Return To Form

Comparative Life Cycle Assessment Study

Author: KL&A Engineers & Builders

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Table of Contents

Executive Summary

How does mass timber compare to traditional structural systems? Is mass timber sustainable? What are the associated dollar cost premiums?

This study of Return to Form, a high-rise multi-family residential building in Denver, Colorado, endeavors to answer these questions. It compares three functionally equivalent[1] structural systems (mass timber, steel, and concrete) and resulting architectural and fire protection systems, in terms of global warming potential (GWP), dollar cost, and construction schedule. It is part of the *Mass Timber Comparative Life Cycle Assessment Series* comparing functionally equivalent structural systems across a variety of building types and geographic locations in the United States, and should be read together with the *Mass Timber Comparative Life Cycle Assessment Series Introduction* (Feitel & Kingsley, 2024).

The Return to Form design team included architect tres birds, structural engineer KL&A Engineers & Builders, and construction partners Swinerton and Timberlab. The design of the mass timber project is complete and submitted for permit, but the building has not yet been constructed at the time of this writing. It is a Type IV-B, 12-story, 84-unit residential building of approximately 139,000 gross ft^2 (12,900 m^2). There is no below-grade construction and the structure consists of a drilled pier foundation system, slab-on-grade at the ground level, three levels of concrete flat plate, and nine levels of mass timber (Level 5 to the roof). The alternative structural systems selected for Levels 5 to the roof are those that would typically be used in Denver for similar projects: composite steel deck with panelized structural cold-formed steel (CFS) walls, identified as the "CFS alternative," and cast-in-place post-tensioned concrete with concrete columns, identified as the "concrete alternative."

Key results of this building study, which incorporates a whole building life cycle assessment (WBLCA) by KL&A Team Carbon and construction cost estimate by Swinerton for each building system, include the following:

Global warming potential (cradle-to-grave): Considering only the structure above the Level 4 podium, the mass timber system GWP is 28 kgCO_2eq/m^2, which is 73% less than the CFS system (GWP of 105 kgCO_2eq/m^2), and 83% less than the concrete system (GWP of 164 kgCO_2eq/m^2) (Figure 1). The major contributor to GWP in the mass timber system is the concrete topping slab on each floor. The wood material contribution is net negative due to the natural ability of mass timber to store biogenic carbon.[2]

Considering the structural and architectural systems above the Level 4 podium (structural gravity and lateral systems and architecture, including the enclosure, fire resistance-rated assemblies, acoustic assemblies, and interior ceiling finishes), the mass timber system GWP is 47% less than the CFS system and 59% less than the concrete system (Figure 2). This savings is equivalent to 155 or 245 gas-powered passenger vehicles driven for one year (compared to CFS and concrete respectively) or the electricity needed to power 135 or 210 homes for one year (United States Environmental Protection Agency, 2023).

Construction duration: The general contractor estimated that, for this building on this site in Denver, the mass timber system would be constructed two months faster than the CFS system (11% faster) and 4.2 months faster (20% faster) than the concrete system. This time savings benefits both the dollar cost and embodied carbon impact of the mass timber system.

Construction cost: It is common for initial cost estimates to show a significant material premium for mass timber over traditional structural materials; Return to Form was no different. Comparing only the structural material costs of the residential floors above the Level 4 podium, the mass timber system showed a striking 42% premium over concrete and 7% premium over CFS. However, when considering the whole building construction cost, including cost savings associated with the shorter construction duration, the mass timber system premium is reduced to 1.8% over CFS and only 0.2% over concrete (Figure 2).

The construction industry has a significant opportunity and responsibility to address climate change by virtue of its outsized contribution to global greenhouse gas (GHG) emissions of 42%. The most immediate way for the industry to reduce GHG emissions is to reduce *embodied carbon*—the emissions associated with physical building materials, through their raw material extraction, production and manufacturing, transportation, installation, and end-of-life scenarios. Mass timber structural systems are one potential strategy for embodied carbon reduction due to the material's relatively low manufacturing GWP impacts and its natural ability to store biogenic carbon for the life of a building (and potentially indefinitely). This building study demonstrates that mass timber systems for buildings like Return to Form are a viable, cost-effective approach to significantly reducing and minimizing a building's embodied carbon impact (Figure 2), with the understanding that building life expectancy, sustainable material sourcing,[3] and end-of-life pathways influence its cradle-to-grave embodied carbon impact.[4]

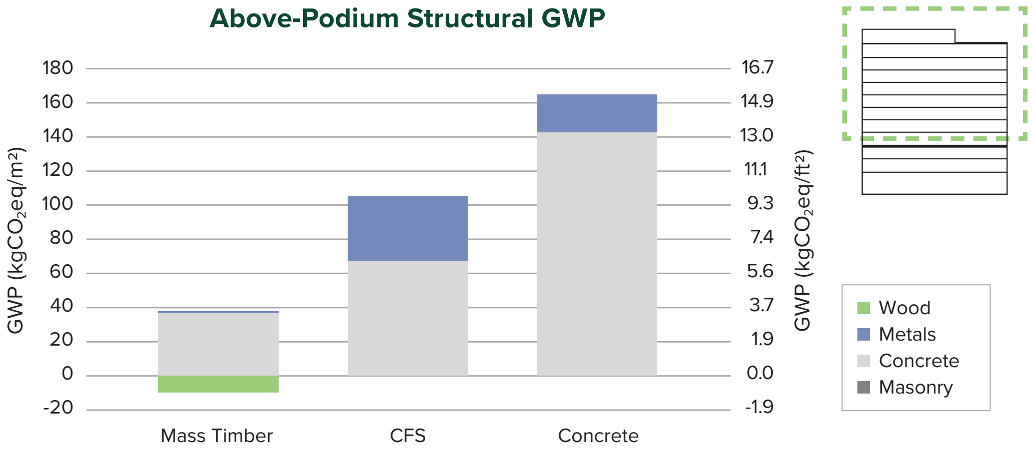


FIGURE 1: Above-podium structural GWP impact comparison of the three systems and material contributions

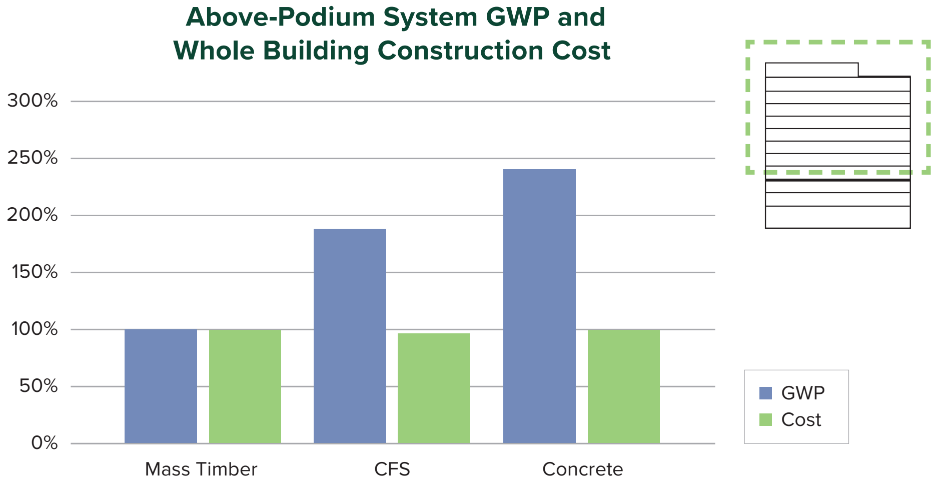


FIGURE 2: Above-podium system GWP (structure and architecture, including the enclosure, fire resistance-rated assemblies, acoustic assemblies, and interior ceiling finishes) and whole building construction cost comparison of the three building systems, normalized to the GWP and cost of the mass timber system

Introduction

The purpose of this building study is to use whole building life cycle assessment (WBLCA) and cost estimating to understand the embodied carbon and dollar cost implications of choosing between functionally equivalent[1] mass timber, steel, or concrete structural systems. It compares a mass timber reference building—Return to Form, located in Denver, Colorado—to alternatives designed in cold-formed steel (CFS) and concrete. Comparisons between the three systems are made in terms of embodied carbon, construction dollar cost, and speed of construction. The variations between architectural designs (construction type, enclosures, fire protection, acoustic performance, and ceiling finishes) are included in the analyses.

The Return to Form building study starts with an introduction to the reference building, followed by a description of the design alternatives and scope of the study, and then the results of the LCAs, dollar cost, and speed of construction analysis. It is intended to be read together with the *Mass Timber Comparative Life Cycle Assessment Series Introduction* (Feitel & Kingsley, 2024), which details aspects common to all studies in the series, including methodology, approach, scope, and code compliance of the comparative designs, LCA and dollar cost analyses, and the importance of embodied carbon and biogenic carbon as part of the building industry's strategy to address climate change and environmental degradation. This study details information specific to Return to Form and any variations from the series introduction.

Project Background and Alternative Designs

This section describes the reference building, design considerations for the alternative systems, and the structural and architectural design results.

