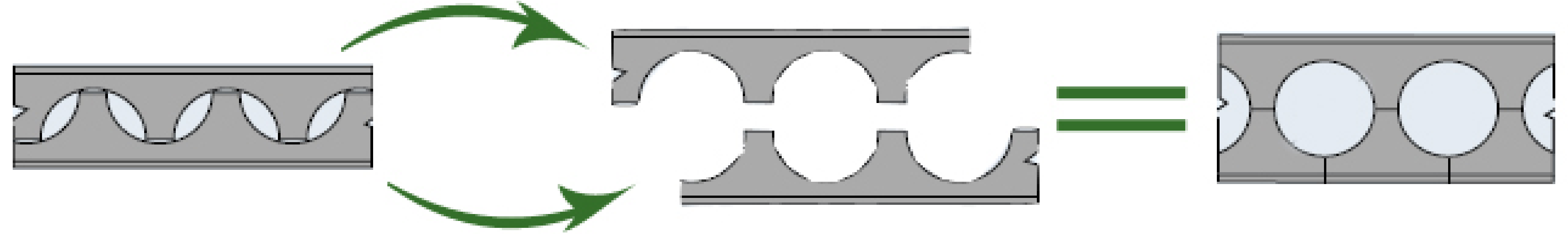
Image from rwiunbraco-gb.inforce.dk



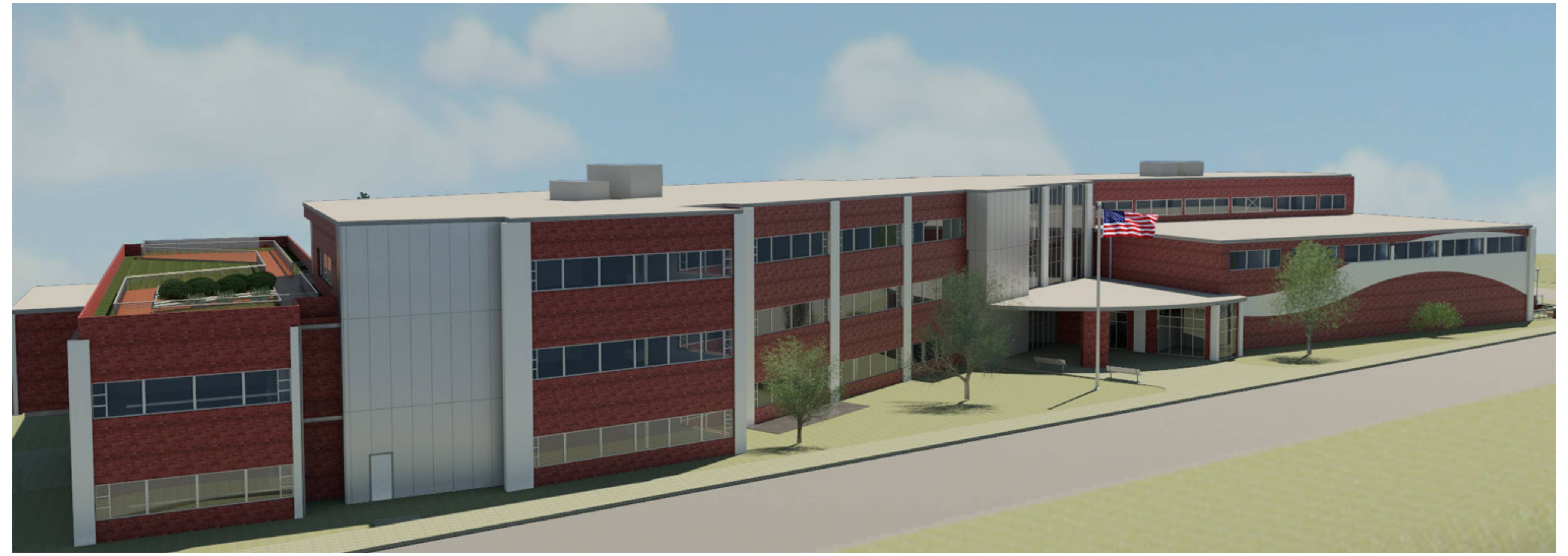
Natatorium

Use of Cellular Beams

- Allows smaller floor to deck heights
  - Decreases vibration issues from Multipurpose space above
    - Pre assembled off site
      - More cost effcient than traditional W-Flange Beams



CONSTRUCTION
Brian Blenner
Matthew Hoerner
LIGHTING / ELECTRICAL
Kyle Houser
Keith McMullen
STRUCTURAL
Eric Cook
Devon Saunders
MECHANICAL
Daniel McGee
Brittany Notor



