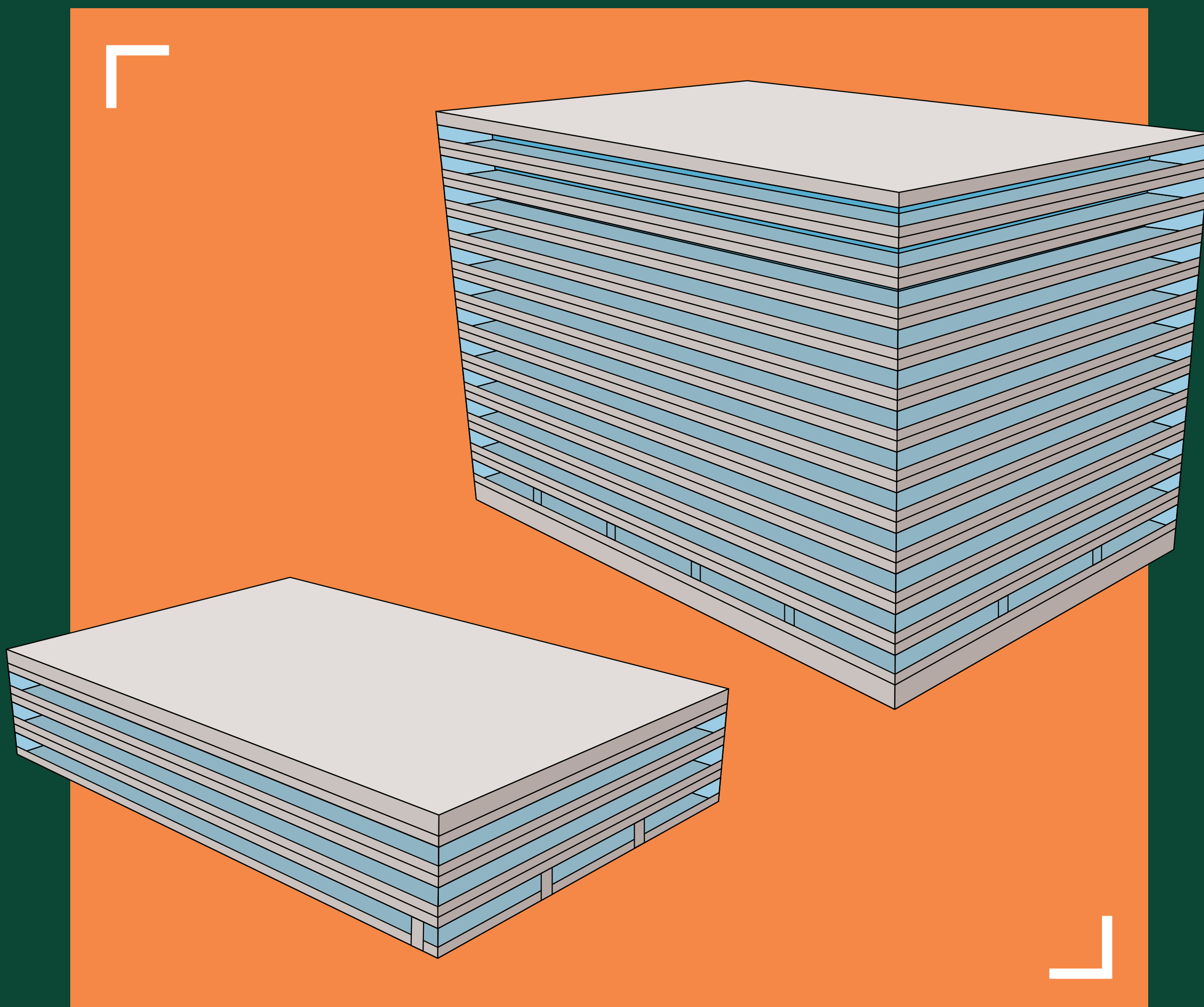
# Life Cycle Assessment of Prototypical Office Buildings in a High-Seismic Location



## About WoodWorks – Wood Products Council

WoodWorks provides education and free project support related to the design, engineering, and construction of commercial and multi-family wood buildings in the U.S. For assistance with a project, visit www.woodworks.org/project-assistance or email help@woodworks.org.

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**LCA Tool**

KPFF's Internal LCA Calculator
(based on Athena Impact Estimator for Buildings)

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# Table of Contents

# 1. Introduction

## 1.1 Overview of Study

This study documents the life cycle assessment (LCA) of prototypical medium and large office buildings at a high-seismic location in the U.S. It is intended to compare the global warming potential (GWP) of different structural configurations across structural systems and life cycle stages, including gravity versus lateral portions of the structural force-resisting system, superstructure versus substructure, and excluding or including biogenic carbon. Five structural system configurations, comprising different combinations of mass timber, structural steel, and reinforced concrete systems, were studied for both the medium and large office buildings. For an LCA of prototypical medium and large office buildings at a moderate-seismic, rather than high-seismic, location in the U.S., see WoodWorks, 2026.

## 1.2 Overview of Buildings

The heights and areas of the medium and large office buildings are taken from the U.S. Department of Energy's prototype building models (DOE, 2025) corresponding to 39 feet (11.9 meters) and 55,000 square feet (5,110 square meters) and 156 feet (47.5 meters) and 500,000 square feet (46,500 square meters), respectively. Since these prototype building descriptions only specify perimeter plan dimensions and building height, this study furthered that information to establish realistic grid spacing, locations of primary vertical circulation (i.e., stairs and elevators), and locations of the lateral force-resisting system (LFRS). See Sections 3 and 4 of this report for more details on the medium and large office buildings, respectively.

Both buildings are assumed to be located in a high-seismic region of the U.S. corresponding to Seismic Design Category D. For this study, San Diego, California was chosen as the representative location. All non-lateral load effects (e.g., dead, live, etc.) were considered in the structural design in combination with seismic loads. Wind loads were assumed not to govern.

## 1.3 Overview of Structural Systems

Five structural system configurations were studied, comprising a mix of mass timber, structural steel, and reinforced concrete in different combinations in the gravity force-resisting system (GFRS) and LFRS, for each of the prototype medium and large office buildings. See Table 1-1.

**TABLE 1-1:** Structural system configurations for both medium and large office buildings

| Gravity Force-Resisting System | Lateral Force-Resisting System |
|---|---|
| Mass timber post-and-beam | Special steel braced frames |
| | Special reinforced concrete shear walls |
| | Post-tensioned timber rocking walls |
| Structural steel post-and-beam | Special steel braced frames |
| Reinforced concrete post-tensioned flat slab and columns | Special reinforced concrete shear walls |

Each design was developed to a 100% schematic design level using a combination of hand/spreadsheet calculations and structural analysis models. Design is in accordance with the following codes and standards:

- 2021 International Building Code (ICC, 2021)
- ASCE/SEI 7-16: Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE, 2016)
- 2018 National Design Specification for Wood Construction® (NDS®) (AWC, 2018)
- 2021 Special Design Provisions for Wind and Seismic (SDPWS) (AWC, 2021)
- ANSI/AISC 360-16: Specification for Structural Steel Buildings (AISC, 2016)
- ANSI/AISC 341-16: Seismic Provisions for Structural Steel Buildings (AISC, 2016)
- ACI 318-19: Building Code Requirements for Structural Concrete (ACI, 2019)

Significant effort was made to achieve functionally equivalent structures for the purpose of comparative LCA. For example, consistent superimposed dead and live loads, deflection limits, and foundation type were used across all structural system configurations for each of the buildings.

# 2. Life Cycle Assessment Methodology

## 2.1 LCA Overview

An LCA was performed to estimate the GWP associated with each of the five structural system configurations described in Section 1.3 for each of the medium and large office buildings. GWP is measured in kilograms of carbon dioxide equivalent (kg$CO_2$eq).

The LCA addresses the life cycle stages shown in Table 2-1 and includes Stages A, C, and D. Stage B (e.g., repair/replacement of interior finishes, operational energy/water use, etc.) does not generally impact LCAs that are primarily focused on structural quantities. Thus, Stage B is excluded from this study. To show the contribution of each life cycle stage, results in Section 5 are reported separately for Stages A, A through C, and A through D. This is important because the assumptions made for many materials in Stages C and D are often uncertain.

**TABLE 2-1:** Life cycle stages; scope inclusions in light green

| Production | | | Construction Process | | Use | | | | | | | End-of-Life | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | A2 | A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
| Raw Material Supply | Transportation | Manufacturing | Transportation | Construction/Installation | Use | Maintenance | Repair | Replacement | Refurbishment | Operational Energy Use | Operational Water Use | Deconstruction/Demolition | Transportation | Waste Processing | Disposal | Benefits and Loads beyond the System Boundary |

## 2.2 **Material and LCA Assumptions**

A structural material quantity take-off was performed for each configuration. The physical scope of quantities is represented in Sections 3.2 through 3.4 and Sections 4.2 through 4.4 for the medium and large office buildings, respectively. Quantities for main structural members were explicitly calculated with the following assumptions and clarifications.

- Steel plate quantities representing gravity glue-laminated timber (glulam) connections were estimated from a typical connection and then applied throughout the project.
- Steel plate quantities representing gravity steel connections were estimated as 1.5% of the explicit take-off of wide-flange (WF) member tonnage.
- The explicit take-off of concrete reinforcement tonnage was increased by 20% to account for laps, splices, hooks, miscellaneous rebar, etc.
- The explicit take-off of steel braced frame tonnage was increased by 5% to account for gussets, stiffener plates, etc.
- All hardware and connections for post-tensioned timber rocking walls were explicitly calculated.

The following elements and components were excluded from this study:

- All nonstructural elements and components including architectural (interior and envelope), mechanical, electrical, plumbing, fire protection, landscape, civil/site work and contents (e.g., casework and furniture)
- Structural elements and components not part of the main force-resisting system as well as other miscellaneous structural elements and components (e.g., stairs, elevator guide rail supports, light-gauge framing of interior and exterior walls, and structural fasteners)
- Excavation and temporary shoring

The GWP of each material was then estimated using GWP intensities pulled from the Athena Impact Estimator for Buildings version 5.5.0113 (Athena), with a few exceptions as described below, and implemented in a spreadsheet-based tool developed for KPFF's internal use. In Athena, the general USA location was selected, rather than a project-specific location, to keep the results general to all high-seismic locations in the U.S. Materials used in this study that are not available in Athena include:

- Gypsum concrete (gypcrete): GWP intensities used for gypcrete are based on a composite of the USG Levelrock 2500/3500 Environmental Production Declaration (EPD) values for Modules A1 through A3 and the Athena Concrete 4000 psi values for Modules A4 through D.
- Steel fireproofing: GWP intensities were taken from TallyLCA version 2025.06.24.01. This material only applies to the large office building.

LCA results are reported both excluding and including biogenic carbon. Biogenic carbon is the carbon stored in wood products and other biological material and is counted as a "negative" carbon emission in an LCA. Excluding biogenic carbon represents the approximate total embodied carbon emissions resulting from the project. For more information on the biogenic carbon accounting methods used in Athena, see *Biogenic Carbon Accounting in WBLCA Tools* (WoodWorks, n.d.) and Athena's user manual (Athena, 2023).

# 3. Medium Office Building Description and Materials

## 3.1 Building Description

The medium office building has three stories above grade and is classified as Business (Group B) occupancy. Each floor is approximately 110x160 feet (34x49 meters) for a total building size of 55,000 square feet (5,110 square meters). Floor-to-floor heights are 13 feet (4 meters). The building is assumed to be Type V-B construction with a 0-hour fire-resistance rating (FRR) for the primary structural frame, bearing and non-bearing walls, floor construction, and roof construction in accordance with the 2021 IBC.