The Return to Form study compares three structural systems for a multi-unit residential building: mass timber, cold-formed steel (CFS), and concrete. The reference mass timber building is a Type IV-B, 12-story, 84-unit residential building, five of which are affordable 2-bedroom units. The building is owned by Katz Development in partnership with Wynkoop Investors LLC and is located in the River North Art District of Denver, Colorado. The Architect of Record is tres birds, the Structural Engineer of Record is KL&A Engineers & Builders (KL&A), and the general contractor is Swinerton with support from Timberlab. A mass timber supplier has not been selected at the time of this analysis. The development is anticipated to be the tallest mass timber building in Colorado, at around 148 ft (45 m), utilizing Denver's early adoption of the 2024 International Building Code (IBC) Type IV-B construction type and exposure allowances for tall wood (International Code Council, Inc., 2023).

Return to Form had been submitted for permit application at the time of this analysis, and the authors made use of the completed Construction Documents. Katz Development's preference for mass timber is due to its market differentiation, low embodied carbon, and biophilic attributes. Mass timber was identified as the project's structural system early in the design process. The project was awarded a grant through the Softwood Lumber Board's 2022 Mass Timber Competition: Building to Net Zero Carbon and a USDA Forest Service Wood Innovation Grant.

Comparative Building Systems

The three building systems compared in this study were designed by KL&A in collaboration with the Return to Form project architect, tres birds (Figure 3).

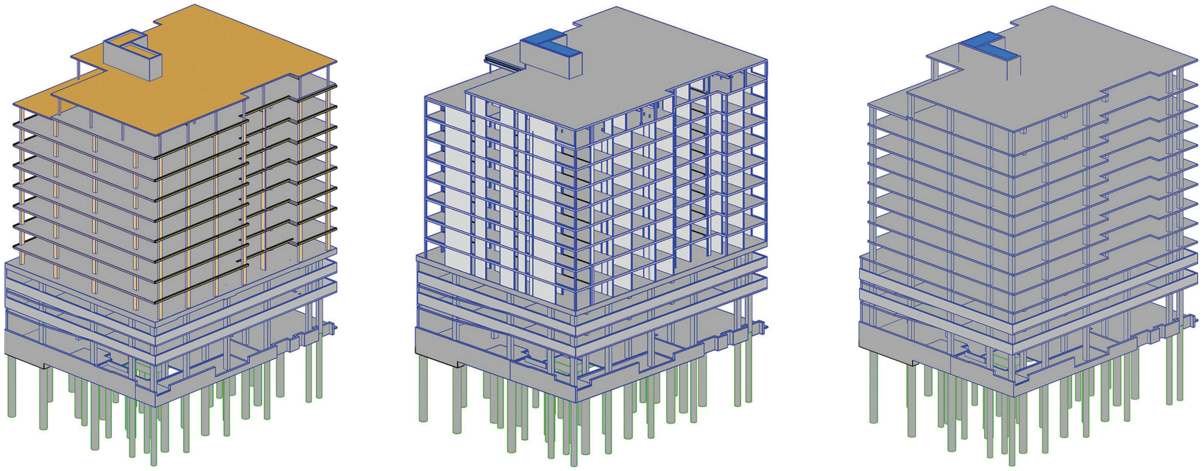


FIGURE 3: Schematic 3D images of the three alternative buildings—designed with mass timber, cold-formed steel, and concrete (left to right)

Reference Building – Return to Form

The reference building, Return to Form, totals approximately 139,000 ft^2 (12,900 m^2) gross floor area, with 12 stories above grade and no below-grade construction. The foundation system consists of grade beams spanning between concrete drilled piers ranging in diameter from 30 to 48 in. Level 1 is a concrete slab-on-grade for mixed use that includes a loading dock, gym, entryway, lobby, and future tenant space. Levels 2 and 3 consist of 8-in.-thick post-tensioned cast-in-place concrete slabs for vehicle parking. Level 4 is the first residential floor, consisting of a post-tensioned cast-in-place concrete podium transfer slab, the thickness of which varies for each alternative building design. These elevated concrete slabs are supported by concrete columns ranging from 18 to 20 in. wide and 30 to 34 in. deep.

Levels 5 to the roof total about 90,000 ft^2 (8,350 m^2) gross floor area and utilize a mass timber framing system, which is described in the Mass Timber Building System section. These levels are relatively repetitive residential floors with penthouse units and an exterior amenity space on Level 12. The alternative structural systems are employed at the residential levels—i.e., Level 5 to the roof. A schematic building section is shown in Figure 4.

Denver is a region of low seismicity and moderate winds with a design ultimate wind speed of 115 mph. Return to Form's lateral design is governed by wind loads. The lateral system at all levels is comprised of ordinary reinforced concrete shear walls supported by cast-in-place concrete mat slabs and drilled piers at the foundation. The shear walls are located at the two stair/elevator cores; see Figure 5 for the plan layout.

The vertical enclosure finish is a combination of glass, metal panel, and stucco. The finishes are typically backed with polyisocyanurate insulation, sheet vapor barrier, fluid-applied water barrier, and gypsum sheathing board. The exterior wall is framed using platform-framed non-load-bearing cold-formed steel studs with glass fiber batt insulation in the stud cavities and gypsum board at the interior. The levels of vehicle parking utilize a partial height, fully grouted, exterior masonry crash wall, instead of a fully enclosed vertical wall.

The roof enclosure consists of an ethylene propylene diene monomer (EPDM) finish over cover board, polyisocyanurate insulation, and a sheet vapor barrier atop the mass timber roof panel. At the Level 12 exterior amenity space, the finish is concrete pavers on pedestals. The pavers are backed by the typical EPDM roofing membrane over gypsum board, polyisocyanurate insulation, and a sheet vapor barrier.

The alternative buildings are functionally equivalent and meet the same design criteria as the reference mass timber building, meaning equivalent floor area, site orientation, occupancy, programmatic layout, geographic location, load criteria, and performance requirements, in accordance with ISO 14044 4.2.3.7 (ISO, 2006) and ASTM E2921 (ASTM, 2022).

All three buildings utilize the same structural system from the Level 4 podium and below, including the foundation, with design modifications for the different loads imposed from above. The residential floors begin at Level 4 and employ alternative structural systems for Levels 5 through 12 and the roof (mass timber, CFS, and concrete). Structural designs were optimized for each material system to show each alternative realistically and fairly. The alternative designs consider the effects of the building's weight on the foundation, as well as gravity and lateral systems.

All three buildings use the same vertical enclosure system, interior wall locations, and residential unit layouts. In general, assumptions regarding aesthetic preferences were avoided; the same exterior finishes, exposure structure, and dropped ceiling locations were maintained unless noted otherwise. The comparative designs consider the building's construction type and its effect on the fire rating and fire protection assemblies, exposure, and material requirements. All three buildings have the same occupancy, which in some cases has more stringent fire ratings than required by the construction type; this was considered in the designs.

The alternative structural systems and their effects on the fire rating, fire protection systems, foundation systems, gravity systems, lateral systems, and floor-to-floor heights are described in the following sections.

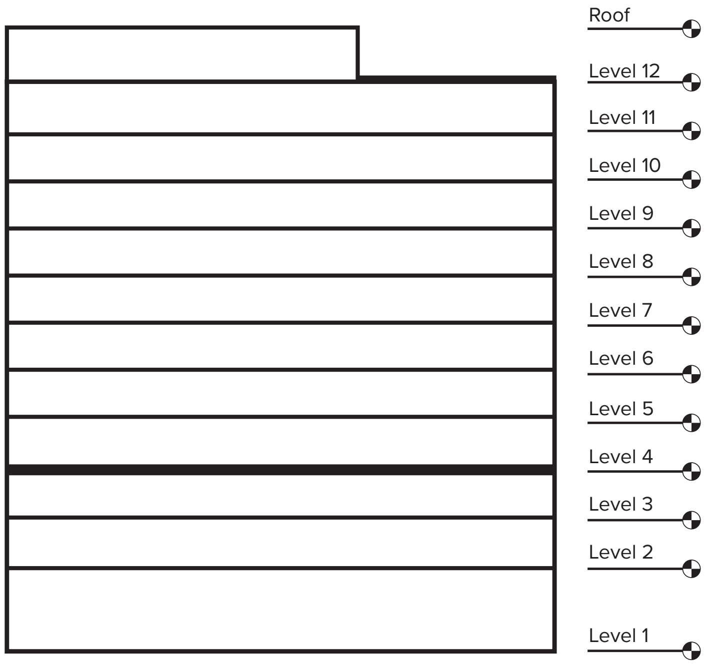


FIGURE 4: Schematic building section of Return to Form

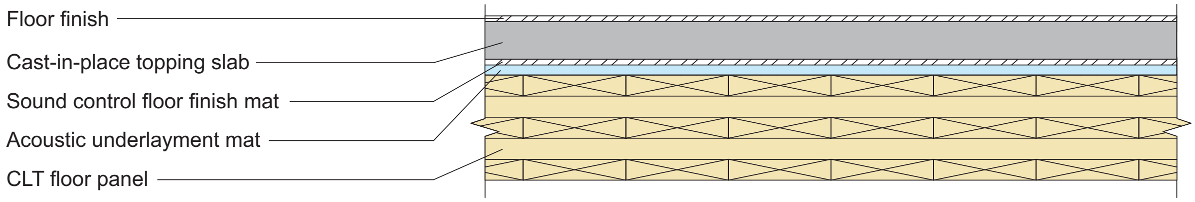
FIGURE 5: Return to Form typical residential floor plan

Mass Timber Building System

The mass timber building system can generally be described as post-and-beam framing. The residential floors, Level 5 through 12, are 5-ply (6-7/8-in.-thick) cross-laminated timber (CLT) floor panels with a ¾-in. acoustic underlayment mat and 3-in. cast-in-place concrete topping slab with floor finishes (Figure 6). The roof is 5-ply CLT panels, with no acoustic mat or topping slab. Floor and roof panels are supported by glued-laminated timber (glulam) beams and columns. Floor framing at the Level 12 exterior amenity space consists of 7-ply (9-5/8-in.-thick) CLT panels to support the additional live load and snow load. Typical beam widths are between 10-¾ and 12-¼ in. with depths ranging between 16 ½ and 24 in. Columns typically vary from 12-¼ to 14-¼ in. wide and 18 to 27 in. deep. The mass timber grid system varies throughout the floor plan and is on average 19x22 ft (5.8x6.7 m). At Level 4, glulam columns are supported on a 28-in.-thick post-tensioned cast-in-place concrete podium transfer slab, with localized areas of thickened slab.