UNITUS
designing for people
enhancing environments
BUILDING TO UNITE US

Reading Elementary School

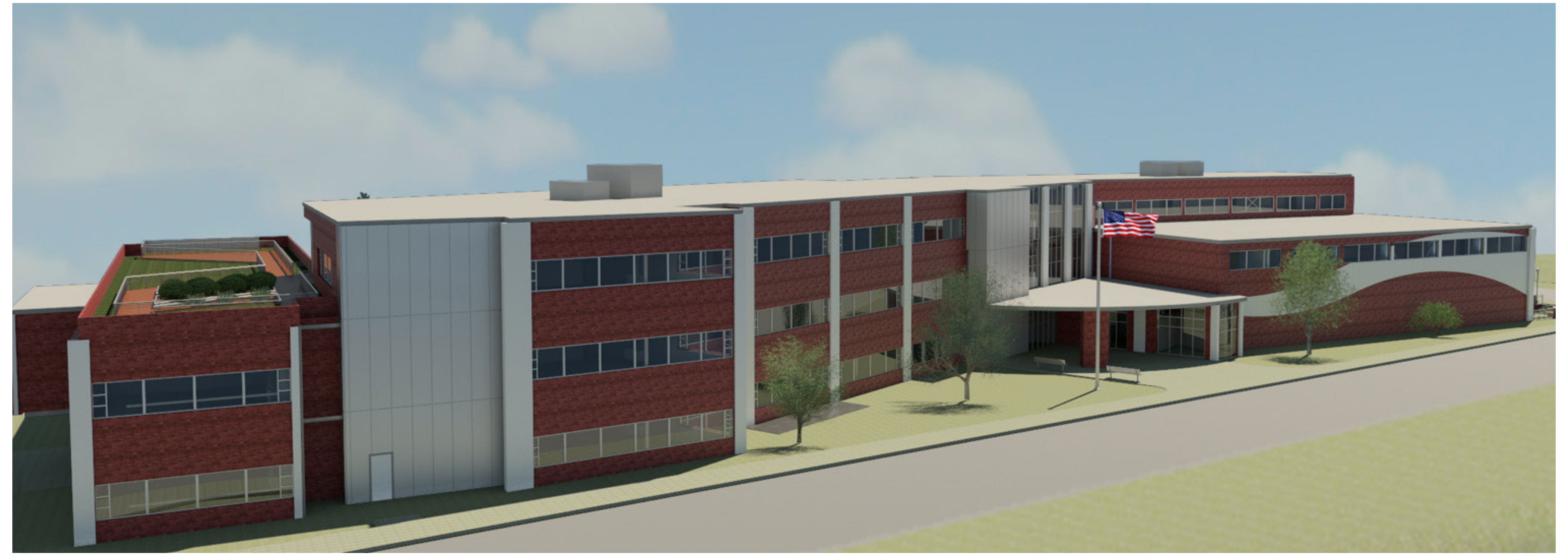
Reading, Pennsylvania

> “In the middle of every difficulty lies opportunity”
>
> - Vaughn D. Spencer, Mayor of Reading, Pennsylvania

April 8, 2013

The Pennsylvania State University
Department of Architectural Engineering

ASCE Charles Pankow Foundation Student Competition



UNITUS
designing for people
enhancing environments
BUILDING TO UNITE US

Reading Elementary School
Reading, Pennsylvania

April 8, 2013

The Pennsylvania State University
Department of Architectural Engineering

ASCE Charles Pankow Foundation Student Competition

Special Thanks to:

- ASCE Charles Pankow Foundation Student Competition
- City of Reading
- Robert Holland
- Kevin Parfitt
- Andres Lepage
- Richard Mistrick
- Craig Dubler
- Jelena Srebric
- Unitus
- Friends & Family

Appendix

Wind Design

6.5.12.2.2 Low-Rise Building. Alternatively, design wind pressures for the MWFRS of low-rise buildings shall be determined by the following equation:

$$p = q_h[(GC_{pf}) - (GC_{pi})] \text{ (lb/ft}^2\text{) (N/m}^2\text{)} \qquad (6\text{-}18)$$

where

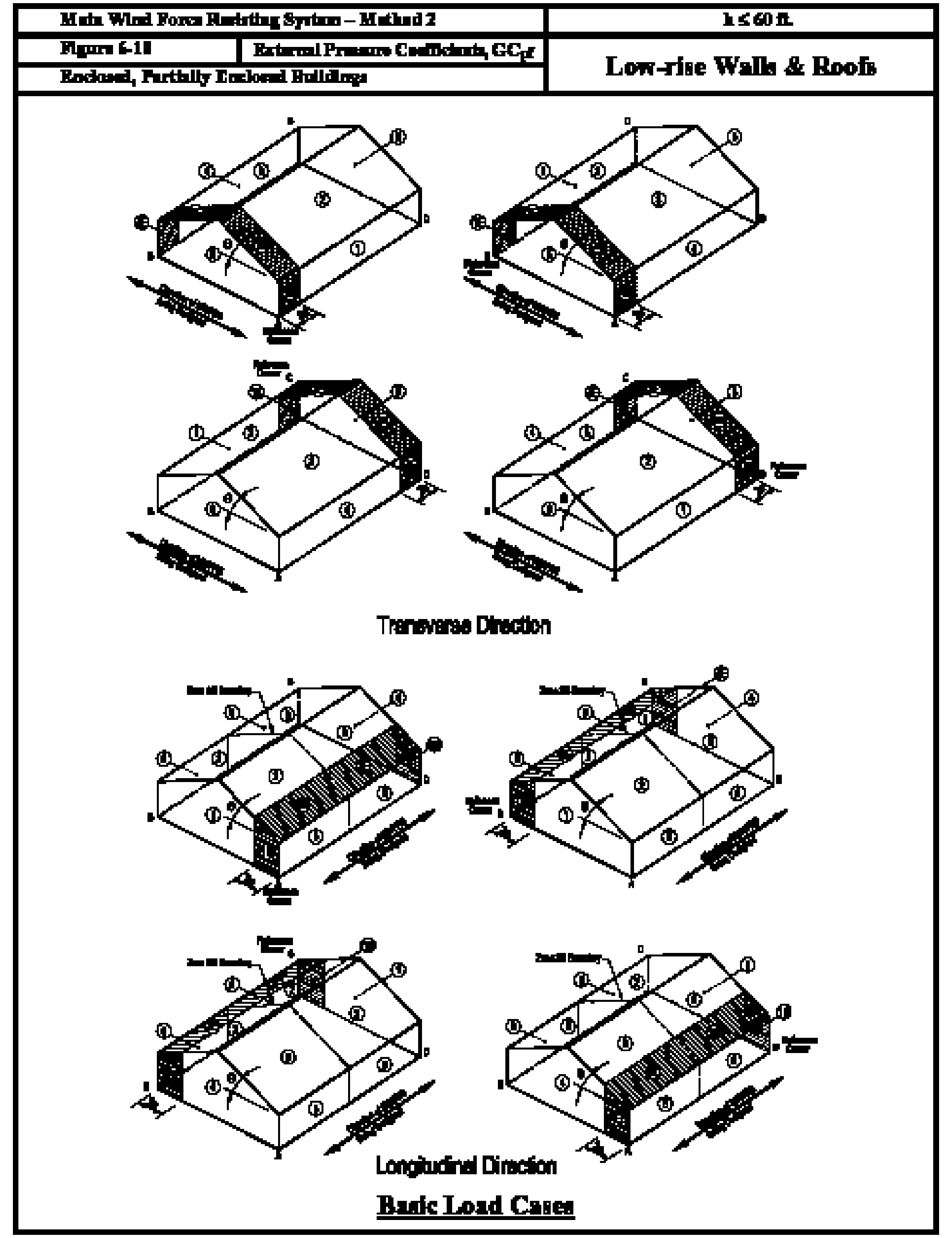
q_h = velocity pressure evaluated at mean roof height h using exposure defined in Section 6.5.6.3
(GC_{pf}) = external pressure coefficient from Fig. 6-10
(GC_{pi}) = internal pressure coefficient from Fig. 6-5