## 3.2 Mass Timber Structure

As shown in Table 1-1, a mass timber post-and-beam GFRS is paired with three types of LFRS: (1) special steel braced frames, (2) special reinforced concrete shear walls, and (3) post-tensioned timber rocking walls. Bays are approximately 23x27 feet (7x8.2 meters). At all levels, 3-ply cross-laminated timber (CLT) panels span to glulam beams, which span to glulam girders and glulam columns. At the floors, the CLT is topped with 2 inches of gypcrete; no gypcrete is present at the roof. The ground floor consists of a reinforced concrete slab on grade. Spread footings

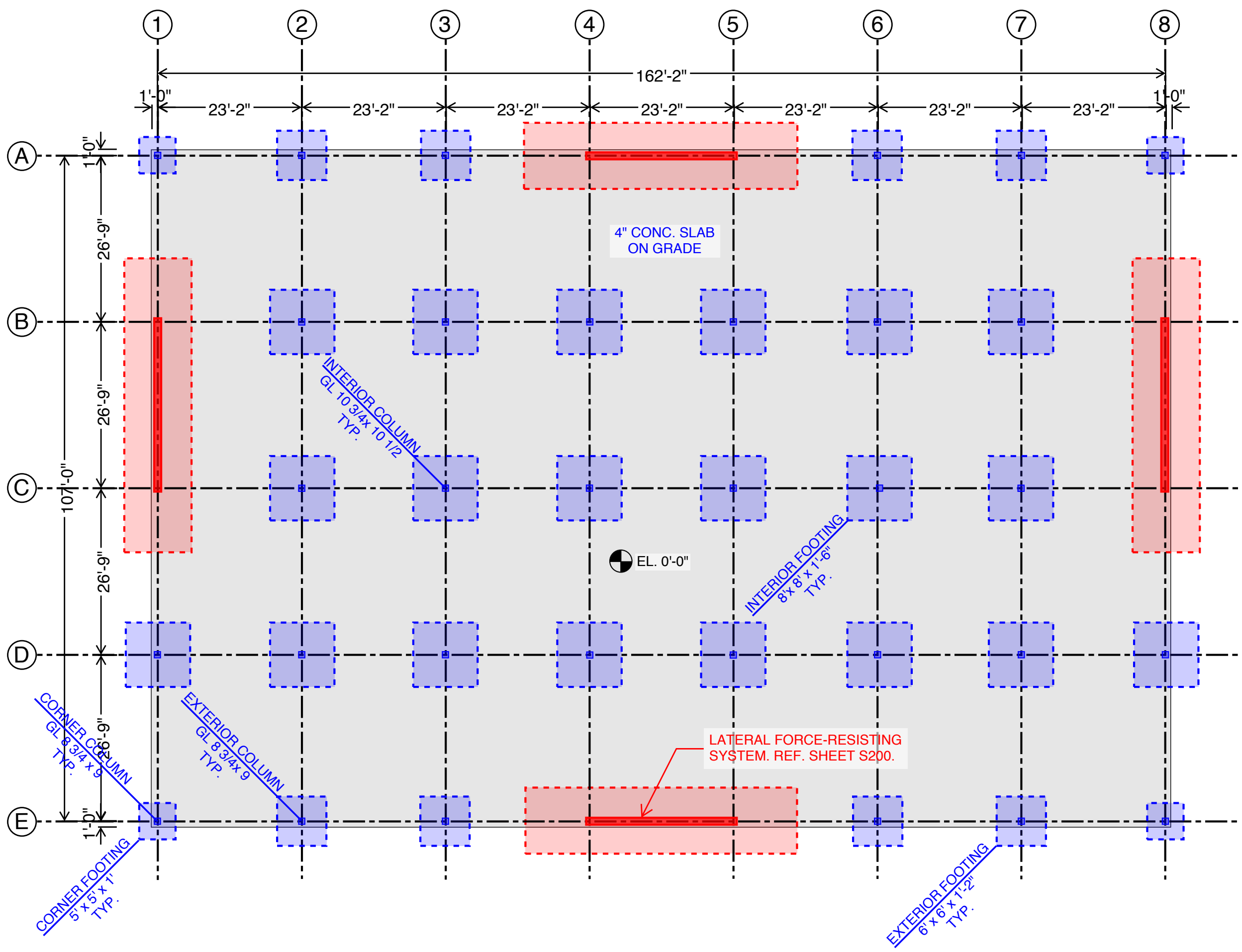


**FIGURE 3-1:** First floor and foundation plan for the medium mass timber office buildings

occur at column locations and strip footings occur under the LFRS elements (e.g., braced frames, concrete walls, or post-tensioned timber walls). The first floor and foundation plan is shown in Figure 3-1; a typical floor plan is shown in Figure 3-2.

The special steel braced frames consist of square hollow structural section (HSS) braces in a chevron configuration at each story with WF steel beams and columns. Special steel braced frames were used in lieu of buckling-restrained braced frames (BRBFs) despite the fact that BRBFs are more common in high-seismic regions. This decision was made to more easily compare the steel braced frame system across regions with lower seismic hazards, in a companion article to this study, where BRBFs are less common. The special reinforced concrete shear walls are 12 inches thick. The post-tensioned timber rocking walls consist of 9-ply CLT wall panels with steel U-shaped flexural plates (UFPs) and post-tensioned threaded rods.

The structural systems, elements, and materials considered in the LCA for the medium mass timber office buildings are shown in Table 3-1.

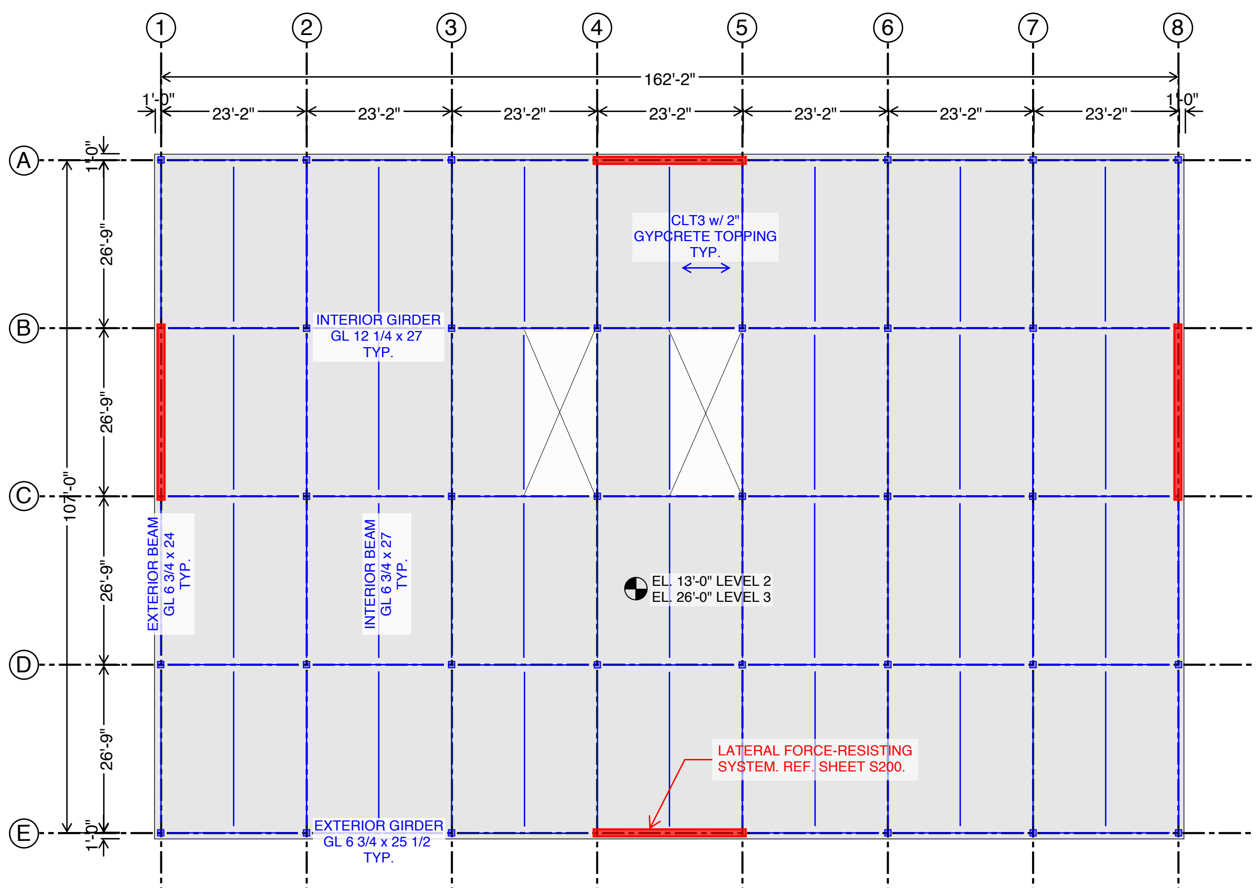


**FIGURE 3-2:** Typical floor plan for the medium mass timber office buildings

**TABLE 3-1:** Scope of structural systems, elements, and materials for the medium mass timber office buildings

| Structural Element | Material Name[a] | Notes |
|---|---|---|
| **Gravity Force-Resisting System** | | |
| Foundations | Concrete 4000 psi | |
| | Rebar | |
| Slab on grade | Concrete 4000 psi | |
| | Rebar | |
| Beams/girders | Glulam | |
| | Steel plate | To account for beam and girder connections |
| Columns | Glulam | |
| | Steel plate | To account for column-to-column and column-to-foundation connections |
| Floor/roof assembly | CLT | |
| | Gypcrete[b] | |
| **Lateral Force-Resisting System** | | |
| **Special Steel Braced Frames** | | |
| Foundations | Concrete 5000 psi | |
| | Rebar | |
| Beams/girders | WF steel | |
| Columns | WF steel | |
| Braces | HSS steel | |
| Chords/collectors | Steel plate | |
| **Special Reinforced Concrete Shear Walls** | | |
| Foundations | Concrete 5000 psi | |
| | Rebar | |
| Walls | Concrete 5000 psi | |
| | Rebar | |
| Chords/collectors | Steel plate | |
| **Post-Tensioned Timber Rocking Walls** | | |
| Foundations | Concrete 5000 psi | |
| | Rebar | |
| Walls | CLT | |
| | Steel plate | To account for UFPs, UFP connections, and post-tensioned rod connections |
| | Screws, nuts, bolts | To account for post-tensioned rods |
| Chords/collectors | Steel plate | |

[a] *Material names correspond to Athena unless noted otherwise.*
[b] *Custom material. See Section 4.1.*

## 3.3 **Steel Structure**

As described in Table 1-1, a structural steel post-and-beam GFRS is paired with special steel braced frames as the LFRS. Bays are approximately 32x36 feet (9.8x11 meters). At the floors, 3-inch normal-weight concrete on 3-inch metal deck spans to WF beams, which span to WF girders. At the roof, the 3-inch metal deck is untopped (i.e., has no concrete topping). The ground floor consists of a reinforced concrete slab on grade. Spread footings occur at column locations and strip footings occur under the steel braced frames. The first floor and foundation plan is shown in Figure 3-3; a typical floor plan is shown in Figure 3-4.

The special steel braced frames use a similar configuration and similar steel shapes for beams, columns, and braces as described for the mass timber building in Section 3.2, except with different sized structural members.

The structural systems, elements, and materials considered in the LCA for the medium structural steel office building are shown in Table 3-2.