The concrete core walls are 12 in. thick from the foundation to the Level 4 podium and 8 in. thick above the podium, supported on 42-in.-thick cast-in-place concrete mat slabs at the foundation.

The mass timber building is Type IV-B construction, which requires primary structural frame elements, bearing walls, and floors to have a 2-hour fire-resistance rating (FRR) and roofs to have a 1-hour FRR. To keep the mass timber (CLT panels and glulam) exposed, these fire ratings are accomplished by ensuring that wood members are sized adequately to achieve a char layer in the event of a fire while maintaining their structural adequacy.[5] At the residential unit bathrooms, dropped ceilings for mechanical electrical plumbing (MEP) routing create a concealed space that requires two layers of gypsum board at the underside of the CLT floor panels.[6] The Level 12 exterior amenity floor assembly also requires two layers of gypsum board on top of the CLT panels to achieve a 1-hour FRR.



Note: Floor finish and sound control floor finish mat are considered architectural finish and excluded from the LCA.

FIGURE 6: Mass timber system floor assembly

To meet the project's sound transmission class (STC) and impact insulation class (IIC) requirements of 56 and 54 respectively, the CLT floor assembly utilizes a 3-in. cast-in-place topping slab and acoustic underlayment mat above the CLT.

Exterior walls are non-load-bearing, which may be unrated or require a 1-hour FRR depending on the fire separation distance. In this case, the north and west exterior walls require 1-hour ratings. South and east exterior walls are not required to be rated but utilize the same exterior wall assembly.

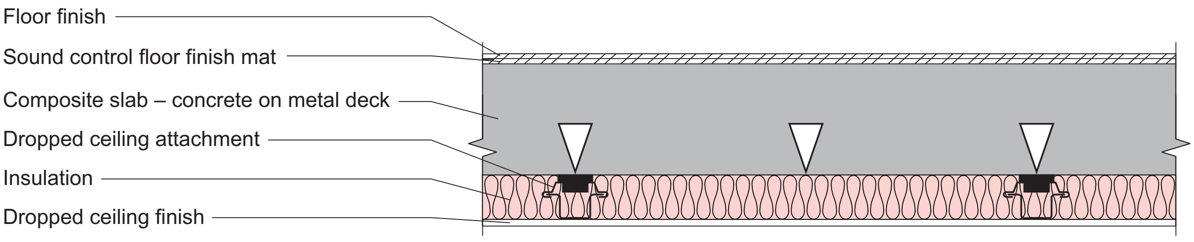
Interior non-load-bearing walls are permitted to be unrated based on the construction type; however, due to the residential R-2 occupancy, dwelling unit separation walls are required to have a 1-hour FRR and corridor walls are required to have a ½-hour FRR. These are designed as non-load-bearing cold-formed steel stud walls with a single layer of gypsum board on either side of the wall and fiber batt insulation inside the stud cavity. See Figure 5 for the different wall locations and their corresponding FRRs.

Cold-Formed Steel Building System

The cold-formed steel (CFS) system can generally be described as a bearing wall system. The residential floors, Level 5 through 12 and the roof, are 5-½-in.-thick composite slabs with 3-½ in. normal weight cast-in-place concrete with finishes on a 2-in. 20-gauge steel deck with a maximum span of 19 ft (Figure 7). In lieu of beams and columns, the decks typically span to cold-formed steel stud bearing walls, utilizing both unit demising walls and interior unit walls. One-way concrete slab-beams, 5-½-in. thick, are used to create support for the deck at wall openings in bearing walls that are less than 12 ft wide. For spans greater than 12 ft, non-composite steel wide-flange beams with depths varying between 10 and 14 in. are used to support the deck. All beams are supported by cold-formed steel stud packs or HSS steel columns. Floor framing at the Level 12 exterior amenity space consists of an 8-in.-thick composite slab with 6 in. of concrete on 2-in. 20-gauge steel deck to support the additional live load and snow load. At Level 4, cold-formed steel bearing walls and columns are supported on a uniform 30-in.-thick post-tensioned cast-in-place concrete podium transfer slab. The weight of the steel building was comparable to the mass timber building; therefore, the concrete core walls and their foundation are identical to the mass timber building—12 in. thick from the foundation to the Level 4 podium slab and 8 in. thick above the podium, supported on 42-in.-thick cast-in-place concrete mat slabs at the foundation.

This cold-formed steel bearing wall system was chosen over a traditional steel post-and-beam framing system to utilize the unit partition walls for both architectural and structural purposes. See the typical residential floor plan for more information (Figure 8). This system has been proven to be cost-effective while still meeting performance requirements for mid-rise residential buildings in the Denver market and is considered standard practice.

The cold-formed steel building is Type I-B construction, which requires primary structural frame elements, bearing walls, and floors to have a 2-hour FRR and roofs to have a 1-hour FRR.[7] The composite deck itself meets the 2-hour fire rating, but not the 56 STC/54 IIC acoustic requirement. A floor assembly was used that includes a dropped ceiling consisting of insulation and one layer of gypsum board at the underside and architectural floor finishes atop to meet the acoustic



Note: Floor finish and sound control floor finish mat are considered architectural finish and excluded from the LCA.

FIGURE 7: Cold-formed steel system floor assembly

requirements, meaning the deck assemblies are visually covered. The authors also considered an alternative composite deck floor assembly comprised of a 5-½-in.-thick composite slab with an acoustic underlayment mat, topping slab, and floor finishes. Although this assembly build-up is closer to the mass timber floor assembly, it is not considered standard practice in the region. The chosen composite deck assembly is to the advantage of the cold-formed steel building system in terms of both embodied carbon (no cast-in-place topping slab) and dollar cost, despite covering the structure.

Wide-flange beams are wrapped with two layers of gypsum board to meet the 2-hour fire-rating requirement.[8] Additional protection of concealed spaces is not required for Type I construction. Therefore, at the residential unit bathrooms, no additional fire protection is required at the dropped ceiling concealed spaces.

The fire ratings of the vertical enclosure and dwelling unit separation walls vary. Some of the vertical enclosure walls are load bearing, requiring a 2-hour FRR per the construction type requirements noted above. This requires an additional layer of gypsum board on either side of the stud wall as compared to the exterior walls used in the mass timber system. Non-bearing exterior walls may be unrated or require a 1-hour rating, depending on the fire separation distance. In this case, the non-load-bearing north and west vertical enclosure walls require a 1-hour FRR, whereas the south and east walls are not required to be rated; all of the non-load-bearing walls use the same 1-hour-rated assembly as the mass timber system.

The composite deck spans to both unit separation walls and some interior unit walls. These load-bearing walls are therefore required to have a 2-hour FRR. Cold-formed steel stud walls are used with fiber batt insulation inside the stud cavity. To achieve the required 2-hour fire rating, two layers of gypsum board are applied on each side of the walls. Due to the residential R-2 occupancy, non-load-bearing corridor walls are required to have a ½-hour FRR and non-load-bearing unit demising walls are required to have a minimum 1-hour FRR. Although the majority of the interior load-bearing walls are dwelling unit separation walls and are also included in the mass timber building, there are additional unit walls utilized within the structural gravity system for the CFS building. See Figure 8 for the different wall locations and their corresponding FRRs. Compared to the mass timber system, this increases both the total length of fire-rated interior walls and the quantity of gypsum board layers.