Basic Wind Speed: 90 mph

Category: Shelter - IV
Main Building - III

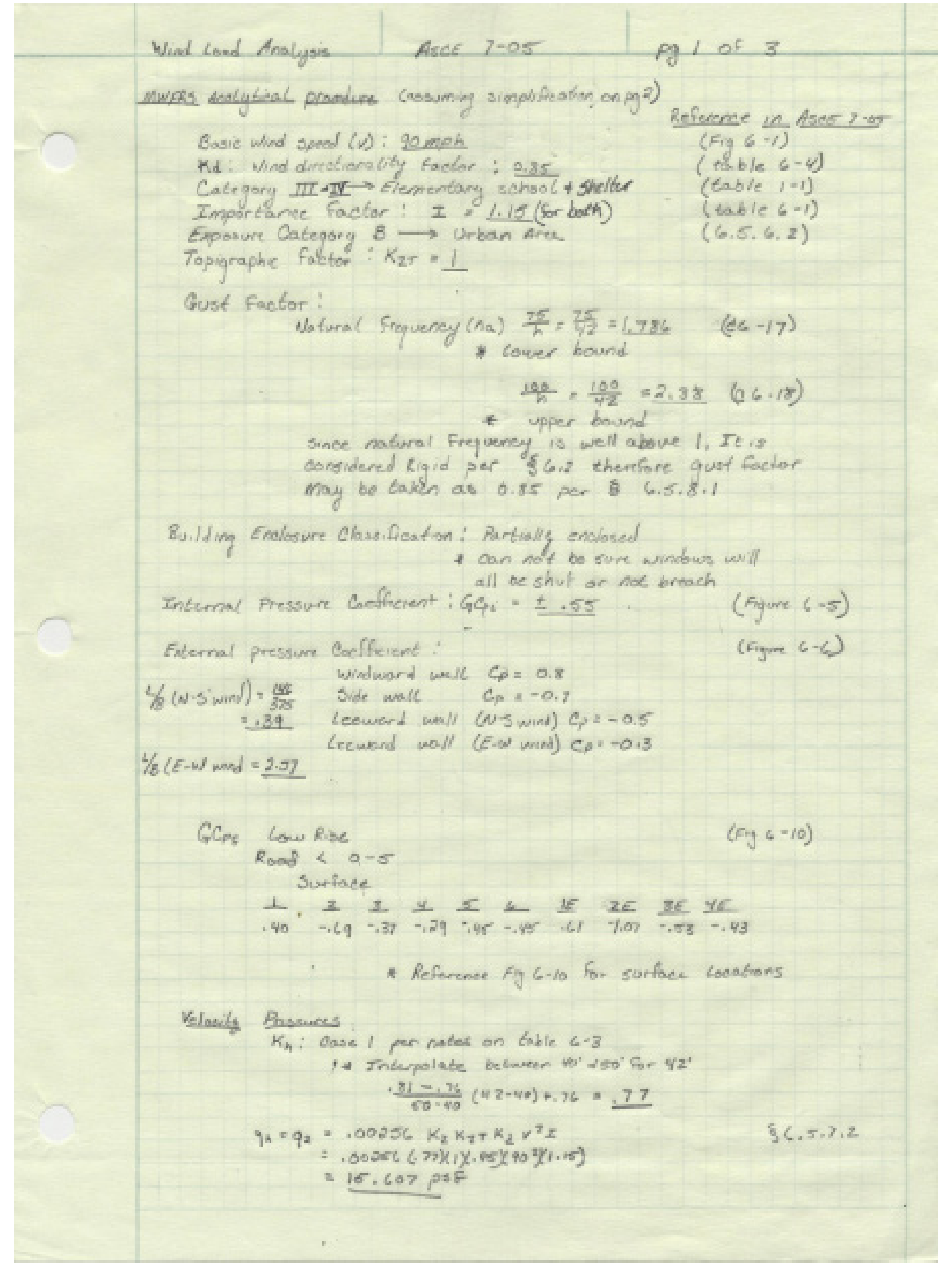
Importance Factor : 1.15

Exposure Category: B



Main Wind Force Resisting System – Method 2		h ≤ 60 ft.
Figure 6-10	External Pressure Coefficients, GC_{pf}	Low-rise Walls & Roofs
Enclosed, Partially Enclosed Buildings		

Page taken from ASCE 7-05



Wind Load Analysis ASCE 7-05 pg 1 of 3

MWFRS analytical procedure (assuming simplification on pg 2)

Reference in ASCE 7-05

Basic wind speed (V) : 90 mph (Fig 6-1)
Kd : wind directionality factor : 0.85 (table 6-4)
Category III & IV → Elementary school & shelter (table 1-1)
Importance Factor : I = 1.15 (for both) (table 6-1)
Exposure Category B → Urban Area (6.5.6.3)
Topographic Factor : K_{zt} = 1

Gust Factor :

Natural Frequency (n_a) $\frac{75}{h} = \frac{75}{42} = 1.786$ (Eq 6-17)
* Lower bound

$\frac{100}{h} = \frac{100}{42} = 2.38$ (Eq 6.18)
* upper bound

since natural Frequency is well above 1, It is considered Rigid per § 6.2 therefore gust factor may be taken as 0.85 per § 6.5.8.1

Building Enclosure Classification : Partially enclosed
* can not be sure windows will all be shut or not breach

Internal Pressure Coefficient : GC_{pi} = ± .55 (Figure 6-5)