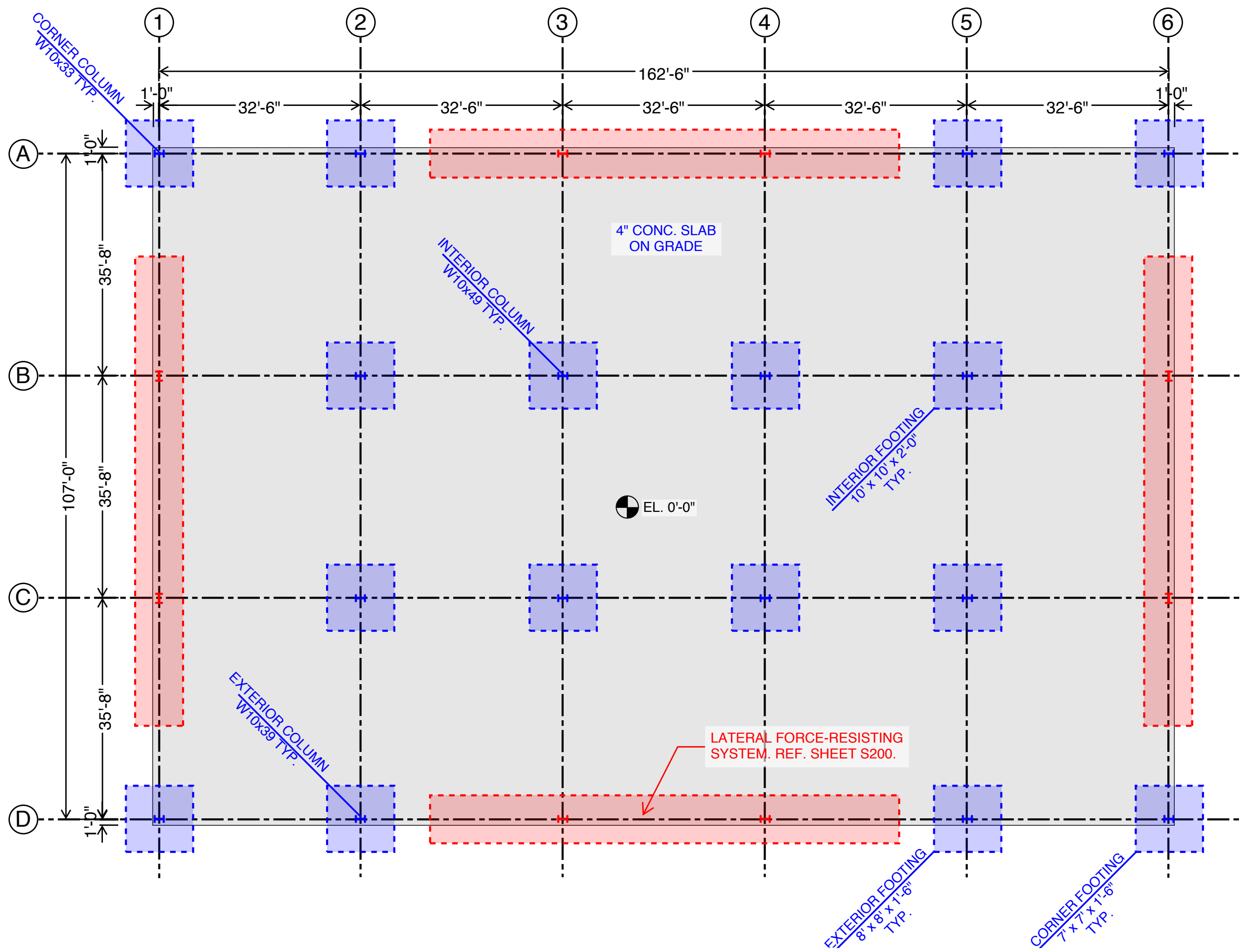


**FIGURE 3-3:** First floor and foundation plan for the medium structural steel office building

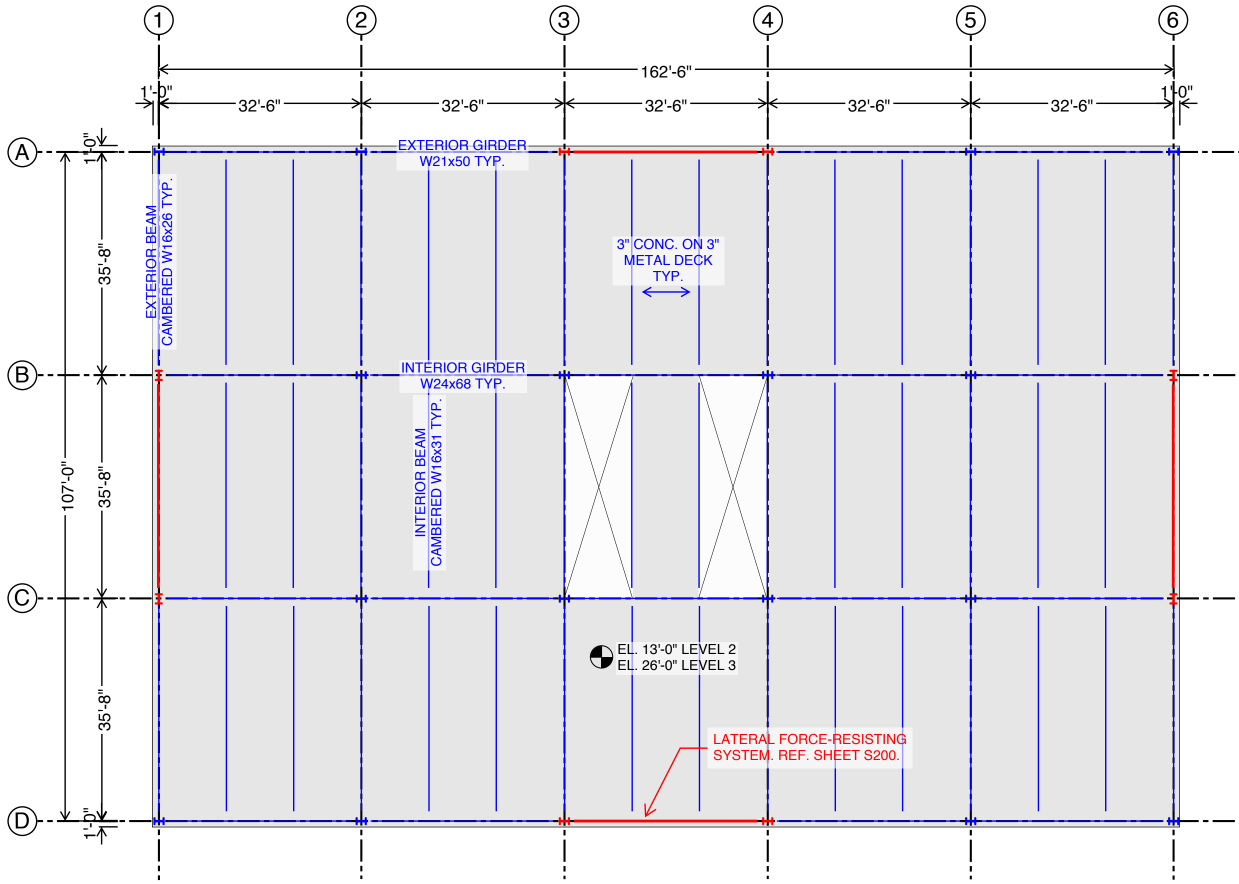


**FIGURE 3-4:** Typical floor plan for the medium structural steel office building

**TABLE 3-2:** Scope of structural systems, elements, and materials for the medium structural steel office building

| Structural Element | Material Name[a] | Notes |
|---|---|---|
| **Gravity Force-Resisting System** | | |
| Foundations | Concrete 4000 psi | |
| | Rebar | |
| Slab on grade | Concrete 4000 psi | |
| | Rebar | |
| Beams/girders | WF steel | |
| | Steel plate | To account for beam and girder connections |
| Columns | WF steel | |
| | Steel plate | To account for column-to-column and column-to-foundation connections |
| Floor/roof assembly | Concrete 4000 psi | |
| | Galvanized decking | To account for metal decking |
| | Rebar | |
| **Lateral Force-Resisting System** | | |
| **Special Steel Braced Frames** | | |
| Foundations | Concrete 5000 psi | |
| | Rebar | |
| Beams/girders | WF steel | |
| Columns | WF steel | |
| Braces | HSS steel | |
| Chords/collectors | WF steel | |

[a] *Material names correspond to Athena unless noted otherwise.*

## 3.4 **Reinforced Concrete Structure**

As described in Table 1-1, a reinforced concrete post-tensioned flat-slab and column GFRS is paired with special reinforced concrete shear walls as the LFRS. Bays are approximately 30x31 feet (9.1x9.4 meters). As is typical in post-tensioned flat-slab buildings, columns are held back from the perimeter to increase slab capacity in the end bays, resulting in cantilevers along the plan north and south edges of the building. Smaller cantilevers also occur at the plan east and west edges. At the floors and roof, a 9-inch post-tensioned flat slab spans to reinforced concrete columns. The ground floor consists of a reinforced concrete slab on grade. Spread footings occur at column locations and strip footings occur under the reinforced concrete shear walls. The first floor and foundation plan is shown in Figure 3-5; a typical floor plan is shown in Figure 3-6.

The special reinforced concrete shear walls use a similar configuration as described for the mass timber building in Section 3.2, except with different thickness, length, and reinforcing.

The structural systems, elements, and materials considered in the LCA for the medium reinforced concrete office building are shown in Table 3-3.

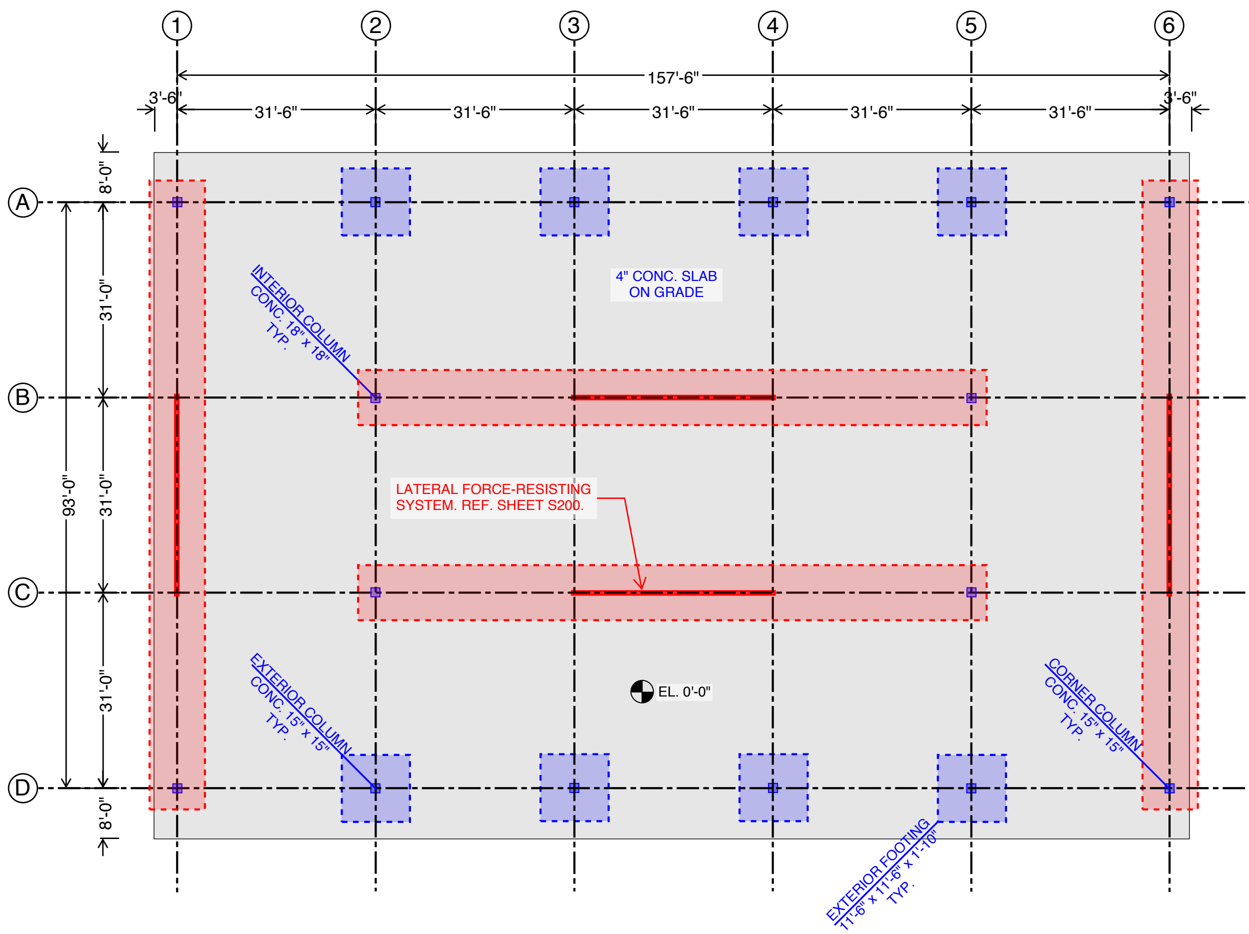


**FIGURE 3-5:** First floor and foundation plan for the medium reinforced concrete office building

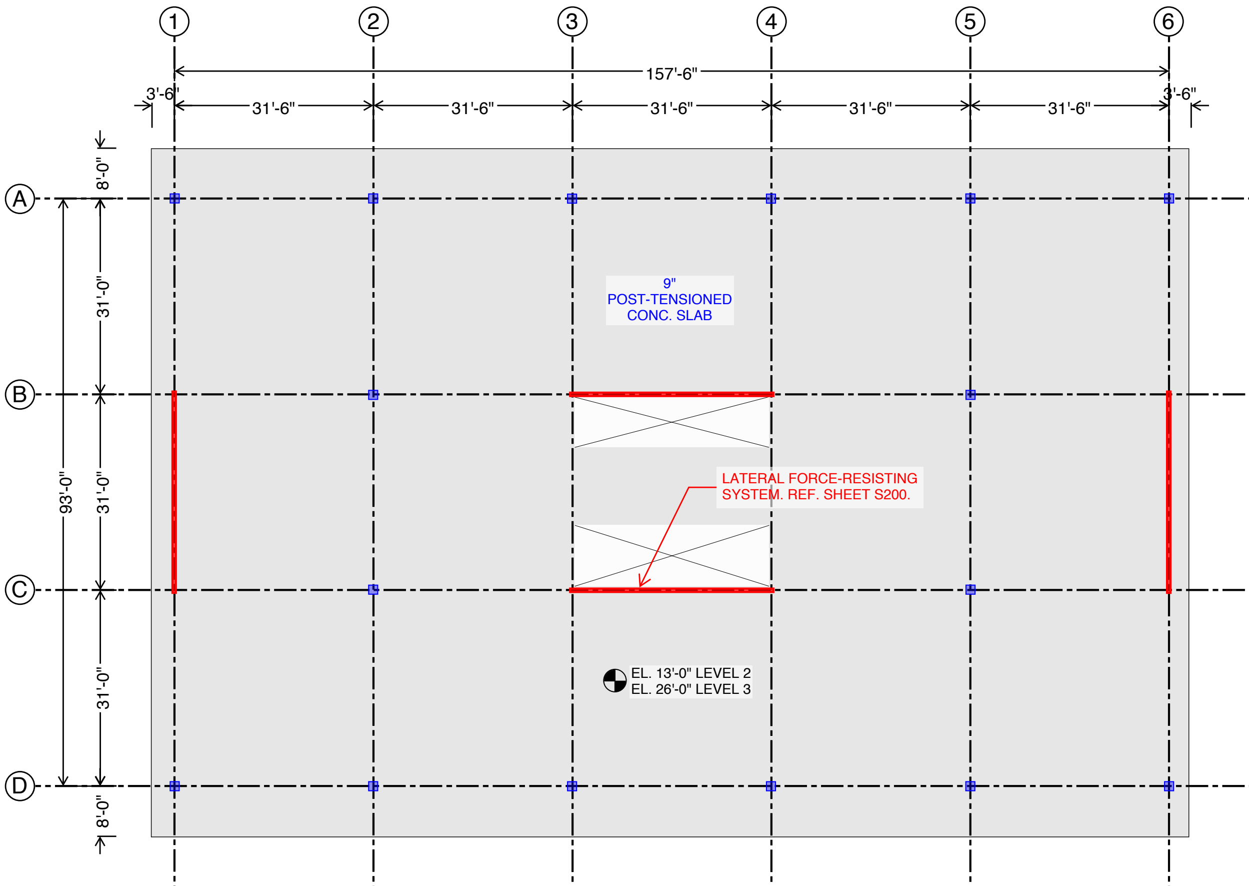


**FIGURE 3-6:** Typical floor plan for the medium reinforced concrete office building

**TABLE 3-3:** Scope of structural systems, elements, and materials for the medium reinforced concrete office building

| Structural Element | Material Name[a] | Notes |
|---|---|---|
| **Gravity Force-Resisting System** | | |
| Foundations | Concrete 5000 psi | |
| | Rebar | |
| Slab on grade | Concrete 4000 psi | |
| | Rebar | |
| Columns | Concrete 5000 psi | |
| | Rebar | |
| Floor/roof assembly | Concrete 5000 psi | |
| | Rebar | |
| | Screws, nuts, bolts | To account for post-tensioning strands |
| **Lateral Force-Resisting System** | | |
| **Special Reinforced Concrete Shear Walls** | | |
| Foundations | Concrete 5000 psi | |
| | Rebar | |
| Walls | Concrete 5000 psi | |
| | Rebar | |
| Chords/collectors | Rebar | |

[a] *Material names correspond to Athena unless noted otherwise.*

# 4. Large Office Building Description and Materials

## 4.1 Building Description

The large office building has 12 stories above grade and one below-grade level and is classified throughout as Business (Group B) occupancy. Each floor is approximately 160x240 feet (49x73 meters) for a total building size of 500,000 square feet (46,500 square meters). Floor-to-floor heights are 13 feet (4 meters). The building is assumed to have a 2-hour FRR for the primary structural frame, bearing walls, and floor construction, a 1-hour FRR for the roof construction, and a 0-hour FRR for non-bearing walls. This aligns with Type IV-B construction for mass timber building configurations and Type I-B construction for steel and concrete building configurations in accordance with the 2021 IBC.