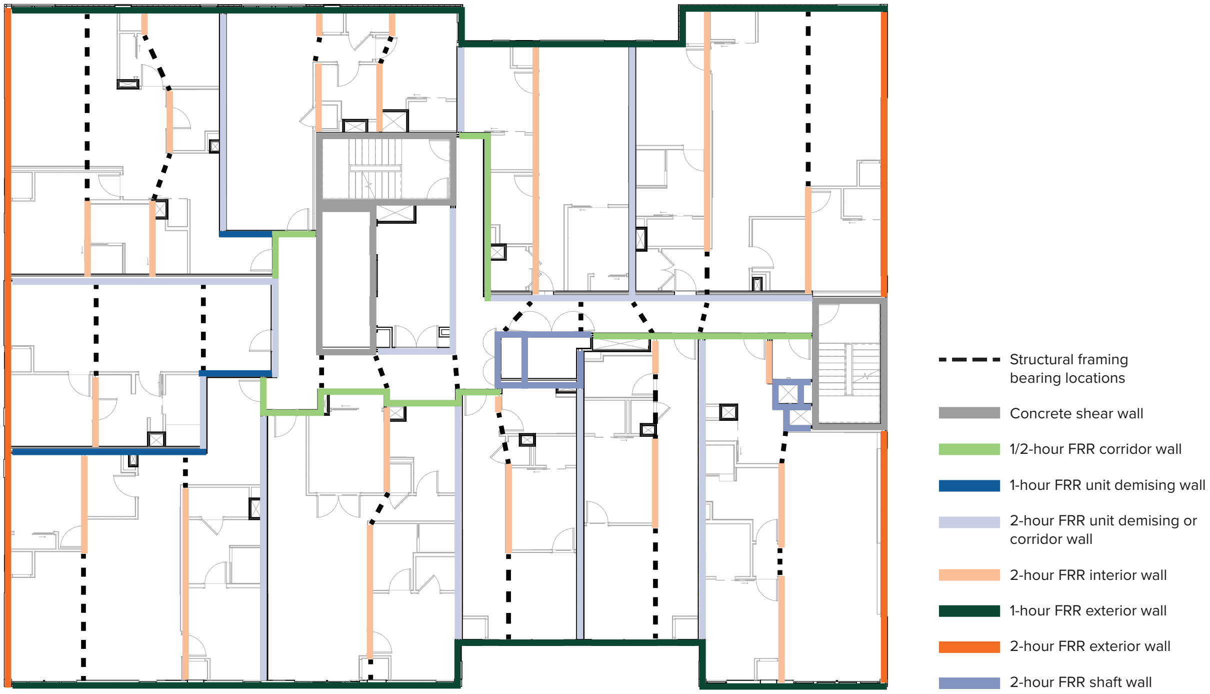
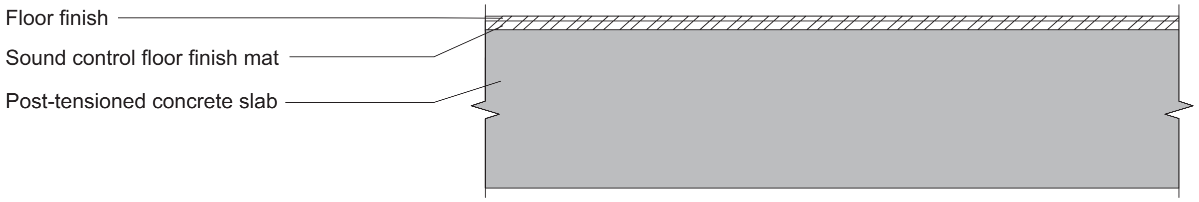


FIGURE 8: Cold-formed steel building typical residential floor plan

Concrete Building System

The post-tensioned concrete system can generally be described as flat plate construction. The residential floors, Level 5 through 12 and the roof, are 8-in. post-tensioned cast-in-place concrete slabs with floor finishes, spanning two directions to cast-in-place concrete columns. Unlike the mass timber and CFS systems, the concrete system's column locations at the residential floors match the column locations at the parking levels below, roughly a 22x25-ft grid, which eliminates the need for a transfer slab at Level 4. Concrete columns vary between 18 and 20 in. wide with depths ranging from 30 to 34 in. Floor framing at the Level 12 exterior amenity space consists of a 12-in.-thick post-tensioned cast-in-place concrete slab due to the additional live load and snow load. The Level 4 slab, no longer a transfer condition, consists of an 8-in. post-tensioned cast-in-place concrete slab, which is typical of all floors above this level (Figure 9). To keep a consistent floor-to-ceiling height at Level 3, the top-of-slab elevation at Level 4 is lowered, compared to the mass timber and cold-formed steel buildings. The concrete building is roughly 25% heavier than the mass timber building, resulting in increased material volume at the foundation and lateral system. The drilled pier socket lengths increased roughly 10% on average, and the mat slabs underneath the core walls are 6 in. thicker (48 in. total). Although wind still controlled the lateral design, the heavier concrete building's diaphragm forces resulted in 12-in.-thick core walls from the foundation to the roof.

Like the CFS building, the concrete building is Type I-B construction, which requires primary structural frame elements, bearing walls, and floors to have a 2-hour FRR and roofs to have a 1-hour rating. Slabs and columns are visually exposed and designed with adequate concrete cover to reinforcing steel to meet the 2-hour FRR as well as acoustic performance requirements. Like the CFS building, no additional fire protection is required at the dropped ceiling concealed spaces at the residential unit bathrooms. The Level 12 exterior amenity floor assembly's 1-hour fire rating is also achieved with the concrete and reinforcing cover.



Note: Floor finish and sound control floor finish mat are considered architectural finish and excluded from the LCA.

FIGURE 9: Concrete system floor assembly

Exterior walls are all non-load-bearing and may therefore be unrated or require a 1-hour FRR depending on the fire separation distance. This results in walls identical to those used in the mass timber building: the north and west exterior walls require 1-hour fire ratings. South and east exterior walls are not required to be rated but utilize the same exterior wall assembly.

The interior dwelling unit separation walls are non-bearing but are required to have a 1-hour rating due to the residential R-2 occupancy. Similarly, the residential R-2 occupancy requires corridor walls to have a ½-hour FRR. This results in walls identical to those used in the mass timber building: non-load bearing cold-formed steel stud walls with a single layer of gypsum board on either side of the wall and fiber batt insulation inside the stud cavity. Dwelling separation and corridor wall locations are shown in Figure 5.

Building Floor-to-Floor Heights

The variation in floor heights above the Level 4 podium are shown in Table 1. The floor elevations for each building design were determined by the project architect, considering dimensional constraints and aesthetic perceptivity specific to each system.

The primary reason for the variation in heights is the variation in structural floor assembly and framing depths. The height from finished floor to finished floor of the reference mass timber system is 10-ft-6-in. The mass timber system and CFS system both have beams supporting the floor plate, while the concrete system does not. The top-of-slab elevation at Level 4 for the concrete building is lowered due to its reduced thickness compared to the mass timber and CFS buildings. These compounding variations in floor elevations result in different total building heights, as well as resulting material quantities for the vertical enclosure, walls, and columns.

Floor Elevations and Building Height				
Structural System	**Floor to Floor**	**Floor to Ceiling[a]**	**Clear Height[b]**	**Total Building Height**
Mass Timber	10'-6"	9'-6"	7'-6"	148'-0"
CFS	9'-8"	9'-2"	8'-0"	137'-0"
Concrete	9'-9"	9'-0"	9'-0"	139'-0"

a. Floor to ceiling is defined as the top of finished floor to bottom of horizontal ceiling surface, either finished ceiling for CFS or exposed structure for concrete and mass timber. The horizontal ceiling surface does not include the dropped beam in the mass timber or CFS buildings.

b. Clear height is defined as top of finished floor to bottom of drop beam where present. There are no drop beams in the concrete system so the clear height is equal to the floor to ceiling height.

TABLE 1: Relative floor heights above the podium and total building heights of the three systems

Concrete Mix Designs

Concrete is a high-embodied carbon material and its GWP impact often dominates a building's total GWP. Table 2 lists the concrete mix designs' 28-day strength and supplemental cementitious material (SCM) content per concrete element used within the three building LCAs. As explained in the introduction to this series, TallyLCA's concrete mix design data references the 2019 National Ready Mixed Concrete Association (NRMCA) *Industry-Average Environmental Product Declaration* (EPD), plus supplemental life cycle inventory (LCI) data. The mix designs selected for this building study reflect the 28-day strengths specified in Return to Form's Construction Documents. However, the SCM content deviated from the Construction Documents with the intention that the selected mixes be as optimistic regarding GWP impact as could reasonably be assumed for material availability and common practice in the Denver market. The SCM included was fly ash (noted as FA in Table 2) per local practice. For the purposes of this study, fly ash content was increased to a reasonable maximum while considering finishability and speed of construction. Concrete elements assigned 20% fly ash content were considered sensitive to finish requirements and sequencing of construction. Elements assigned 40% fly ash content were those for which it was acceptable to reach their specified strength beyond 28 days.

Concrete Property Assumptions

Element	Concrete (psi, SCM%)
PT Slab	6000, 20% FA
SOG	4000, 20% FA
Columns	6000, 20% FA
Pier Cap & Mat Slab	6000, 40% FA
Drilled Piers	4000, 40% FA
Grade Beams	5000, 40% FA
Foundation/Core Walls	5000, 40% FA
Topping Slabs	4000, 20% FA

TABLE 2: Concrete mix design assumptions for all three buildings

Life Cycle Assessment Methodology

The methodology, approach, and codecompliance of the individual building LCAs and their comparisons are detailed in the companion document, *Mass Timber Comparative Life Cycle Assessment Series Introduction*. Major methodology and assumptions are described in this section with variations from the general series.