External pressure Coefficient : (Figure 6-6)
Windward wall C_p = 0.8
L/B (N-S wind) = $\frac{146}{375}$ = .39 Side wall C_p = -0.7
Leeward wall (N-S wind) C_p = -0.5
Leeward wall (E-W wind) C_p = -0.3
L/B (E-W wind) = 2.57

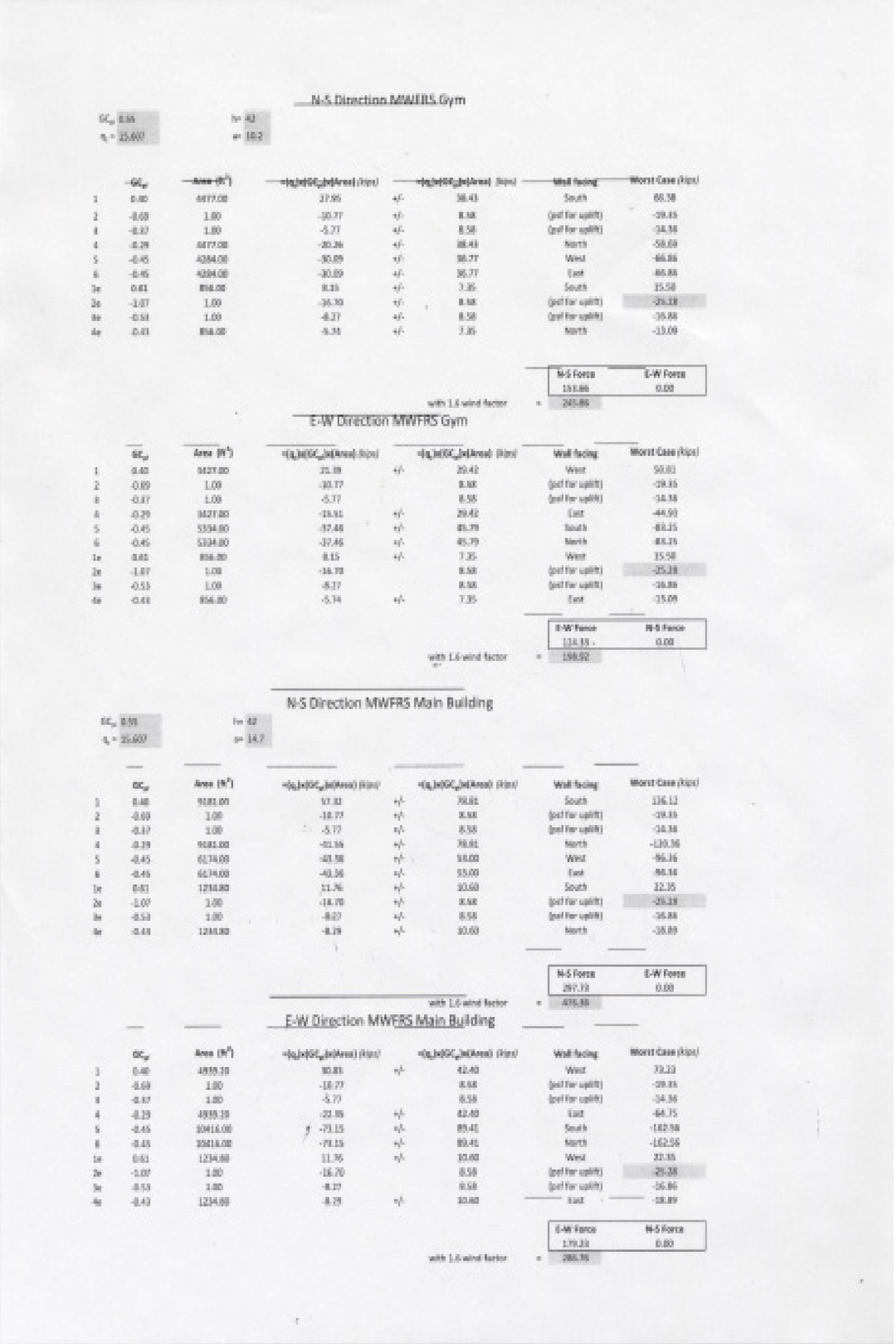
GC_{pf} Low Rise (Fig 6-10)
Roof < 0-5
Surface

1	2	3	4	5	6	1E	2E	3E	4E
.40	-.69	-.37	-.29	-.45	-.45	.61	-1.07	-.53	-.43

* Reference Fig 6-10 for surface locations

Velocity Pressures
K_h : Case 1 per notes on table 6-3
* Interpolate between 40' & 50' for 42'
$\frac{.81 - .76}{50 - 40}(42-40) + .76 = .77$

$q_h = q_z = .00256 K_z K_{zt} K_d V^2 I$ § 6.5.10
$= .00256 (.77)(1)(.85)(90^2)(1.15)$
$= 15.607$ psf



Appendix

Grade Beams and Pile Caps

Grade Beams

Per ACI Chapter 21.12.3

- Smallest x-sect dim shall be > clr span between columns/20, hence 16" width.
- Grade beams can be separated from SOG
- Closed ties at < smallest x-sect dim/2, so 16"/2 = 8"

- Depth = designed for 24"
- Width = 16"
- Reinf w/ (5) #9's, 3" cc
- Increased to 24" depth to match 24" pile caps.
- Checked for simplified deflections [ACI 318] – l/21 (Beams, both ends continuous), accounts for sink hole formations
- Loads Considered: Self Weight , Pre-Fab Panel Weight , and Live Loads

Piles and Pile Caps

Per CRSI 2008

- Embed piles into caps by 6"
- Rebar cc is 3" min
- Pile spacing min = 3' for piles up to 12" dia
- Checked for two way action

- 3 Pile, 4 Pile, and 6 Pile system designed for flexure and punch shear
- 3 Pile Cap Reinf = (6) #5 @ 6" 3-ways
- 4 Pile Cap Reinf = (9) #5 @ 6 1/2" each way
- 6 Pile Cap Reinf = (15) #5 @ 6 3/4" long
  (9) #5 @ 6 1/2" short
- 8" steel encased concrete pile designed for bearing capacity of 66 kips