## 4.2 Mass Timber Structure

As described in Table 1-1, a mass timber post-and-beam GFRS is paired with three types of LFRS: (1) special steel braced frames, (2) special reinforced concrete shear walls, and (3) post-tensioned timber rocking walls. Bays are approximately 30x32 feet (9.1x9.8 meters). At all levels, 5-ply CLT panels span to glulam beams, which span to glulam girders and glulam columns. At the floors, the CLT is topped with 2 inches of gypcrete; no gypcrete is present at the roof.

The ground floor consists of a 9-inch post-tensioned concrete flat slab, and there is a 12-inch-thick reinforced concrete retaining wall around the perimeter of the basement level. The foundation consists of a reinforced concrete mat foundation, locally thickened under the LFRS. The basement level and foundation plan is shown in Figure 4-1. The ground floor plan is shown in Figure 4-2 and a typical upper floor plan is shown in Figure 4-3.

The special steel braced frames consist of WF braces in a two-story super-X configuration. A super-X configuration involves alternating chevron and V (inverse chevron) bracing at each story to create a two-story X of braces. Beams and columns are also WF steel. As with the medium office building, special steel braced frames were used in lieu of BRBFs despite the fact that BRBFs are more common in high-seismic regions. This decision was made to more easily compare the steel braced frame system across regions with lower seismic hazards, in a companion article to this study, where BRBFs are less common. The special reinforced concrete shear walls consist of 32- to 48-inch-thick reinforced concrete shear walls with coupling beams over doors and elevator lobby openings. The post-tensioned timber rocking walls consist of 9-ply CLT wall panels with steel UFPs and post-tensioned threaded rods.

The structural systems, elements, and materials considered in the LCA for the large mass timber office buildings are shown in Table 4-1.

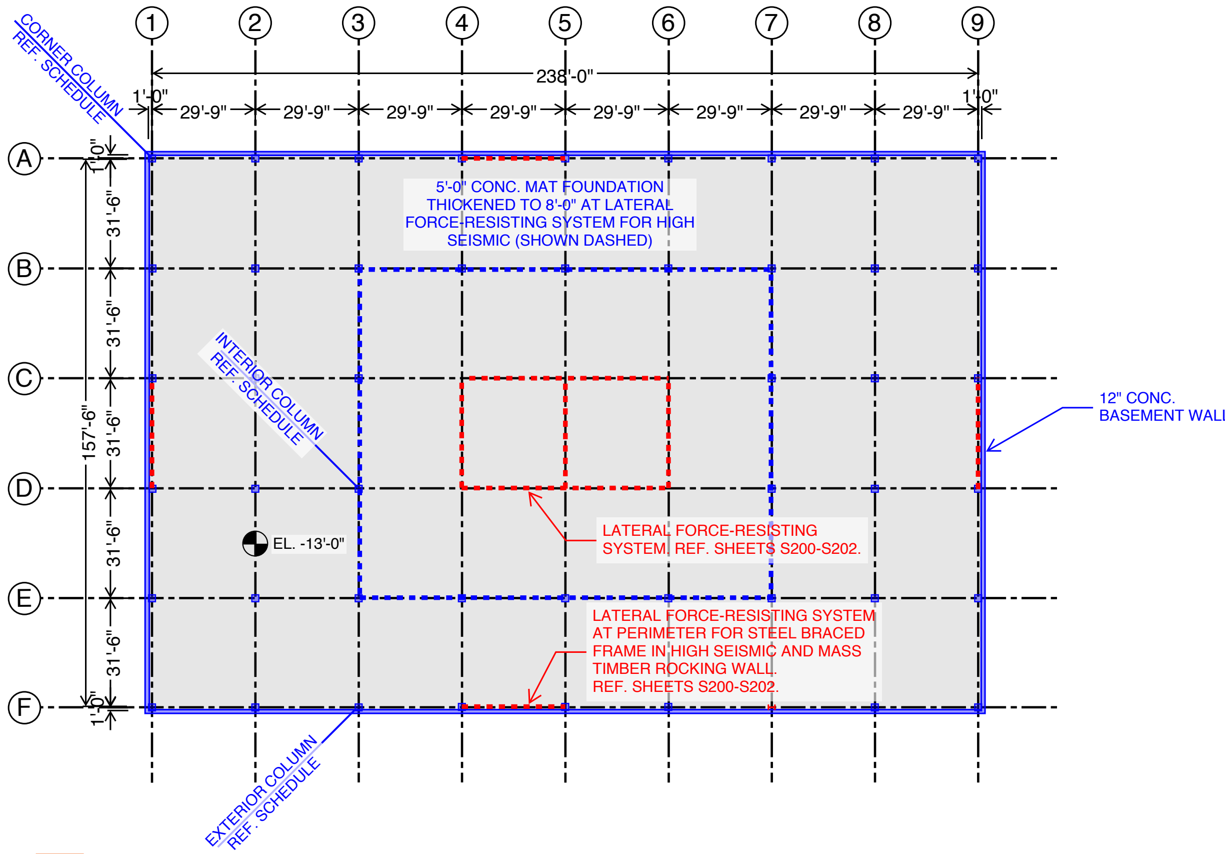


**FIGURE 4-1:** Basement level and foundation plan for the large mass timber office buildings

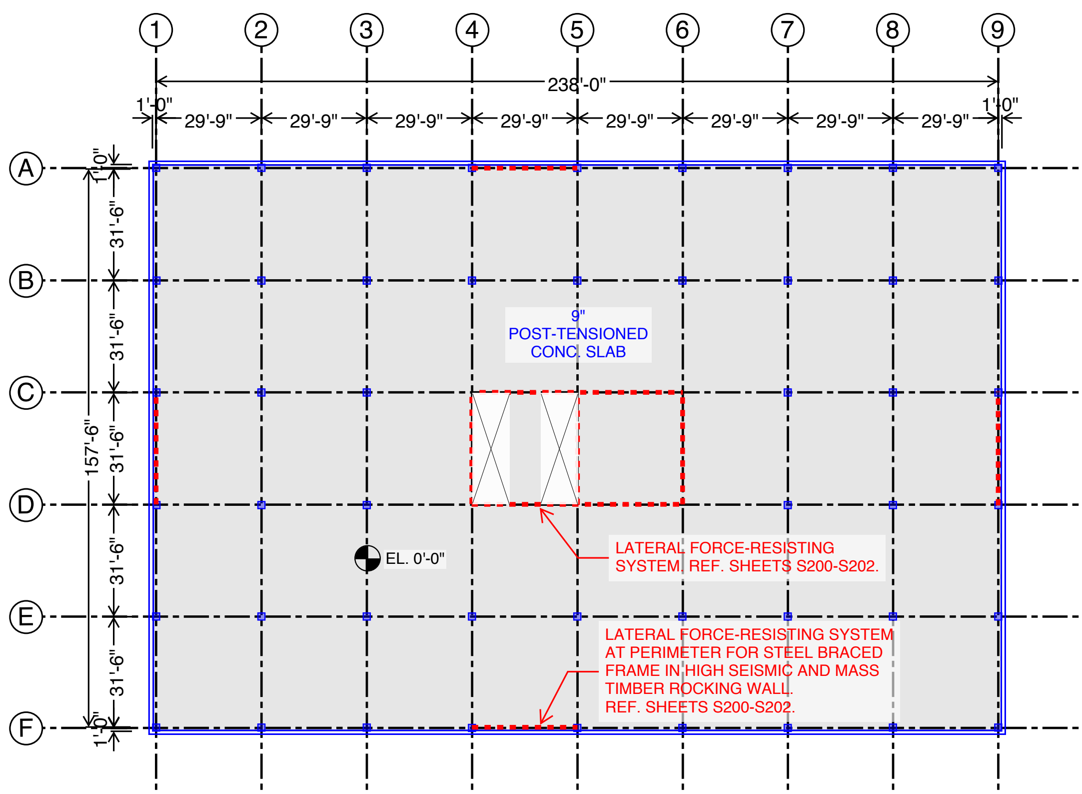


**FIGURE 4-2:** Ground floor plan for the large mass timber office buildings

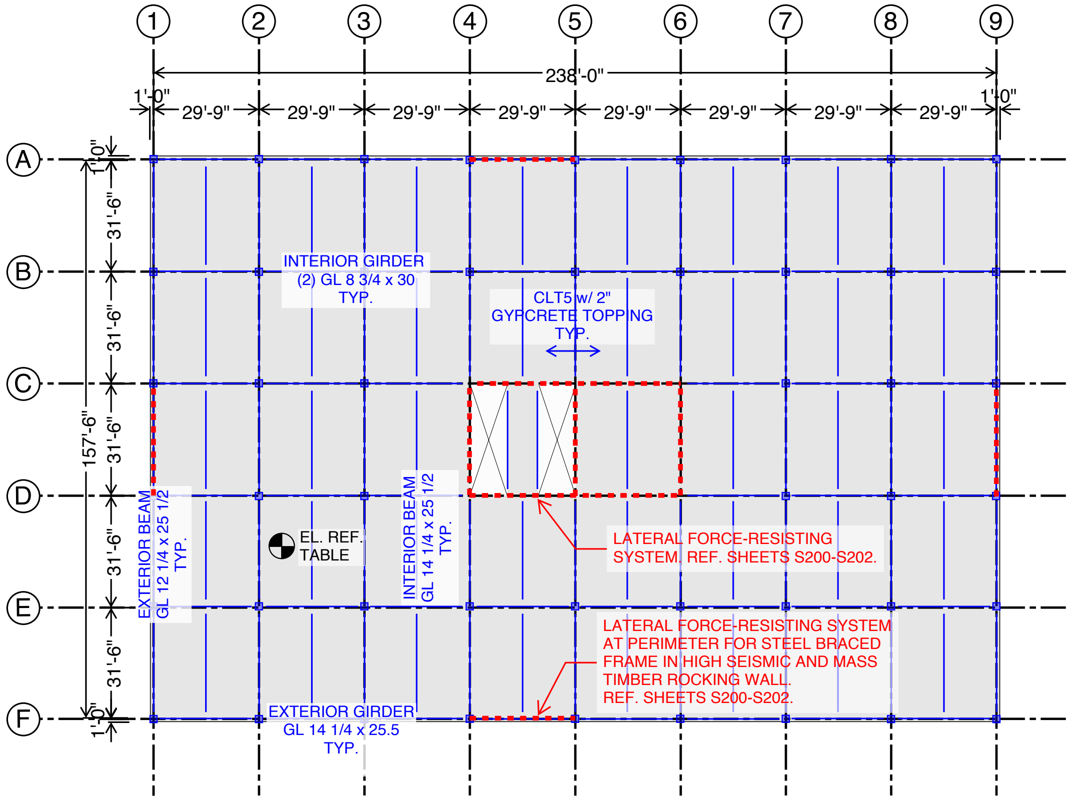


**FIGURE 4-3:** Typical upper floor plan for the large mass timber office buildings

**TABLE 4-1:** Scope of structural systems, elements, and materials for the large mass timber office buildings

| Structural Elemen | Material Name[a] | Notes |
|---|---|---|
| **Gravity Force-Resisting System** | | |
| Foundations | Concrete 4000 psi | |
| | Rebar | |
| Basement walls | Concrete 4000 psi | |
| | Rebar | |
| Level 1 slab | Concrete 5000 psi | |
| | Rebar | |
| | Screws, nuts, bolts | To account for post-tensioning strands |
| Beams/girders | Glulam | |
| | Steel plate | To account for beam and girder connections |
| Columns | Glulam | |
| | Steel plate | To account for column-to-column and column-to-foundation connections |
| | Concrete 5000 psi | |
| | Rebar | |
| Floor/roof assembly | CLT | |
| | Gypcrete[b] | |

*Continued on page 16*

**TABLE 4-1:** Scope of structural systems, elements, and materials for the large mass timber office buildings *(Continued)*

| Structural Element | Material Name[a] | Notes |
|---|---|---|
| **Lateral Force-Resisting System** | | |
| **Special Steel Braced Frames** | | |
| Foundations | Concrete 4000 psi | |
| | Rebar | |
| Basement walls | Rebar | |
| Level 1 slab | Rebar | |
| Beams/girders | WF steel | |
| Columns | WF steel | |
| Braces | WF steel | |
| Chords/collectors | Steel plate | |
| Spray-applied fireproofing | Fireproofing, cementitious[c] | |
| **Special Reinforced Concrete Shear Walls** | | |
| Foundations | Concrete 4000 psi | |
| | Rebar | |
| Basement walls | Rebar | |
| Level 1 slab | Rebar | |
| Walls | Concrete 8000 psi | |
| | Rebar | |
| Chords/collectors | Steel plate | |
| **Post-Tensioned Timber Rocking Walls** | | |
| Foundations | Concrete 4000 psi | |
| | Rebar | |
| Basement walls | Rebar | |
| Level 1 slab | Rebar | |
| Columns | Glulam | |
| | Steel plate | To account for column-to-column and column-to-foundation connections |
| | Concrete 5000 psi | |
| | Rebar | |
| Walls | CLT | |
| | Steel plate | To account for UFPs, UFP connections, and post-tensioned rod connections |
| | Screws, nuts, bolts | To account for post-tensioned rods |
| Chords/collectors | Steel plate | |

[a] *Material names correspond to Athena unless noted otherwise.*
[b] *Custom material. See Section 4.1.*
[c] *TallyLCA material. See Section 4.1.*

## 4.3 Steel Structure

As described in Table 1-1, a structural steel post-and-beam gravity system is paired with special steel braced frames as the LFRS. Bays are approximately 30x32 feet (9.1x9.8 meters). At the floors, 3-inch normal-weight concrete on 3-inch metal deck spans to WF beams, which span to WF girders. At the roof, the 3-inch metal deck is untopped (i.e., has no concrete topping).