Life Cycle Assessment Material Scope

The component and material scope of the LCAs includes primary structure, vertical and horizontal enclosures, fire resistance-rated assemblies, acoustic assemblies, and interior ceiling finishes as they are described in the section, Comparative Building Systems. As such, they are considered whole building life cycle assessments. Material quantities are based on the designed quantities and do not consider final bill of materials or estimates for construction waste.

The primary structure includes substructure (foundation system) and superstructure elements (gravity system: floors, roofs, beams, columns, bearing walls; lateral system; slab-on-grade). Reinforcing steel within concrete elements is included in the LCAs.[9] Connections and accessory structural elements such as miscellaneous metals (elevator support, stairs, handrails, canopies) are excluded. Topping slabs are designated as structural scope for the purposes of the LCAs.

The vertical enclosure includes the exterior finish, windows and curtain wall systems, waterproofing, insulation, wall framing, and gypsum board. The horizontal enclosure includes the exterior finish, waterproofing, insulation, framing, fire protection materials, and acoustic materials. Shaft walls and their fire-rated assemblies are included. The interior fire-rated wall and floor assemblies are included within the LCAs, whether or not they serve as structural members. Non-load-bearing interior partition walls that are not fire-rated are excluded from the LCAs. The exterior finish and ceiling finishes are included. All other architectural finishes (floor finishes, interior wall finishes, furnishings, paints, stains, sealers, etc.) are excluded. Fireproofing detailing at window heads and sills is also excluded.

Other exclusions are site work, civil, landscape, MEP, and all interior furnishings.

A noteworthy exclusion is the acoustic underlayment mat that is inherent to the CLT floor assembly in order to achieve the STC rating (Figure 6). At the time of writing, there are only a handful of EPDs available for acoustic underlayment mat products in North America, such as Pliteq's GenieMat FF series, United States Gypsum Company's Levelrock Brand SAM-N Ultra series, and U.S. Rubber Recycling Inc.'s QuietSound Acoustical Underlayment series (Pliteq Inc., 2023; United States Gypsum Company, 2022; U.S. Rubber Recycling, Inc., 2019). Some European product EPDs have also been published. However, there are no acoustic underlayment mat EPDs, LCI data sets, or appropriate data substitutions available within TallyLCA. At the time of this analysis, EC3 does not house any acoustic mat EPD data either. See the Supplemental Life Cycle Assessment Results section for calculations performed outside of TallyLCA to illustrate the potential impacts of the acoustic underlayment mat on the mass timber building system's total GWP. Sound control floor finish mats typically used with hard surface finishes to increase the IIC rating of a floor assembly are excluded from the LCAs for all three floor systems because they are considered a finish material for the purposes of this building study (Figure 10).

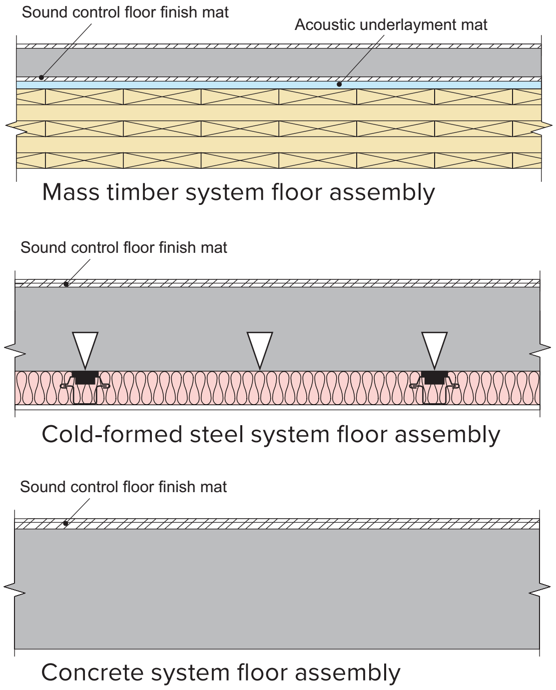


FIGURE 10: Floor assemblies for the three systems, illustrating the acoustic underlayment mat and sound control floor finish mat

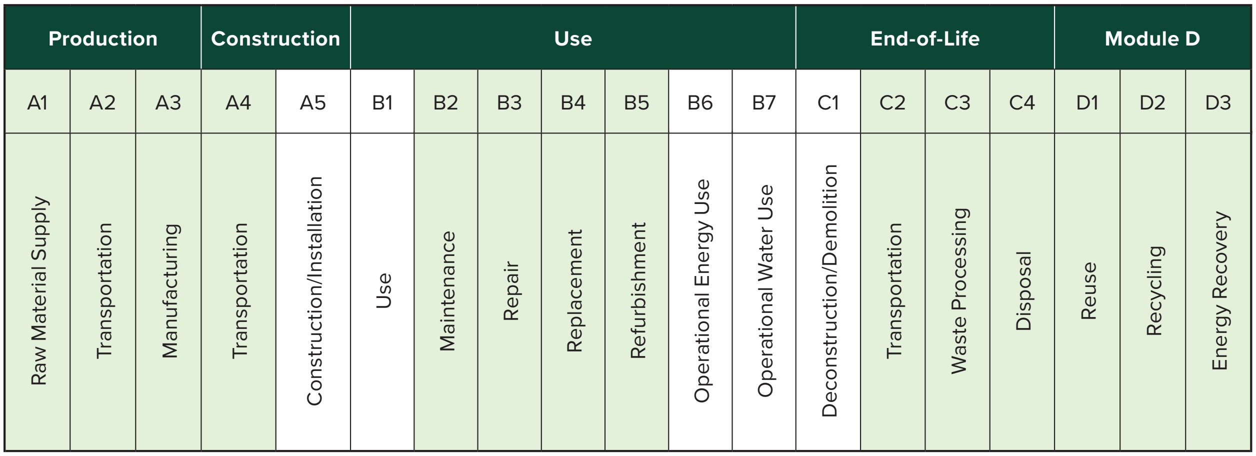
Life Cycle Assessment System Boundary

The LCA system boundary is cradle-to-grave (A-C, plus D), inclusive of Modules A1-A3, A4, B2-B5, C2-C4, and Module D (Figure 11). The service life of each building is 75 years, representing the reference study period. The service life for all materials and components matches that of the buildings, except roof enclosure finishes and waterproofing, and windows in the vertical enclosures, which are defined to have 40-year service lives.

Concrete carbonation is excluded.

Biogenic carbon flows are included. The end-of-life mix allocation assumptions are dictated by TallyLCA's methodology. See the introduction to this series for more detail.

Life Cycle Stages:
Cradle-to-Grave + Module D



Production			Construction		Use							End-of-Life				Module D		
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3
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	Reuse	Recycling	Energy Recovery

Note that the stages and information modules shown here deviate slightly from the naming convention used in ISO 21930 (ISO, 2017). However, this series generally uses terminology consistent with ISO 21930.

FIGURE 11: LCA life cycle stages; scope inclusions in light green

Life Cycle Assessment Data Methodology

For the LCA data methodology, assumptions, uncertainty, software limitations, and end-of-life methodology, reference the series introduction. The Supplemental Life Cycle Assessment Results section of this study addresses the data limitations within TallyLCA identified for glulam, CLT, and the acoustic underlayment mat. See the Appendix for the specific material quantities and EPD and LCI data selections used to perform the individual LCAs.

Comparative Results and Discussion

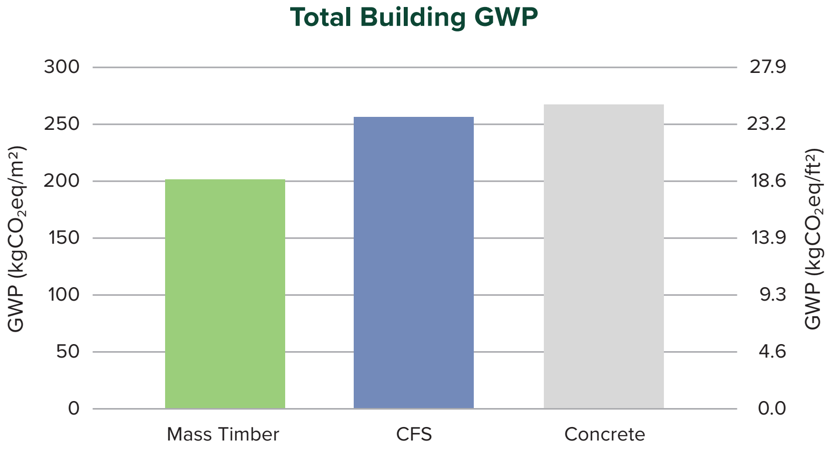
Results of the building study are described in this section. Global warming potential (GWP) is the focus of these results, measured in kilograms of carbon dioxide equivalent ($kgCO_2eq$).

Typically, the results are presented in terms of GWP per gross floor area ($kgCO_2eq/m^2$ and $kgCO_2eq/ft^2$), which is the industry standard.

Life Cycle Assessment Results

Overall, when considering the total GWP impact of the building, including both architectural and structural systems through WBLCA, the mass timber building's GWP is 21% less than the CFS building, and 25% less than concrete (Figure 12). The total GWP impact is 2,616,100 $kgCO_2eq$ (202 $kgCO_2eq/m^2$) for the mass timber building, 3,310,365 $kgCO_2eq$ (256 $kgCO_2eq/m^2$) for CFS, and 3,485,064 $kgCO_2eq$ (270 $kgCO_2eq/m^2$) for concrete.