UNITUS
designing for people
enhancing environments
BUILDING TO UNITE US

OUTLINE

CONSTRUCTION
Brian Blenner
Matthew Hoerner

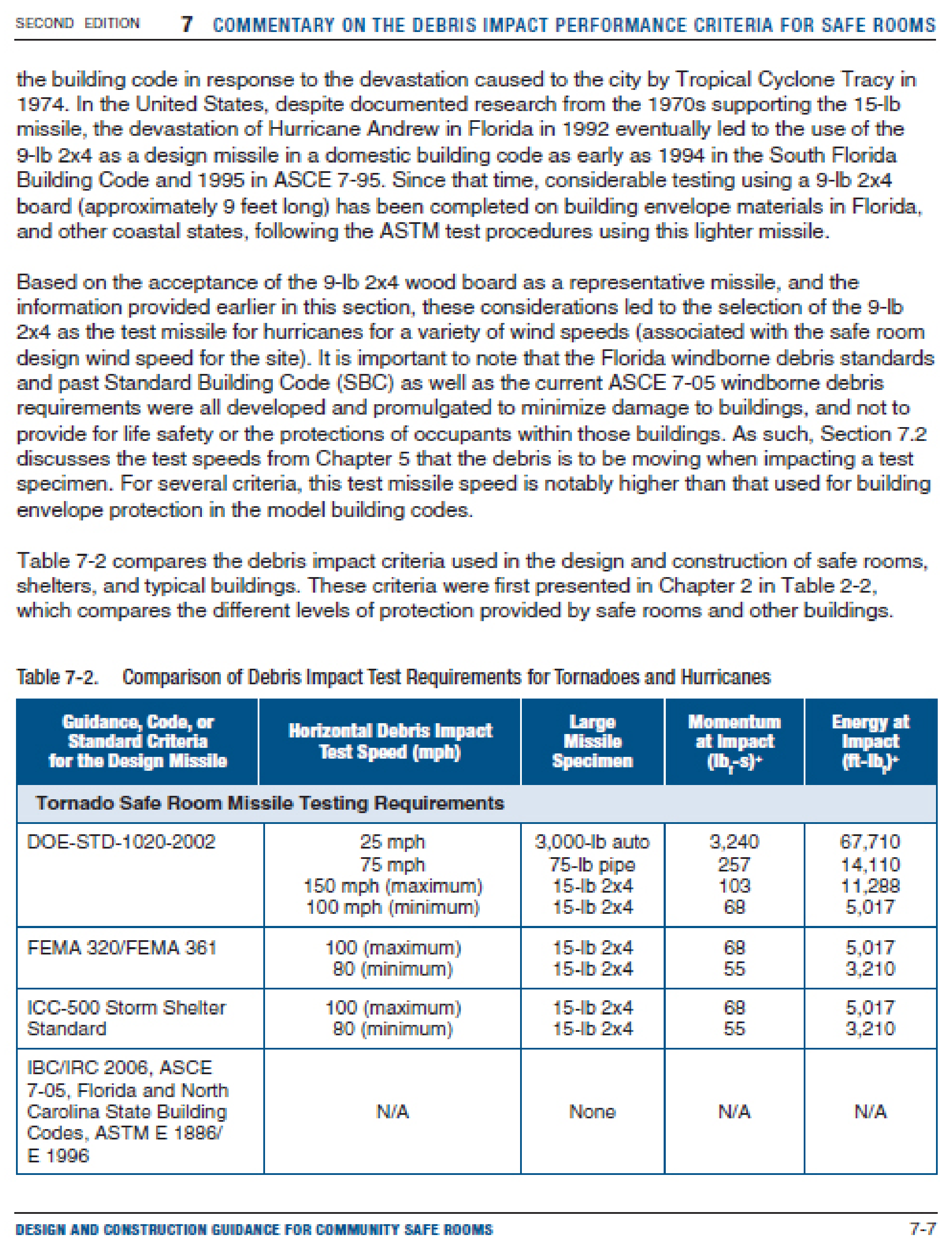
LIGHTING / ELECTRICAL
Kyle Houser
Keith McMullen