The ground floor consists of a 9-inch post-tensioned concrete flat slab, and there is a 12-inch-thick reinforced concrete retaining wall around the perimeter of the basement level. The foundation consists of a reinforced concrete mat foundation, locally thickened under the steel braced frames.

The basement level and foundation plan is shown in Figure 4-4. The ground floor plan is shown in Figure 4-5 and a typical upper floor plan is shown in Figure 4-6.

The special steel braced frames use a similar configuration and similar steel shapes for beams, columns, and braces as described for the mass timber building in Section 4.2, except with different sized structural members.

The structural systems, elements, and materials considered in the LCA for the large structural steel office building are shown in Table 4-2.

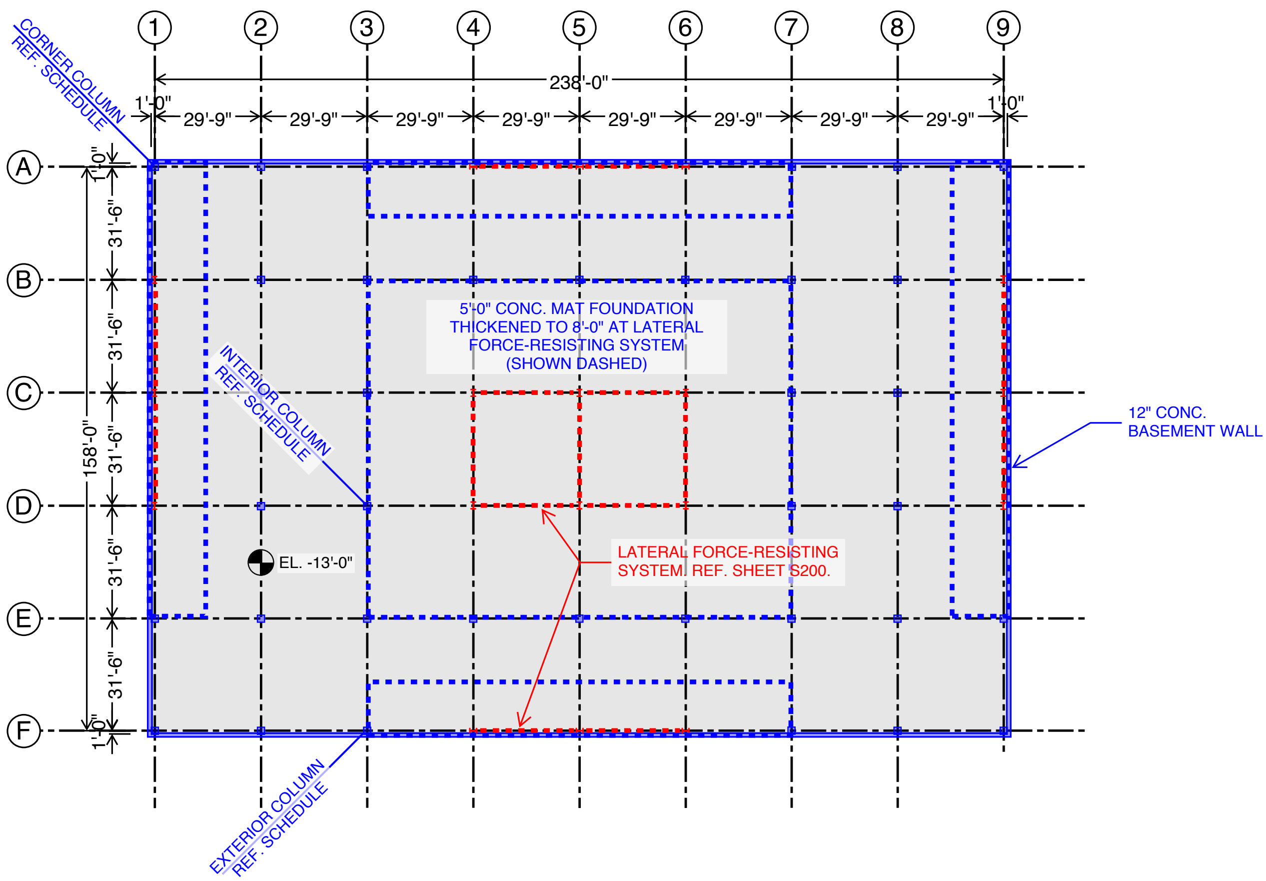


**FIGURE 4-4:** Basement level and foundation plan for the large structural steel office building

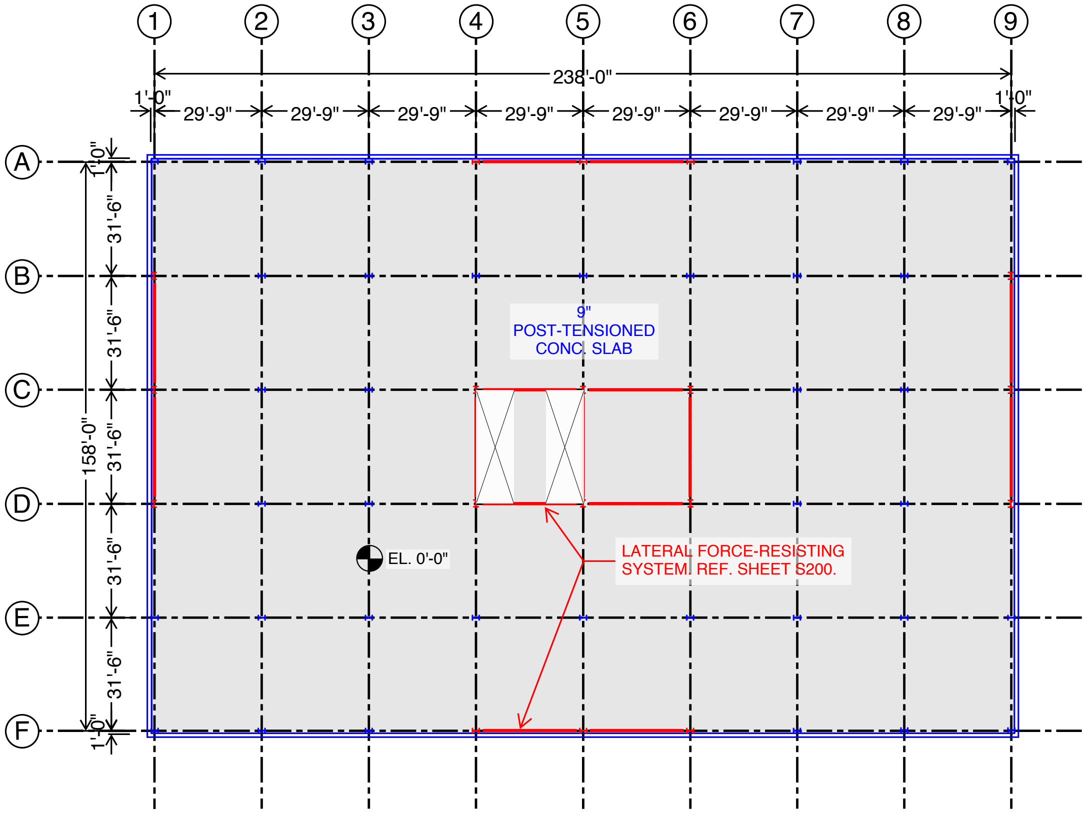


**FIGURE 4-5:** Ground floor plan for the large structural steel office building

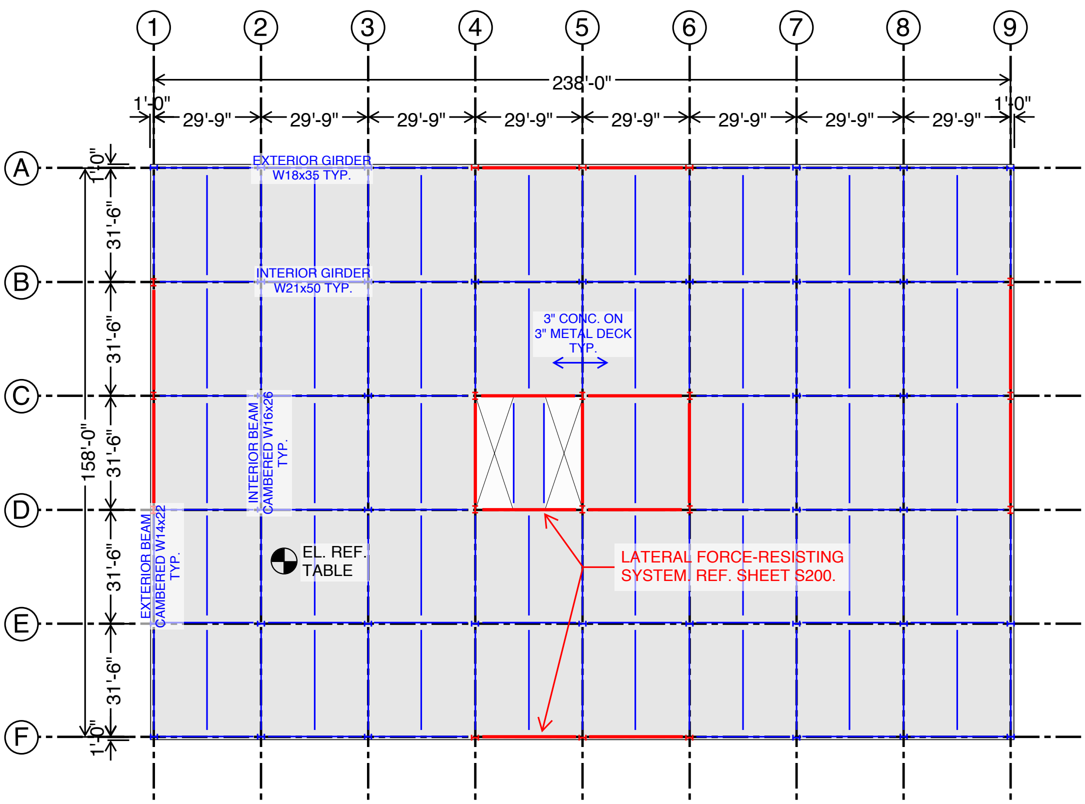


**FIGURE 4-6:** Typical upper floor plan for the large structural steel office building

**TABLE 4-2:** Scope of structural systems, elements, and materials for the large structural steel office building

| Structural Element | Material Name[a] | Notes |
|---|---|---|
| **Gravity Force-Resisting System** | | |
| Foundations | Concrete 4000 psi | |
| | Rebar | |
| Basement walls | Concrete 4000 psi | |
| | Rebar | |
| Level 1 slab | Concrete 5000 psi | |
| | Rebar | |
| | Screws, nuts, bolts | To account for post-tensioning strands |
| Beams/girders | WF steel | |
| | Steel plate | To account for beam and girder connections |
| Columns | WF steel | |
| | Steel plate | To account for column-to-column and column-to-foundation connections |
| | Concrete 5000 psi | |
| | Rebar | |
| Floor/roof assembly | Concrete 4000 psi | |
| | Galvanized decking | To account for metal decking |
| | Rebar | |
| Spray-applied fireproofing | Fireproofing, cementitious[b] | |
| **Lateral Force-Resisting System** | | |
| **Special Steel Braced Frames** | | |
| Foundations | Concrete 4000 psi | |
| | Rebar | |
| Basement walls | Rebar | |
| Level 1 slab | Rebar | |
| Beams/girders | WF steel | |
| Columns | WF steel | |
| Braces | WF steel | |
| Chords/collectors | WF steel | |

[a] *Material names correspond to Athena unless noted otherwise.*
[b] *TallyLCA material. See Section 4.1.*

## 4.4 Reinforced Concrete Structure

As described in Table 1-1, a reinforced concrete post-tensioned flat-slab and column gravity system was paired with special reinforced concrete shear walls. Bays are approximately 30x30 feet (9.1x9.1 meters). As is typical in post-tensioned flat-slab buildings, columns were held back from the perimeter to increase slab capacity in the end bays, resulting in cantilevers along the plan north and south edges of the building. Smaller cantilevers also occur at the plan east and west edges. At the floors and roof, a 9-inch post-tensioned flat slab spans to reinforced concrete columns.

The ground floor consists of a 9-inch post-tensioned concrete flat slab, and there is a 12-inch-thick reinforced concrete retaining wall around the perimeter of the basement level. The foundation consists of a reinforced concrete mat foundation, locally thickened under the special reinforced concrete shear walls. The basement level and foundation plan is shown in Figure 4-7. The ground floor plan is shown in Figure 4-8 and a typical upper floor plan is shown in Figure 4-9.