Figure 13 provides further detail on the total GWP impacts by reporting the contribution of each material category and the breakdown between structural and architectural components for each building. Isolating the structural components, the mass timber building has 24% less GWP than CFS and 31% less than concrete. The architectural components of the mass timber building have 8% less GWP than CFS and 9% more than concrete. The structural components contribute between 79% and 86% of the total building GWP. The wood material contribution to the mass timber system is net negative due to its stored biogenic carbon, offsetting the positive GWP impact.



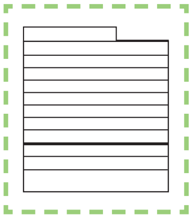


FIGURE 12: Total building GWP (structure and architecture) comparison of the three buildings

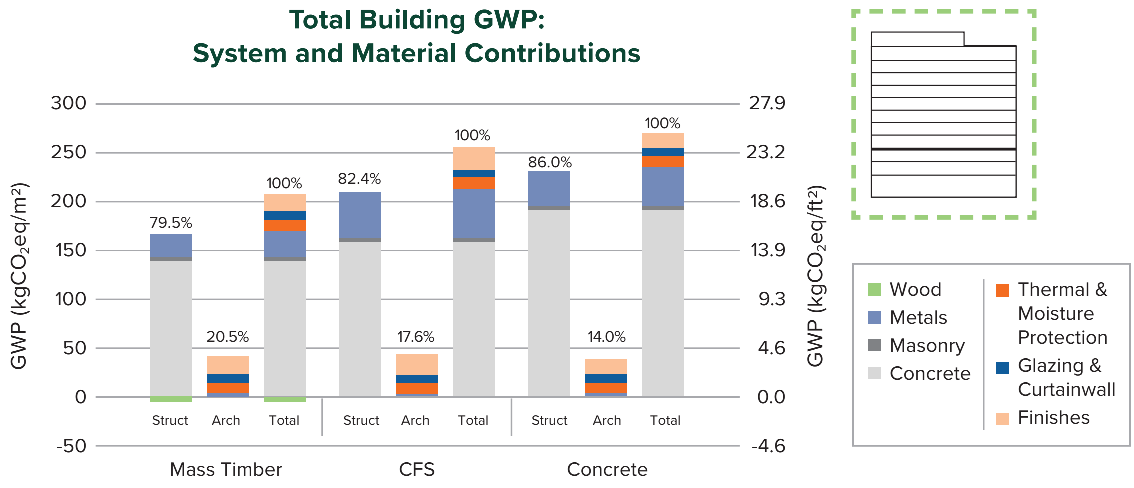


FIGURE 13: Total building GWP comparison of the three buildings by structural and architectural components and their material contributions

The concrete material dominates the GWP impact in all three buildings.[10] One reason for its high GWP contribution is the GWP intensity associated with a unit of concrete. However, the primary reason is the high relative volume of concrete required in all three buildings. Compared to the concrete building, the mass timber building has just 23% less concrete volume and the CFS building has only 11% less. Because concrete dominates the building material volumes and GWP impacts, it is helpful to isolate the varying structural systems at Levels 5 through 12 and the roof to better understand the impact of choosing mass timber in lieu of more conventional construction. This isolation of results is termed "above podium" and refers only to the structural floor plate (including topping slabs), framing, columns, and bearing walls above the Level 4 podium slab (Figure 14). The concrete core walls are excluded from above-podium results, as this will dilute the structural system comparison. When discussing the above-podium architectural components, the results include all architectural components outlined in the LCA scope that occur above Level 4. All above-podium results are presented in terms of GWP per gross floor area ($kgCO_2eq/m^2$ and $kgCO_2eq/ft^2$) above the podium (Level 5 through the roof).

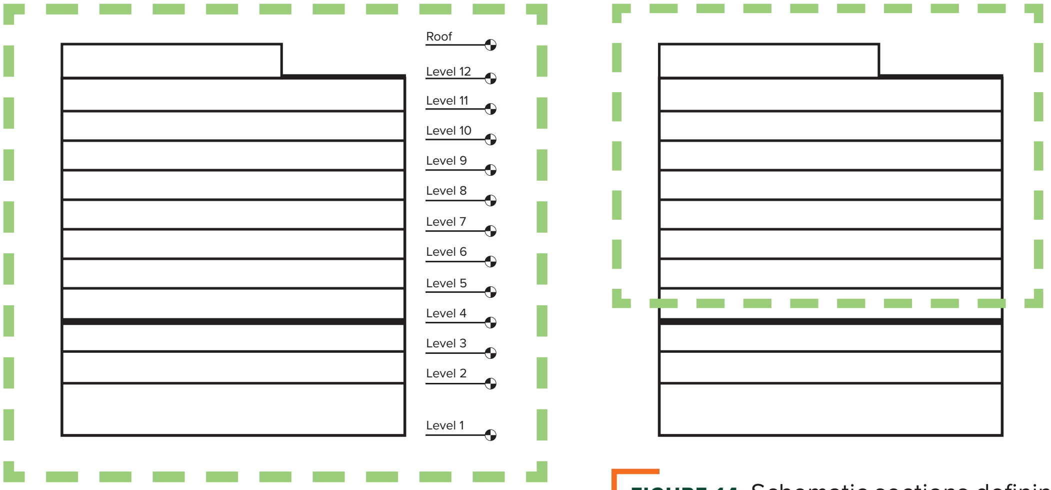


FIGURE 14: Schematic sections defining the meaning of "full building" (left) and "above podium" (right)

Figure 15 illustrates the above-podium GWP impact of the varying structural systems. The mass timber system has a 73% lower GWP than the CFS system and an 83% lower GWP than the concrete system. The major contributor to GWP in the mass timber system is the concrete topping slabs and their reinforcement on the CLT floor panels. The wood material contribution to the mass timber system is net negative due to its stored biogenic carbon, offsetting the positive GWP impact. The GWP savings associated with the mass timber structural system is equivalent to 144 or 254 gas-powered passenger vehicles driven for one year (CFS and concrete respectively), or the electricity used to power 126 or 222 homes for one year (United States Environmental Protection Agency, 2023).

Figure 16 shows the relative percentage of each structural material's mass compared to its relative GWP contribution for all three above-podium systems. Steel is the material with the highest GWP intensity by weight. However, the required volume of concrete for each system's floor assembly dominates the total GWP impact of all three buildings. The wood material's GWP contribution in the mass timber system is net negative due to stored biogenic carbon and wood does not show as a contributor to the mass timber building's GWP.

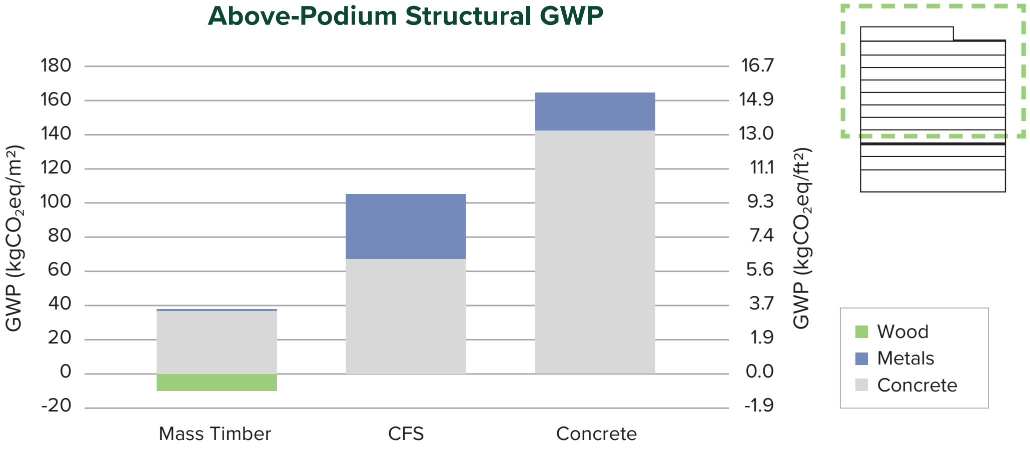


FIGURE 15: Above-podium structural GWP impact comparison of the three systems and material contributions

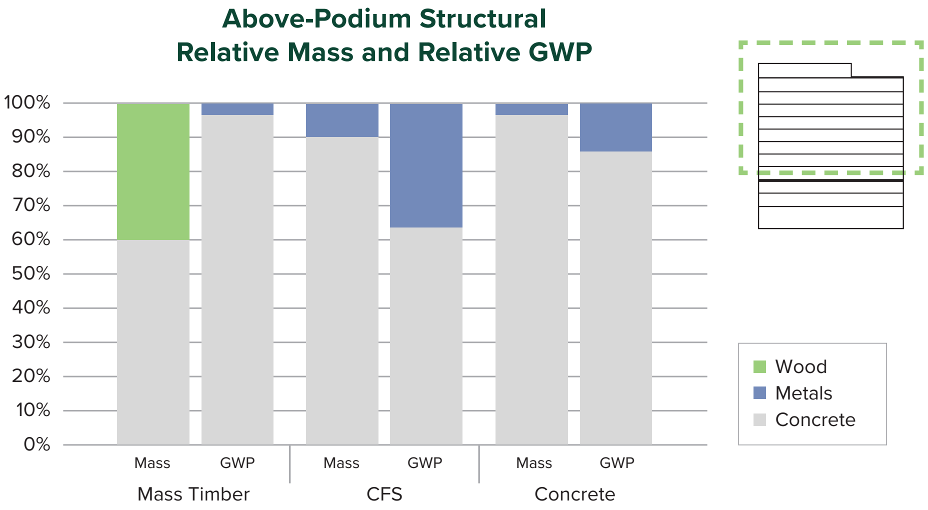


FIGURE 16: Relative mass and GWP comparison for the three above-podium structural systems

Figure 17 shows the GWP impact of the above-podium architectural components, separated into four use categories contributing to the total: vertical enclosure, horizontal enclosure, interior walls, and ceilings. The architectural component impacts of the mass timber system are 7% less than the CFS system and 9% more than concrete.