STRUCTURAL
Eric Cook
Devon Saunders

MECHANICAL
Daniel McGee
Brittany Notor

Appendix

FEMA Shelter Design Guidelines



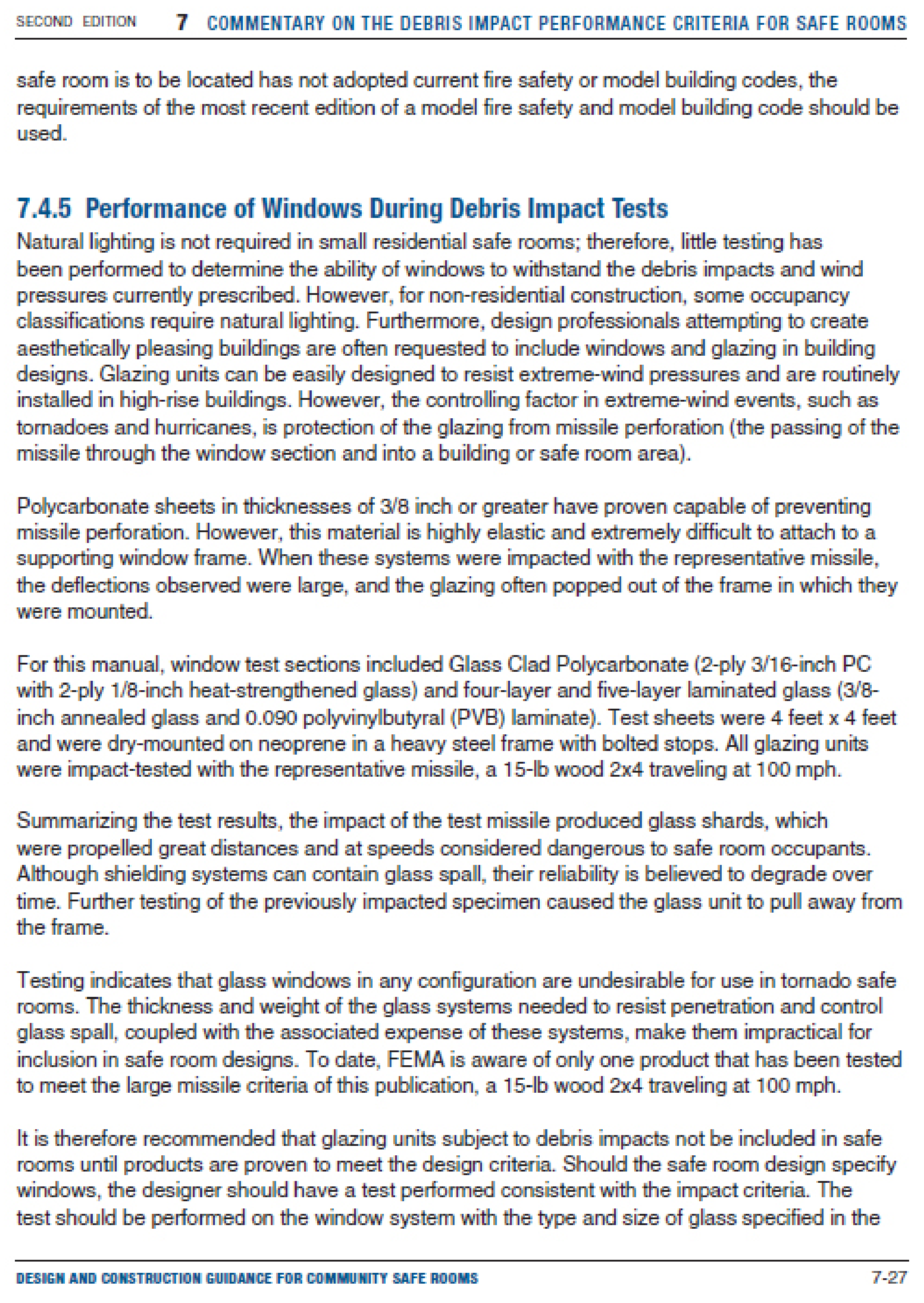
the building code in response to the devastation caused to the city by Tropical Cyclone Tracy in 1974. In the United States, despite documented research from the 1970s supporting the 15-lb missile, the devastation of Hurricane Andrew in Florida in 1992 eventually led to the use of the 9-lb 2x4 as a design missile in a domestic building code as early as 1994 in the South Florida Building Code and 1995 in ASCE 7-95. Since that time, considerable testing using a 9-lb 2x4 board (approximately 9 feet long) has been completed on building envelope materials in Florida, and other coastal states, following the ASTM test procedures using this lighter missile.

Based on the acceptance of the 9-lb 2x4 wood board as a representative missile, and the information provided earlier in this section, these considerations led to the selection of the 9-lb 2x4 as the test missile for hurricanes for a variety of wind speeds (associated with the safe room design wind speed for the site). It is important to note that the Florida windborne debris standards and past Standard Building Code (SBC) as well as the current ASCE 7-05 windborne debris requirements were all developed and promulgated to minimize damage to buildings, and not to provide for life safety or the protections of occupants within those buildings. As such, Section 7.2 discusses the test speeds from Chapter 5 that the debris is to be moving when impacting a test specimen. For several criteria, this test missile speed is notably higher than that used for building envelope protection in the model building codes.

Table 7-2 compares the debris impact criteria used in the design and construction of safe rooms, shelters, and typical buildings. These criteria were first presented in Chapter 2 in Table 2-2, which compares the different levels of protection provided by safe rooms and other buildings.

Table 7-2. Comparison of Debris Impact Test Requirements for Tornadoes and Hurricanes

Guidance, Code, or Standard Criteria for the Design Missile	Horizontal Debris Impact Test Speed (mph)	Large Missile Specimen	Momentum at Impact (lb_f-s)+	Energy at Impact (ft-lb_f)+
Tornado Safe Room Missile Testing Requirements				
DOE-STD-1020-2002	25 mph 75 mph 150 mph (maximum) 100 mph (minimum)	3,000-lb auto 75-lb pipe 15-lb 2x4 15-lb 2x4	3,240 257 103 68	67,710 14,110 11,288 5,017
FEMA 320/FEMA 361	100 (maximum) 80 (minimum)	15-lb 2x4 15-lb 2x4	68 55	5,017 3,210
ICC-500 Storm Shelter Standard	100 (maximum) 80 (minimum)	15-lb 2x4 15-lb 2x4	68 55	5,017 3,210
IBC/IRC 2006, ASCE 7-05, Florida and North Carolina State Building Codes, ASTM E 1886/ E 1996	N/A	None	N/A	N/A



safe room is to be located has not adopted current fire safety or model building codes, the requirements of the most recent edition of a model fire safety and model building code should be used.

7.4.5 Performance of Windows During Debris Impact Tests

Natural lighting is not required in small residential safe rooms; therefore, little testing has been performed to determine the ability of windows to withstand the debris impacts and wind pressures currently prescribed. However, for non-residential construction, some occupancy classifications require natural lighting. Furthermore, design professionals attempting to create aesthetically pleasing buildings are often requested to include windows and glazing in building designs. Glazing units can be easily designed to resist extreme-wind pressures and are routinely installed in high-rise buildings. However, the controlling factor in extreme-wind events, such as tornadoes and hurricanes, is protection of the glazing from missile perforation (the passing of the missile through the window section and into a building or safe room area).

Polycarbonate sheets in thicknesses of 3/8 inch or greater have proven capable of preventing missile perforation. However, this material is highly elastic and extremely difficult to attach to a supporting window frame. When these systems were impacted with the representative missile, the deflections observed were large, and the glazing often popped out of the frame in which they were mounted.