The special reinforced concrete shear walls use a similar configuration as described for the mass timber building in Section 4.2, except with different thickness, length, and reinforcing.

The structural systems, elements, and materials considered in the LCA for the large reinforced concrete office building are shown in Table 4-3.

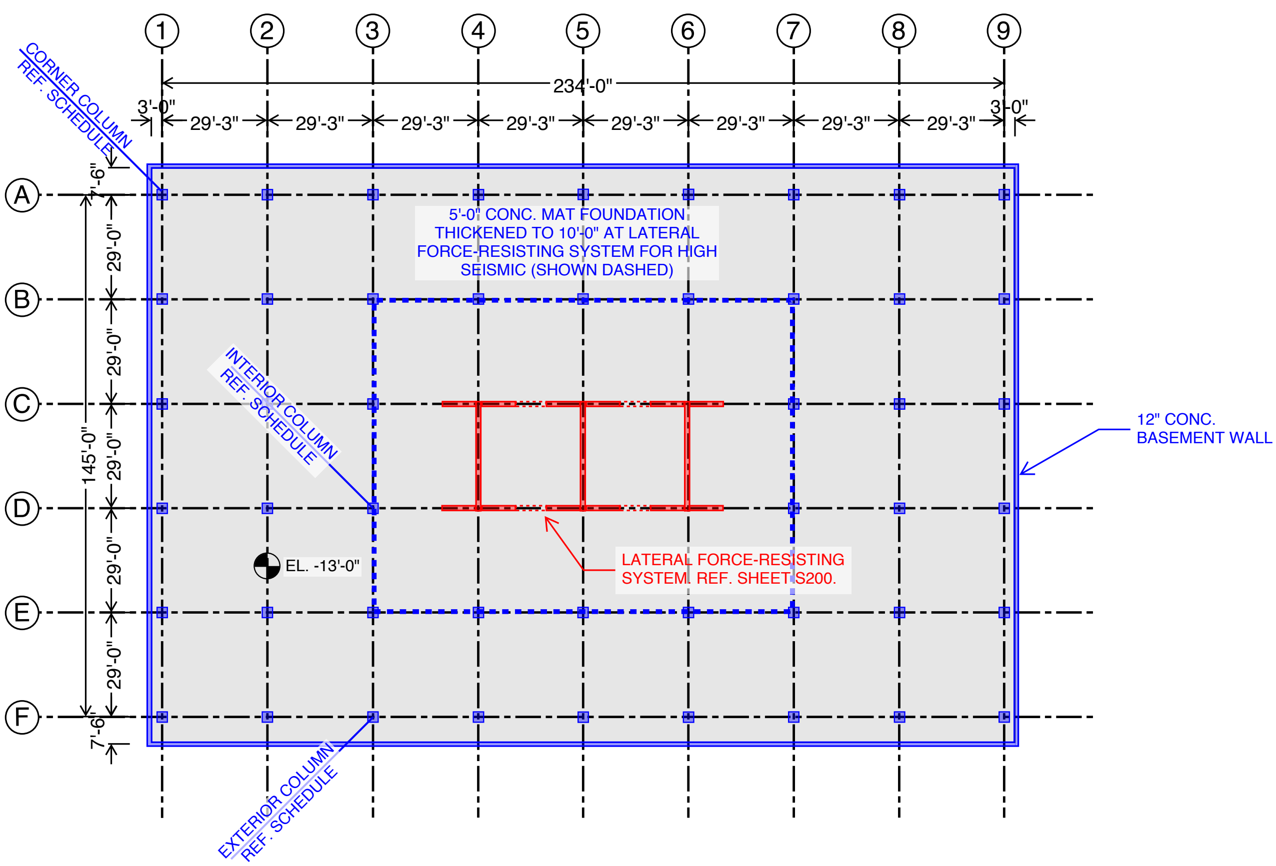


**FIGURE 4-7:** First floor and foundation plan for the large reinforced concrete office building

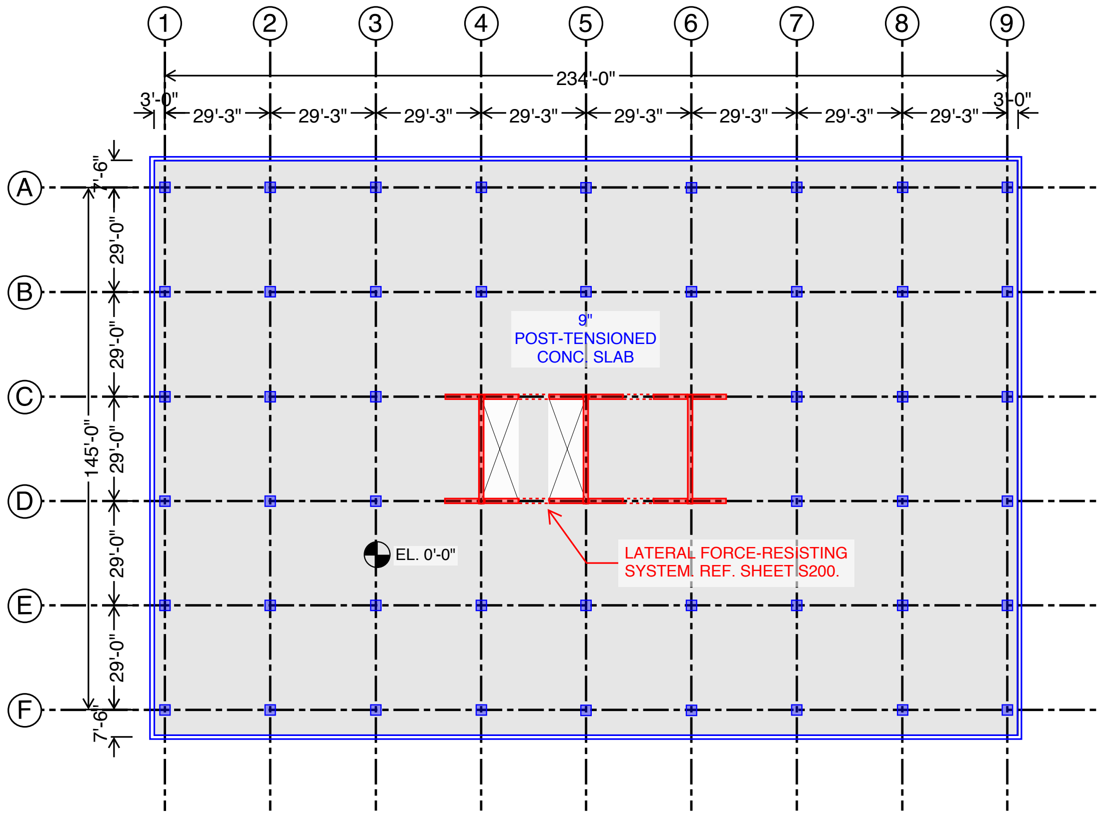


**FIGURE 4-8:** Ground floor plan for the large reinforced concrete office building

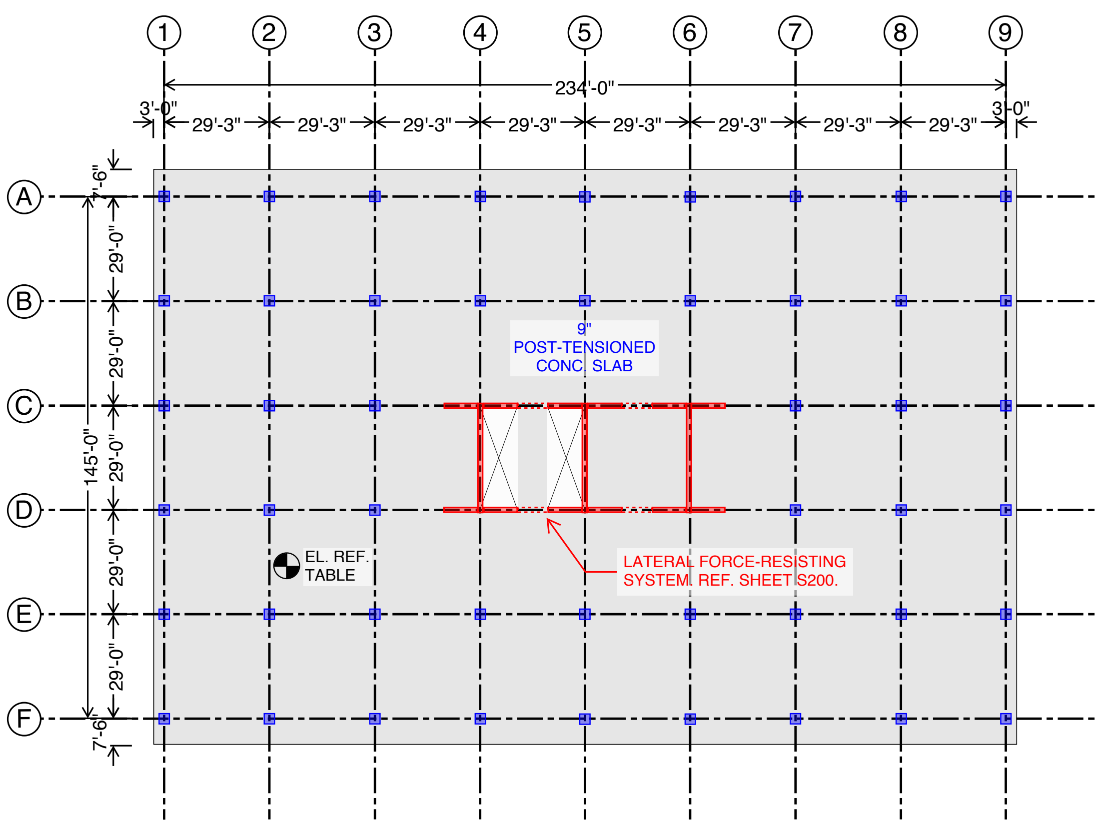


**FIGURE 4-9:** Typical upper floor plan for the large reinforced concrete office building

**TABLE 4-3:** Scope of structural systems, elements, and materials for the large reinforced concrete office building

| Structural Element | Material Name[a] | Notes |
|---|---|---|
| **Gravity Force-Resisting System** | | |
| Foundations | Concrete 5000 psi | |
| | Rebar | |
| Basement walls | Concrete 4000 psi | |
| | Rebar | |
| Level 1 slab | Concrete 5000 psi | |
| | Rebar | |
| | Screws, nuts, bolts | To account for post-tensioning strands |
| Columns | Concrete 6000 psi | |
| | Rebar | |
| Floor/roof assembly | Concrete 5000 psi | |
| | Rebar | |
| | Screws, nuts, bolts | To account for post-tensioning strands |
| **Lateral Force-Resisting System** | | |
| **Special Reinforced Concrete Shear Walls** | | |
| Foundations | Concrete 5000 psi | |
| | Rebar | |
| Basement walls | Concrete 4000 psi | |
| | Rebar | |
| Level 1 slab | Rebar | |
| Walls | Concrete 8000 psi | |
| | Rebar | |
| Chords/collectors | Rebar | |

[a] *Material names correspond to Athena unless noted otherwise.*

# 5. Results and Discussion

## 5.1 Medium Office Building

A comparison of the GWP values for each structural system for the medium office building across life cycle stages and materials is shown in Figures 5-1 and 5-2 when excluding and including biogenic carbon, respectively. The study considered Stages A, A through C, and A through D. Materials contributing to the LCA (discussed in Section 3) were grouped into the following categories: concrete/gypcrete, rebar, steel (hot-rolled), steel (cold-formed), and timber. A comparison of the relative GWP contributions for each structural system across life cycle stages for superstructure versus substructure and GFRS versus LFRS is shown in Figure 5-3 when excluding biogenic carbon. Numerical values of GWP are reported in Table 5-1.

GWP results excluding biogenic carbon (Figure 5-1a) for the mass timber GFRS, with any of the LFRS options, vary between approximately 95 and 120 $kgCO_2eq/m^2$ depending on which life cycle stages are considered. GWP results for the structural steel building vary between approximately 170 and 185 $kgCO_2eq/m^2$, whereas those for the reinforced concrete building vary between approximately 215 and 270 $kgCO_2eq/m^2$. This indicates that the mass timber buildings have significantly lower GWP than the structural steel building, which has significantly lower GWP than the reinforced concrete building. Figure 5-1a also shows that Stage A, particularly Modules A1 through A3, contributes the most to GWP. Interestingly, the variation in GWP between LFRS configurations for the mass timber GFRS is minimal, as explained in the discussion of Figure 5-3.

Relative GWP contributions by material (Figure 5-1b) are dominated by concrete/gypcrete. For the mass timber buildings and structural steel building, concrete/gypcrete contributes approximately 40-50% of the total GWP. For the reinforced concrete building, concrete contributes approximately 70-80%. Somewhat intuitively, timber and hot-rolled structural steel are the next largest contributors to GWP for the mass timber buildings and structural steel building, respectively.

Results including biogenic carbon (Figure 5-2) show considerable reductions in total GWP for the mass timber GFRS as a result of the biogenic carbon stored in the timber materials. Timber materials exhibit net negative GWP values (i.e., net carbon storage) across all life cycle stages, including when end-of-life assumptions (Stage C) are considered. Total GWP varies between approximately -60 and 35 $kgCO_2eq/m^2$ for the mass timber buildings, depending on the life cycle stages considered, with approximately 85-95 $kgCO_2eq/m^2$ stored in the timber components of the building when considering Stages A through D. Since no materials with biogenic carbon are included in the structural steel or reinforced concrete buildings, the results of Figure 5-2 are identical to those of Figure 5-1a for these buildings.