Gypsum board used as horizontal fire protection, including covering of the steel wide-flange beams in the CFS system, is included in the "ceiling" category. Similarly, the gypsum board providing fire protection on interior vertical surfaces is included in the "interior wall" category whether it protects structural bearing walls or non-load-bearing demising walls. Parapets are categorized as "vertical enclosure."

The different floor-to-floor heights for each of the building systems results in different floor elevations for Levels 4 through 12 and the roof, and thus different material quantities for both exterior and interior wall assemblies (and structural columns). The CFS system has more interior wall surfaces compared to the mass timber and concrete systems because it utilizes interior unit partitions for structural load-bearing walls, increasing the quantity and total length of fire-protected walls.

The horizontal enclosure's GWP is nearly identical among the three systems, the only difference being additional layers of gypsum board at the underside of the mass timber system's exterior Level 12 amenity assembly.

Ceilings have the greatest variance between the three systems: the CFS system's floor was covered at the underside with an additional layer of insulation and gypsum board (as is common practice for acoustic and aesthetic purposes in residential buildings throughout the Denver market) and the wide-flange beams are wrapped in two layers of gypsum board for fire protection; the mass timber system has two additional layers of gypsum board at the dropped ceilings in unit bathrooms; the concrete system has no additional floor fire protection.

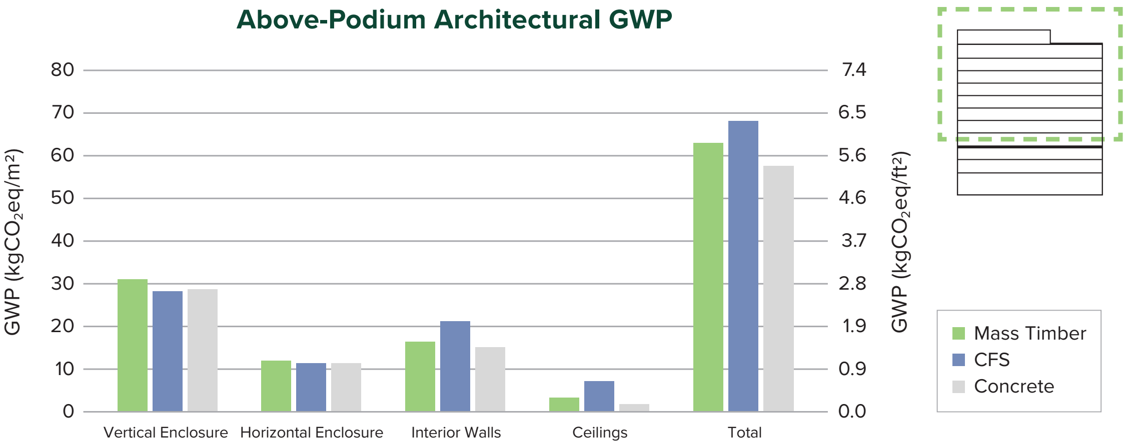


FIGURE 17: Above-podium architectural GWP impact comparison of the three systems by use category

Figure 18 illustrates the percent contributions of architectural versus structural system GWP impacts for the three above-podium building systems. The structural components dominate the GWP impacts of the concrete and CFS buildings, whereas the architectural components have greater GWP impacts with the mass timber building system. The mass timber system GWP is 47% less than the CFS system and 59% less than the concrete system. This GWP savings is equivalent to 155 or 245 gas-powered passenger vehicles driven for one year (CFS or concrete respectively) or the electricity to power 135 or 210 homes for one year (United States Environmental Protection Agency, 2023).

Considering the impacts of the Level 4 podium and structural components below, there are similarities between the three systems. Figure 19 shows each building's "podium and below" structural system GWP impact and the GWP contribution of the foundation systems. The term "podium and below" refers to the total structural GWP minus the above-podium impacts; thus, all structural components from the Level 4 podium slab through the foundations are included, plus the full height of the core walls from Level 1 to the roof. Foundations, also referred to as substructure in this building study, specifically refer to the drilled piers, mat slabs, grade beams, and foundation walls, and exclude the slab-on-grade.

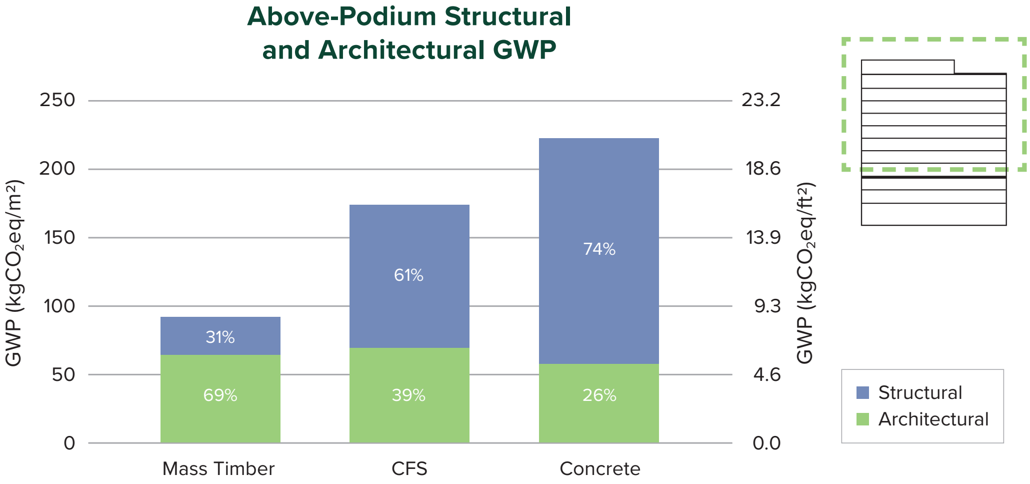


FIGURE 18: Above-podium, relative structural and architectural GWP impact of the three systems

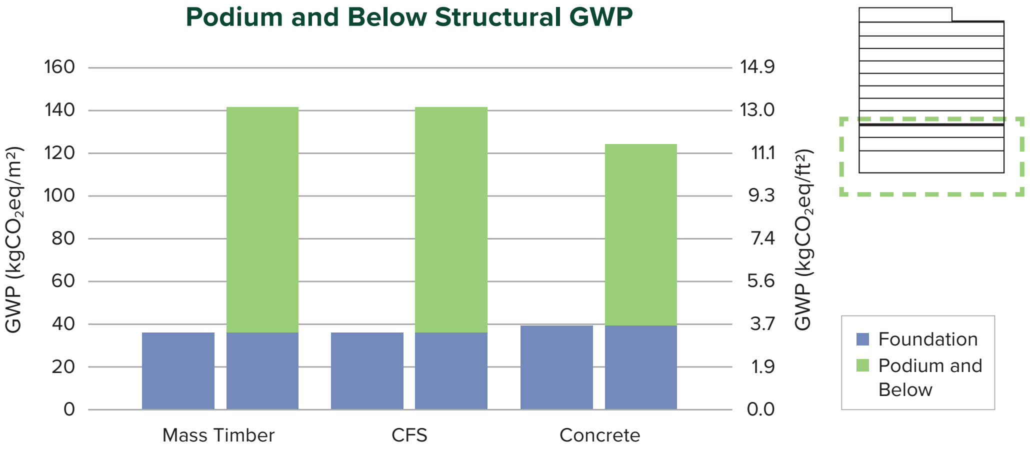


FIGURE 19: Structural GWP comparison of the three buildings' foundation systems and podium and below systems (including full height of the core walls and foundations)

The mass timber and CFS buildings have very similar foundation and podium and below results. The concrete building has a roughly 10% increase in foundation GWP due to the additional concrete volumes required to support the heavier building weight. Even with the increase in drilled pier lengths and core wall thicknesses, the concrete system has a 12% reduction in GWP impact for the podium and below results due to the Level 4 podium slab thickness reduction,[11] since it is not transferring columns and bearing walls, as is the case for the other two systems.

Figure 20 illustrates the substructure versus superstructure's percent contribution to the total structural GWP for each building. Superstructure refers to all elements not part of the foundation system, including the slab-on-grade. All three structural systems have a roughly 20/80% ratio of substructure to superstructure, even when considering the variations in material volumes and GWP impacts.