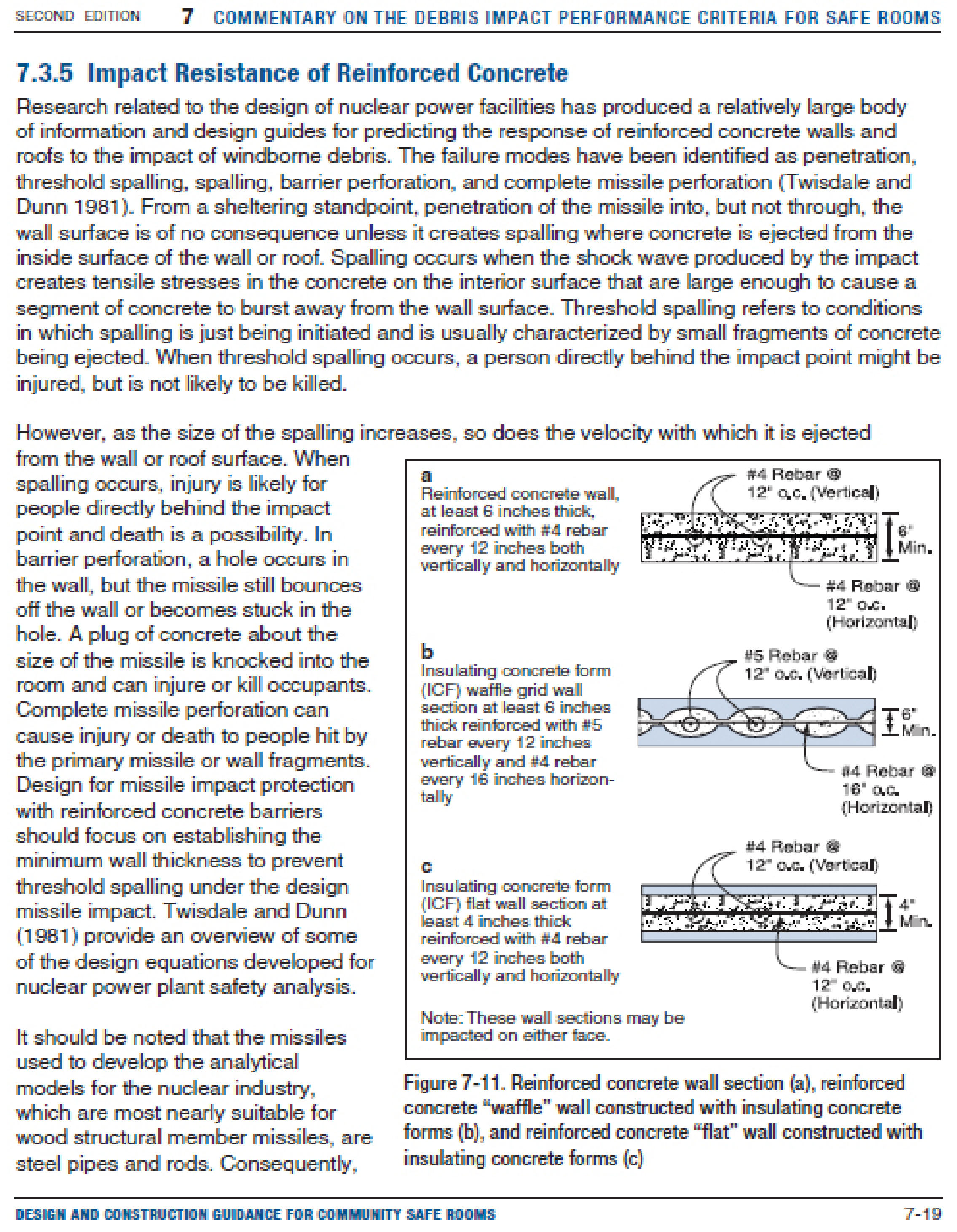
For this manual, window test sections included Glass Clad Polycarbonate (2-ply 3/16-inch PC with 2-ply 1/8-inch heat-strengthened glass) and four-layer and five-layer laminated glass (3/8-inch annealed glass and 0.090 polyvinylbutyral (PVB) laminate). Test sheets were 4 feet x 4 feet and were dry-mounted on neoprene in a heavy steel frame with bolted stops. All glazing units were impact-tested with the representative missile, a 15-lb wood 2x4 traveling at 100 mph.

Summarizing the test results, the impact of the test missile produced glass shards, which were propelled great distances and at speeds considered dangerous to safe room occupants. Although shielding systems can contain glass spall, their reliability is believed to degrade over time. Further testing of the previously impacted specimen caused the glass unit to pull away from the frame.

Testing indicates that glass windows in any configuration are undesirable for use in tornado safe rooms. The thickness and weight of the glass systems needed to resist penetration and control glass spall, coupled with the associated expense of these systems, make them impractical for inclusion in safe room designs. To date, FEMA is aware of only one product that has been tested to meet the large missile criteria of this publication, a 15-lb wood 2x4 traveling at 100 mph.

It is therefore recommended that glazing units subject to debris impacts not be included in safe rooms until products are proven to meet the design criteria. Should the safe room design specify windows, the designer should have a test performed consistent with the impact criteria. The test should be performed on the window system with the type and size of glass specified in the