Relative GWP contributions when excluding biogenic carbon in Figure 5-3 demonstrate that the GFRS contributes approximately 50-75% to the total GWP across all structure configurations and life cycle stages, with the remainder coming from the LFRS. Of the GWP attributable to the LFRS, the largest contribution is from the substructure (i.e., foundations) rather than the superstructure elements. This is true for all structure system configurations and life cycle stages considered in this study. This also explains why there was little variation between the three LFRS options used with the mass timber GFRS (Figure 5-1a). Because all three systems were designed for the same seismic forces (i.e., response modification coefficient, *R*, equal to 6, which also determines foundation forces), the material quantities for the lateral foundations of all three systems are very similar. Figure 5-3 shows that the LFRS GWP is driven by the foundations; thus, it follows that little variation in total GWP is observed between the different LFRS alternatives considered for the mass timber buildings.


**FIGURE 5-1:** Comparison across structural system configurations and life cycle stages (excluding biogenic carbon) for the medium office building in terms of (a) GWP in $kgCO_2eq/m^2$ and (b) relative GWP contribution

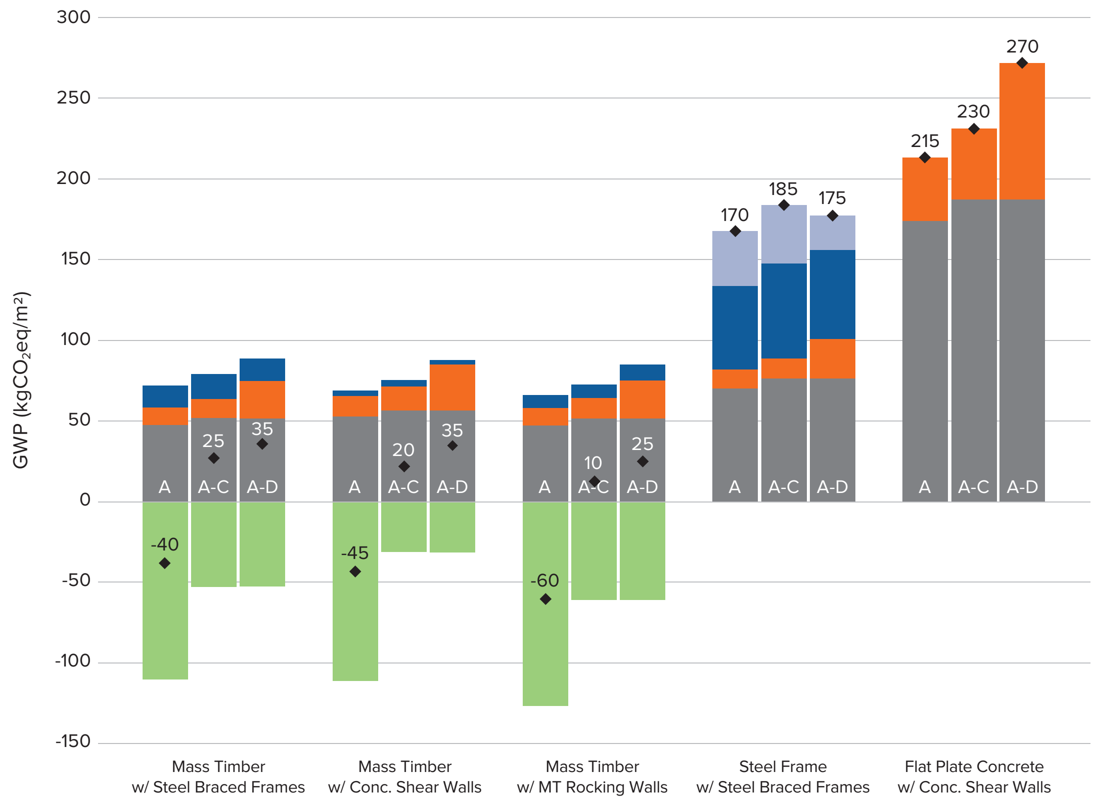


**FIGURE 5-2:** Comparison across structural system configurations and life cycle stages (including biogenic carbon) for the medium office building in terms of GWP in $kgCO_2eq/m^2$

- Timber
- Steel (Cold-Formed)
- Steel (Hot-Rolled)
- Rebar
- Concrete/Gypcrete
- Total GWP

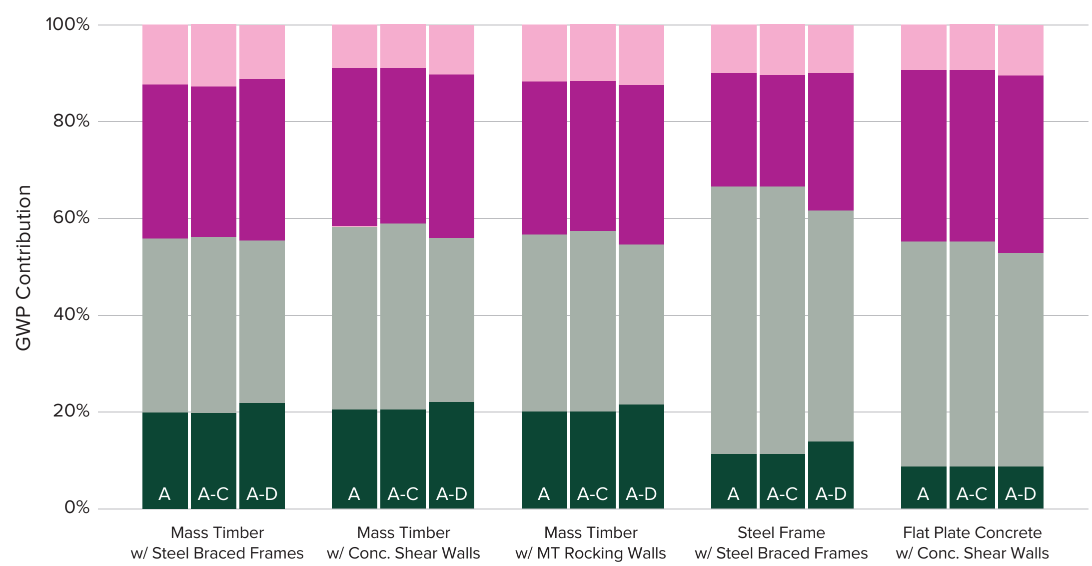


**FIGURE 5-3:** Relative GWP contribution between the LFRS versus GFRS and the superstructure versus substructure across structural system configurations and life cycle stages (excluding biogenic carbon) for the medium office building

- Lateral Superstructure
- Lateral Substructure
- Gravity Superstructure
- Gravity Substructure

**TABLE 5-1:** GWP values rounded to the nearest 5 $kgCO_2eq/m^2$ across structural system configurations and life cycle stages for the medium office building

| Structural System | | GWP Excluding Biogenic Carbon | | | GWP Including Biogenic Carbon (Stored Biogenic Carbon) | | |
|---|---|---|---|---|---|---|---|
| | | Life Cycle Stages | | | | | |
| GFRS | LFRS | A | A-C | A-D | A | A-C | A-D |
| Mass timber post-and-beam | Special steel braced frames | 100 | 110 | 120 | -40 (140) | 25 (85) | 35 (85) |
| | Special reinforced concrete shear walls | 95 | 105 | 120 | -45 (140) | 20 (85) | 35 (85) |
| | Post-tensioned timber rocking walls | 100 | 105 | 120 | -60 (160) | 10 (95) | 25 (95) |
| Structural steel post-and-beam | Special steel braced frames | 170 | 185 | 175 | 170 (0) | 185 (0) | 175 (0) |
| Reinforced concrete post-tensioned flat slab and column | Special reinforced concrete shear walls | 215 | 230 | 270 | 215 (0) | 230 (0) | 270 (0) |

*Values in parentheses represent stored biogenic carbon.*
*(0) indicates that no materials with biogenic carbon are included in the LCA of these buildings.*
*GWP values including biogenic carbon are therefore equivalent to those excluding biogenic carbon.*

## 5.2 Large Office Building

A comparison of the GWP values for each structural system across life cycle stages and materials is shown in Figures 5-4 and 5-5 when excluding and including biogenic carbon, respectively. The study considered Stages A, A through C, and A through D. Materials contributing to the LCA (discussed in Section 4) were grouped into the following categories: concrete/gypcrete, rebar, steel (hot-rolled), steel (cold-formed), timber, and other. The “other” category primarily corresponds to fireproofing spray-applied to steel. A comparison of relative GWP contributions for each structural system across life cycle stages for superstructure versus substructure and GFRS versus LFRS is shown in Figure 5-6 when excluding biogenic carbon. Numerical values of GWP are reported in Table 5-2.

GWP results excluding biogenic carbon (Figure 5-4a) for the mass timber GFRS vary between approximately 165 and 210 $kgCO_2eq/m^2$, 210 and 290 $kgCO_2eq/m^2$, and 160 and 200 $kgCO_2eq/m^2$, depending on which life cycle stages are considered, for special steel braced frames, special reinforced concrete shear walls, and post-tensioned timber rocking walls, respectively. GWP results for the structural steel building vary between approximately 245 and 300 $kgCO_2eq/m^2$, whereas those for the reinforced concrete building vary between approximately 315 and 460 $kgCO_2eq/m^2$ depending on which life cycle stages are considered. This indicates that the mass timber building with either steel braced frames or post-tensioned timber rocking walls has significantly lower GWP than the mass timber building with reinforced concrete shear walls or the structural steel building. And the reinforced concrete building has the highest GWP of all five configurations. Figure 5-4a also shows that Stage A, particularly Modules A1 through A3, contributes the most to GWP.

Relative GWP contributions by material (Figure 5-4b) are dominated by concrete/gypcrete but rebar is also a substantial contributor, especially in the two configurations with reinforced concrete shear walls. For the mass timber buildings and structural steel building, concrete/gypcrete contributes approximately 35-45% of the total GWP. For the reinforced concrete building, concrete contributes approximately 50-65%. When considering both concrete/gypcrete and rebar, the contribution to total GWP can reach approximately 55-80% for the mass timber and structural steel buildings (and, obviously, essentially 100% for the reinforced concrete building). The high concrete and rebar contributions to GWP for buildings with reinforced concrete shear walls can be explained by the fact that, for a building of this height in a high-seismic region, the ACI 318-19 shear amplification requirements drive a design toward thick, heavily reinforced concrete shear walls. Therefore, these designs have a proportionally large quantity of concrete and rebar. Somewhat intuitively, timber and hot-rolled structural steel are the next largest contributors to GWP for the mass timber buildings and structural steel building, respectively.

Results including biogenic carbon (Figure 5-5) show considerable reductions in total GWP for the mass timber GFRS, especially when paired with post-tensioned timber rocking walls as the LFRS, as a result of the biogenic carbon stored in the timber materials. Timber materials exhibit net negative GWP values (i.e., net carbon storage) across all life cycle stages, including when end-of-life assumptions (Stage C) are considered. Total GWP varies between approximately -35 and 90 $kgCO_2eq/m^2$, 10 and 170 $kgCO_2eq/m^2$, and -115 and 35 $kgCO_2eq/m^2$ for the mass timber buildings, depending on the life cycle stages considered, with special steel braced frames, special reinforced concrete shear walls, and post-tensioned timber rocking walls, respectively. When considering Stages A through D, approximately 120 $kgCO_2eq/m^2$ is stored in the timber components of the mass timber building with special steel braced frames or special reinforced concrete shear walls; approximately 165 $kgCO_2eq/m^2$ is stored in the mass timber building with post-tensioned timber rocking walls. Since no materials with biogenic carbon are included in the structural steel or reinforced concrete buildings, the results of Figure 5-5 are identical to those of Figure 5-4a for these buildings.

Relative GWP contributions when excluding biogenic carbon in Figure 5-6 demonstrate that the GFRS contributes approximately 50-75% to the total GWP across all structure types and life cycle stages, with the remainder coming from the LFRS. Greater percentage contributions to total GWP occur for buildings with special reinforced concrete shear walls, exceeding 50% of total GWP when certain life cycle stages are considered. This is explained by the ACI 318-19 shear amplification requirements described previously.

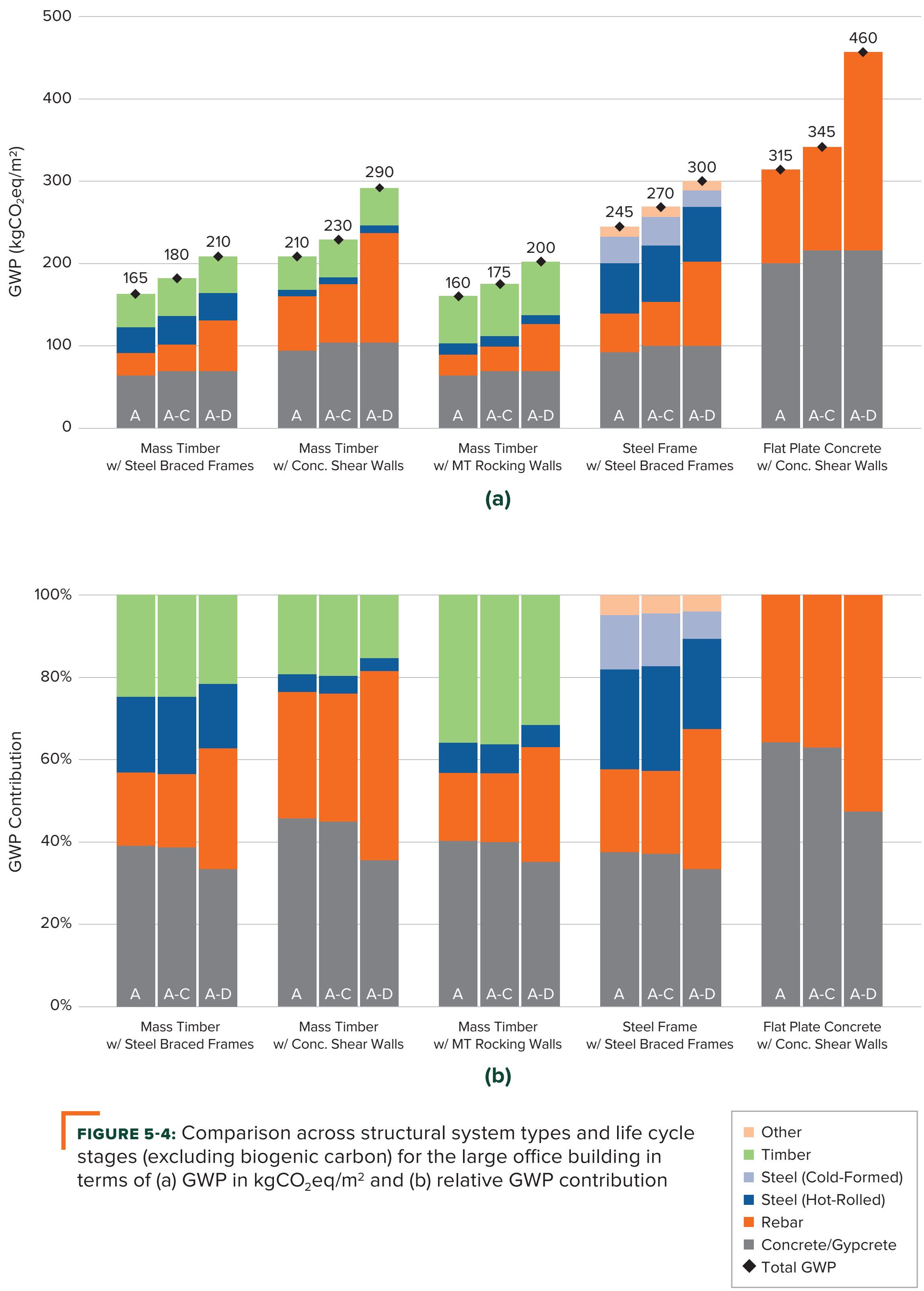


**FIGURE 5-4:** Comparison across structural system types and life cycle stages (excluding biogenic carbon) for the large office building in terms of (a) GWP in $kgCO_2eq/m^2$ and (b) relative GWP contribution

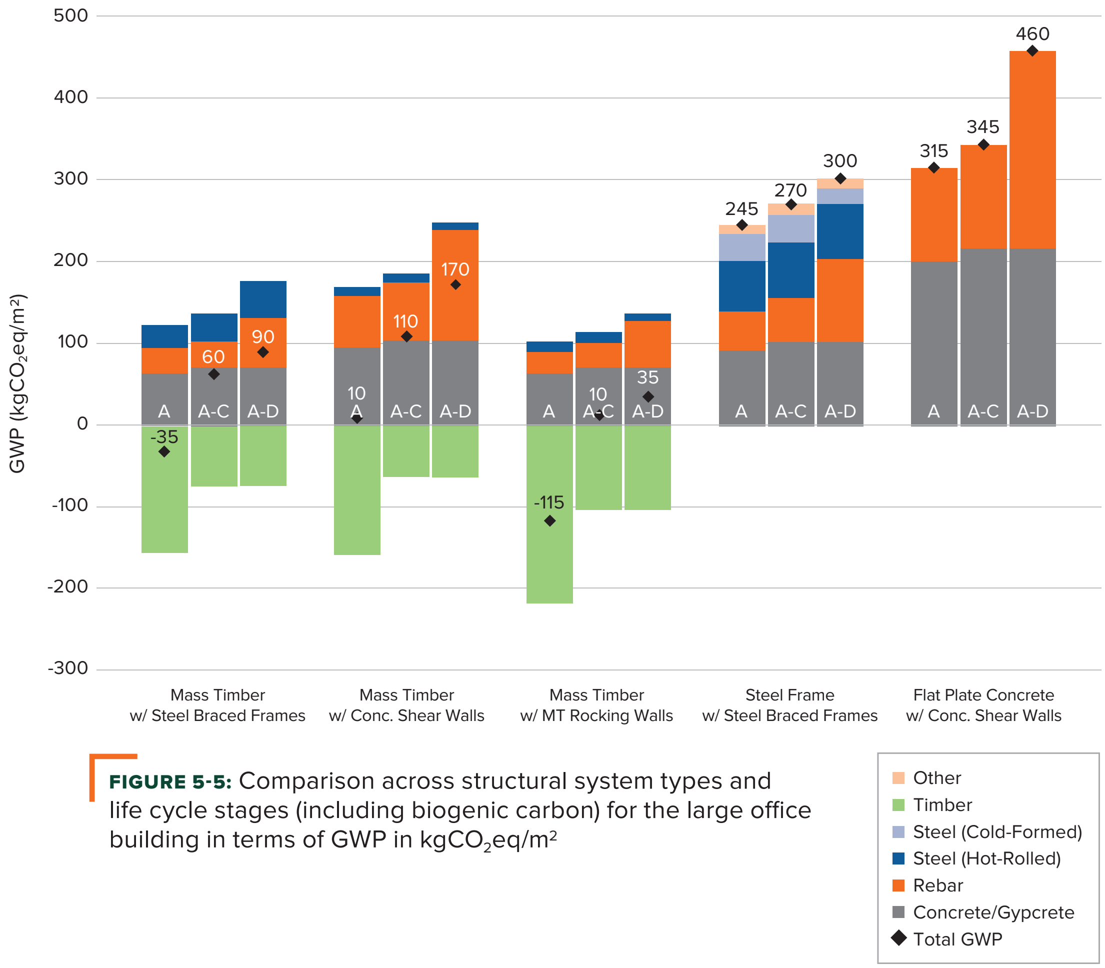


**FIGURE 5-5:** Comparison across structural system types and life cycle stages (including biogenic carbon) for the large office building in terms of GWP in $kgCO_2eq/m^2$

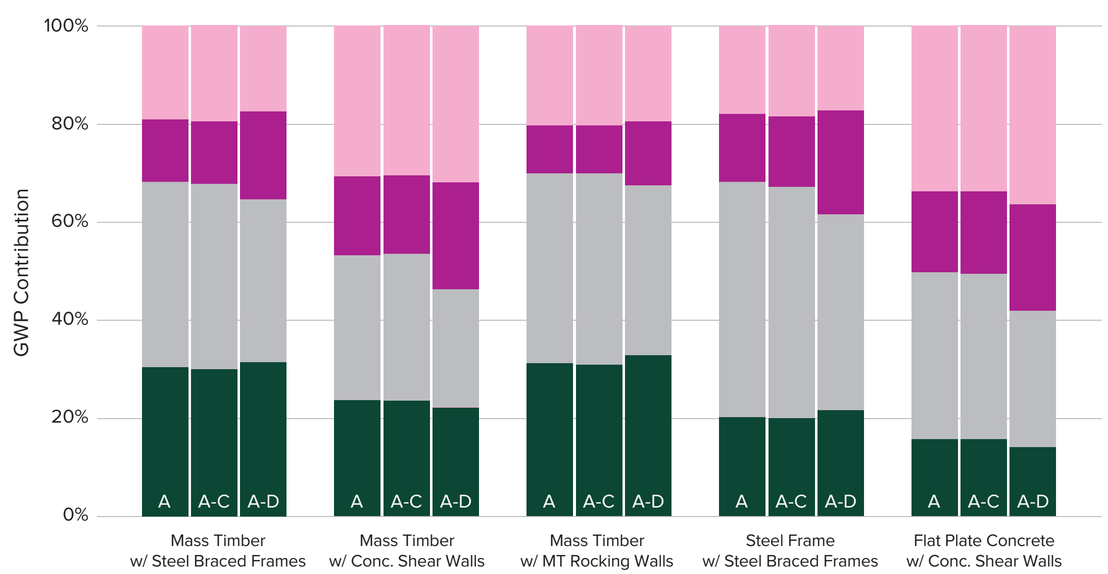


**FIGURE 5-6:** Relative GWP contribution between the LFRS versus GFRS and the superstructure versus substructure across structural system types and life cycle stages (excluding biogenic carbon) for the large office building

**TABLE 5-2:** GWP values rounded to the nearest 5 $kgCO_2eq/m^2$ across structural system types and life cycle stages for the large office building

| Structural System | | GWP Excluding Biogenic Carbon | | | GWP Including Biogenic Carbon (Stored Biogenic Carbon) | | |
|---|---|---|---|---|---|---|---|
| | | Life Cycle Stages | | | | | |
| Gravity | Lateral | A | A-C | A-D | A | A-C | A-D |
| Mass timber post-and-beam | Special steel braced frames | 165 | 180 | 210 | -35 (200) | 60 (120) | 90 (120) |
| | Special reinforced concrete shear walls | 210 | 230 | 290 | 10 (200) | 110 (120) | 170 (120) |
| | Post-tensioned timber rocking walls | 160 | 175 | 200 | -115 (275) | 10 (165) | 35 (165) |
| Structural steel post-and-beam | Special steel braced frames | 245 | 270 | 300 | 245 (0) | 270 (0) | 300 (0) |
| Reinforced concrete post-tensioned flat slab and column | Special reinforced concrete shear walls | 315 | 345 | 460 | 315 (0) | 345 (0) | 460 (0) |

*Values in parentheses represent stored biogenic carbon.*
*(0) indicates that no materials with biogenic carbon are included in the LCA of these buildings.*
*GWP values including biogenic carbon are therefore equivalent to those excluding biogenic carbon.*

# 6. Summary and Conclusions

## 6.1 Summary

This study documents the LCA of prototypical medium and large office buildings at a high-seismic location in the U.S. corresponding to Seismic Design Category D. It compares the GWP of structural elements in functionally equivalent buildings across five structural system configurations and all life cycle stages (i.e., Stages A, A through C, and A through D) using Athena. The five structural system configurations, using various gravity force-resisting system (GFRS) and lateral force-resisting system (LFRS) combinations, included:

- Mass timber post-and-beam GFRS paired with steel braced frames as the LFRS
- Mass timber post-and-beam GFRS paired with reinforced concrete shear walls as the LFRS
- Mass timber post-and-beam GFRS paired with post-tensioned timber rocking walls as the LFRS
- Structural steel post-and-beam GFRS paired with steel braced frames as the LFRS
- Reinforced concrete post-tensioned flat slab and column GFRS paired with reinforced concrete shear walls as the LFRS

Relative GWP contributions are presented for the gravity versus lateral portions of the structural force-resisting system, the superstructure versus substructure, and excluding or including biogenic carbon.

## 6.2 **Medium Office Building**

In terms of material contribution to GWP, concrete/gypcrete contributes almost half of the total GWP when excluding biogenic carbon, even for the mass timber buildings. When including biogenic carbon, the contribution of concrete/gypcrete is even larger. All other material groups combined, including rebar, steel (hot-rolled), steel (cold-formed), and timber, make up approximately the other half. This emphasizes the continued importance of reducing concrete GWP through concrete volume reduction, replacement of concrete with other materials, and/or use of lower-carbon concrete mixes.

For each mass timber building configuration, the GFRS and LFRS contributed approximately equally to the total GWP when excluding biogenic carbon. For the structural steel and reinforced concrete buildings, the GFRS contributed a larger portion of total GWP. Notably, the contribution of the LFRS to total GWP was dominated by the substructure (i.e., foundation), emphasizing the importance of efficient foundation design, potentially more so than choice of LFRS, for office buildings of this height.

Ultimately, the mass timber buildings, regardless of LFRS, had significantly lower GWP than the structural steel building, which had significantly lower GWP than the reinforced concrete building even when excluding biogenic carbon. When biogenic carbon was included, the GWP of the mass timber buildings was reduced by considerably more.

## 6.3 **Large Office Building**

In terms of material contribution to GWP, concrete/gypcrete and rebar contributes half to more than three-quarters of the total GWP when excluding biogenic carbon, even for the mass timber buildings. This dominance of concrete and rebar was especially pronounced for buildings that used special reinforced concrete shear walls, presumably as a result of ACI 318-19 wall shear amplification requirements. This emphasizes the continued importance of reducing reinforced concrete GWP through concrete volume reduction, using higher-strength reinforcing to reduce rebar tonnage, replacing concrete with other materials (e.g., switching from special reinforced concrete shear walls to another, non-concrete LFRS), and/or using lower-carbon concrete mixes.

For the mass timber buildings, the GFRS was shown to contribute between half and three-quarters of the total GWP when excluding biogenic carbon, with the remainder made up by the LFRS. In general, the superstructure is a larger contributor to total GWP than the substructure (i.e., foundation) for all structural systems studied, although the substructure also contributes significantly.

Ultimately, the mass timber buildings, especially those with a special steel braced frame or post-tensioned timber rocking wall LFRS, had substantially lower GWP than the structural steel building, which had substantially lower GWP than the reinforced concrete building even excluding biogenic carbon. The mass timber building with special reinforced concrete shear walls had similar total GWP to the structural steel building with special steel braced frames when biogenic carbon was excluded. When biogenic carbon was included, the GWP of all the mass timber buildings was significantly less than the structural steel or reinforced concrete buildings, especially the mass timber building with post-tensioned timber rocking walls.

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WW-LCA-12 – Life Cycle Assessment of Prototypical Office Buildings in a High-Seismic Location




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