Pages taken from FEMA P-361, Second Edition / August 2008



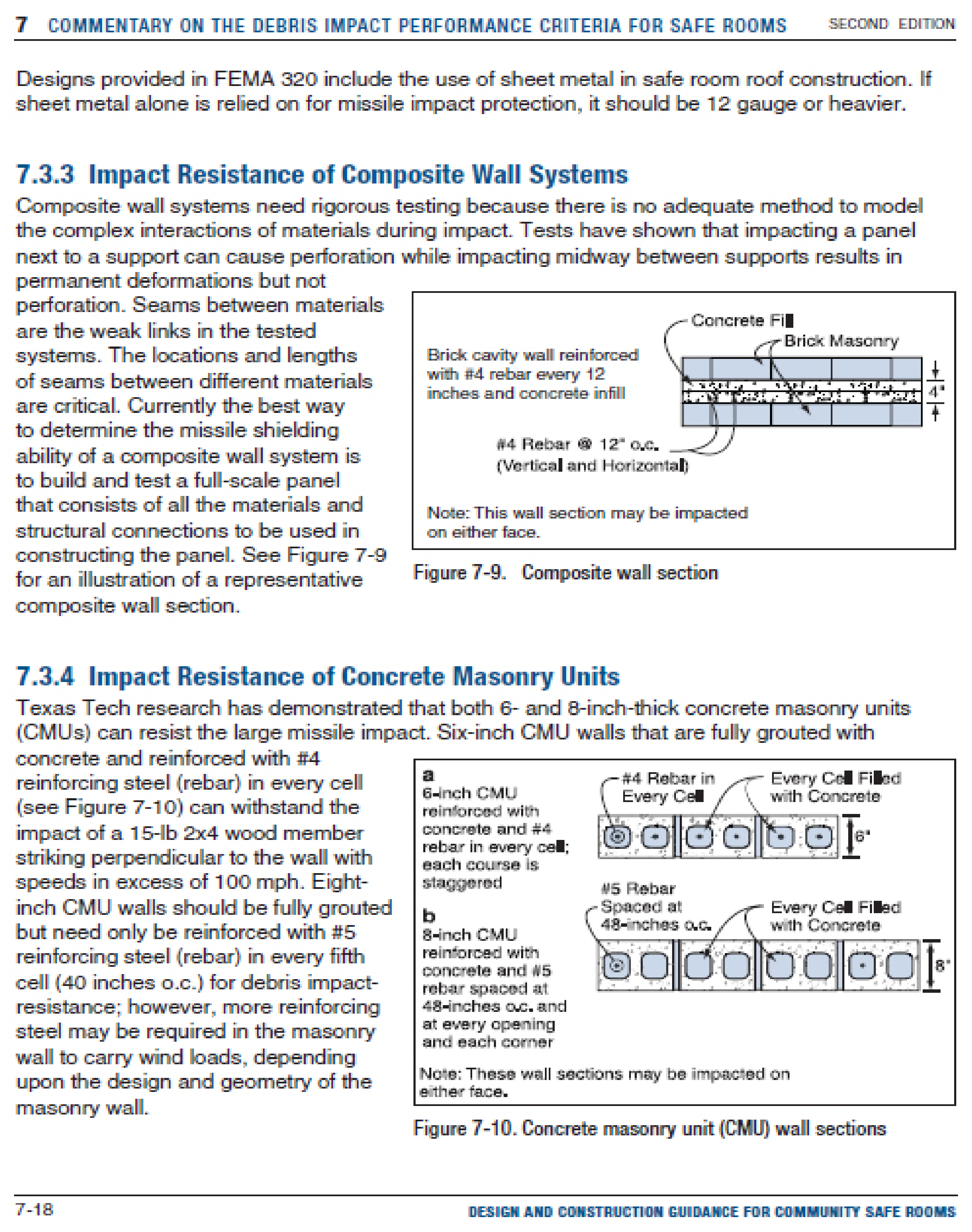
7.3.5 Impact Resistance of Reinforced Concrete

Research related to the design of nuclear power facilities has produced a relatively large body of information and design guides for predicting the response of reinforced concrete walls and roofs to the impact of windborne debris. The failure modes have been identified as penetration, threshold spalling, spalling, barrier perforation, and complete missile perforation (Twisdale and Dunn 1981). From a sheltering standpoint, penetration of the missile into, but not through, the wall surface is of no consequence unless it creates spalling where concrete is ejected from the inside surface of the wall or roof. Spalling occurs when the shock wave produced by the impact creates tensile stresses in the concrete on the interior surface that are large enough to cause a segment of concrete to burst away from the wall surface. Threshold spalling refers to conditions in which spalling is just being initiated and is usually characterized by small fragments of concrete being ejected. When threshold spalling occurs, a person directly behind the impact point might be injured, but is not likely to be killed.

However, as the size of the spalling increases, so does the velocity with which it is ejected from the wall or roof surface. When spalling occurs, injury is likely for people directly behind the impact point and death is a possibility. In barrier perforation, a hole occurs in the wall, but the missile still bounces off the wall or becomes stuck in the hole. A plug of concrete about the size of the missile is knocked into the room and can injure or kill occupants. Complete missile perforation can cause injury or death to people hit by the primary missile or wall fragments. Design for missile impact protection with reinforced concrete barriers should focus on establishing the minimum wall thickness to prevent threshold spalling under the design missile impact. Twisdale and Dunn (1981) provide an overview of some of the design equations developed for nuclear power plant safety analysis.

It should be noted that the missiles used to develop the analytical models for the nuclear industry, which are most nearly suitable for wood structural member missiles, are steel pipes and rods. Consequently,

Figure 7-11. Reinforced concrete wall section (a), reinforced concrete "waffle" wall constructed with insulating concrete forms (b), and reinforced concrete "flat" wall constructed with insulating concrete forms (c)



Designs provided in FEMA 320 include the use of sheet metal in safe room roof construction. If sheet metal alone is relied on for missile impact protection, it should be 12 gauge or heavier.

7.3.3 Impact Resistance of Composite Wall Systems

Composite wall systems need rigorous testing because there is no adequate method to model the complex interactions of materials during impact. Tests have shown that impacting a panel next to a support can cause perforation while impacting midway between supports results in permanent deformations but not perforation. Seams between materials are the weak links in the tested systems. The locations and lengths of seams between different materials are critical. Currently the best way to determine the missile shielding ability of a composite wall system is to build and test a full-scale panel that consists of all the materials and structural connections to be used in constructing the panel. See Figure 7-9 for an illustration of a representative composite wall section.

Figure 7-9. Composite wall section

7.3.4 Impact Resistance of Concrete Masonry Units

Texas Tech research has demonstrated that both 6- and 8-inch-thick concrete masonry units (CMUs) can resist the large missile impact. Six-inch CMU walls that are fully grouted with concrete and reinforced with #4 reinforcing steel (rebar) in every cell (see Figure 7-10) can withstand the impact of a 15-lb 2x4 wood member striking perpendicular to the wall with speeds in excess of 100 mph. Eight-inch CMU walls should be fully grouted but need only be reinforced with #5 reinforcing steel (rebar) in every fifth cell (40 inches o.c.) for debris impact-resistance; however, more reinforcing steel may be required in the masonry wall to carry wind loads, depending upon the design and geometry of the masonry wall.

Figure 7-10. Concrete masonry unit (CMU) wall sections

Pages taken from FEMA P-361, Second Edition / August 2008