Figure 21 illustrates the life cycle stage contributions to the total building GWP. The dominant stage for all three buildings is the Production Stage (A1-A3). While the mass timber building looks like it has a relatively low Production Stage contribution, the value includes the negative GWP effects of stored biogenic carbon, resulting in a low net A1-A3 GWP impact.

Transportation (A4) has a minimal impact for all three buildings. The transportation distance is typically set to TallyLCA's default distance, based on U.S. averages, specific to the material. A mass timber supplier had not been chosen for Return to Form at the time of this analysis. Therefore, distances between Return to Form's location, Denver, Colorado, and all North American mass timber suppliers were studied. The authors chose 1,400 miles (2,250 km) as a moderate transportation distance for the mass timber material, which is roughly the distance between Vancouver, BC, Canada and Denver, Colorado. The total A4 transportation impact of the mass timber building system is equivalent to 6% of the stored biogenic carbon within the mass timber material, highlighting the importance of material choice over transportation distances to minimize a building's GWP impact.

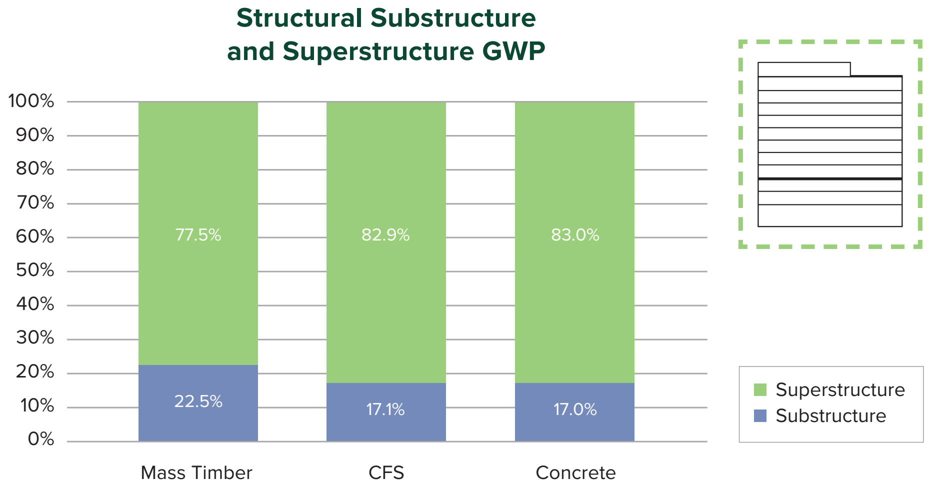


FIGURE 20: Structural substructure and superstructure relative contributions to total structural GWP of the three buildings

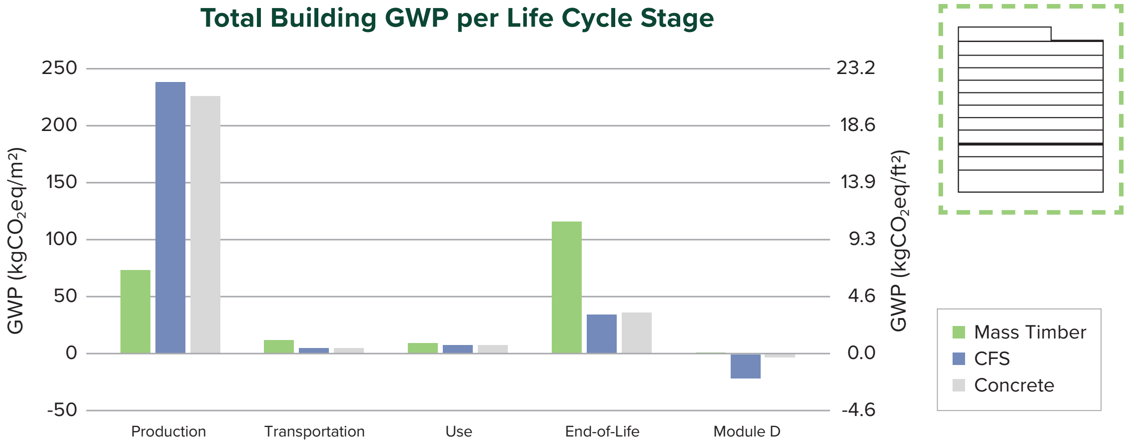


FIGURE 21: Total building GWP per life cycle stage comparison of the three buildings

The Maintenance, Repair, Replacement and Refurbishment modules (B2-B5) have a minimal impact as only roof finishes, roof waterproofing, and windows are assumed to be replaced at 40 years, before the end of the building's service life.

The End-of-Life Stage (C2-C4) has the highest impact for the mass timber building due to the release of stored biogenic carbon from the mass timber products. The LCA assumes 31.75% of the biogenic carbon is permanently stored. Reference the series introduction for a description of TallyLCA's end-of-life assumptions and mix allocation.

Finally, Module D has a minimal impact except in the case of the CFS building, which has a net negative impact. This is due to the recyclability of steel material; the system is credited for recycling their respective portions of net scrap.

Module D is considered outside of a building's system boundary (A-C) and its benefits and burdens ultimately belong to the next system, such as another building or physical product. TallyLCA does not allow the exclusion or proper separation of benefits and impacts that occur beyond the system boundary from the analysis. Therefore, as discussed in the series introduction, Module D is included and reported for all material systems in this building study.

The CFS building system receives the largest relative and numerical benefit by the inclusion of Module D, due to the assumption that 98% of steel material is recycled and the net scrap is credited as avoided burden (Figure 21). This means that the more virgin material used to manufacture the product (Stage A), the higher the benefits (credits) to the material in Module D, as is the case for HSS, metal deck, and CFS studs, as shown in Figure 22. If the percentage of recycled content of the product exceeds the percent allocated to recycling at end of life, the product will have a net burden in Module D, such as wide-flange steel (Steel ASTM A992) and steel reinforcement.

Twenty-one percent of the steel in the CFS building comprises the composite metal deck and 46% is steel reinforcement by weight. Although the material is highly recyclable, both elements present a challenge for end-of-life recovery and recycling since they are interlocked with concrete material.

Figure 22 illustrates the life cycle stage contributions of the major materials in this study. Stage A1-A3 dominates the GWP contribution of all materials. Materials that have a replacement period in Stage B have nearly equal impacts in Stage A1-A3 and Stage B.

There are trends related to concrete-reinforcing steel in all three buildings. The ratio of GWP contributions between the concrete material and reinforcing steel material for an individual concrete element varies widely, depending on the specified concrete mix design and steel reinforcement ratio. Reinforcing material in vertical elements such as drilled piers and columns can have a GWP contribution as high as 30%, while steel reinforcement in horizontal elements such as slab-on-grades, composite slabs, and topping slabs can be as low as 3%.

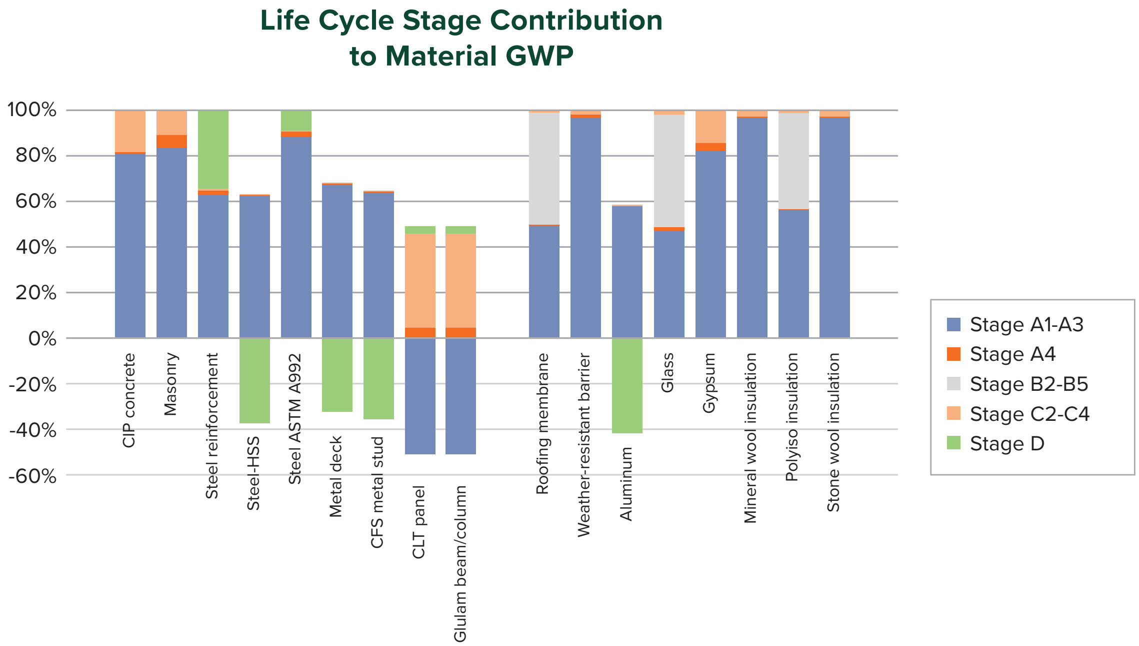


FIGURE 22: Life cycle stage GWP contributions per material

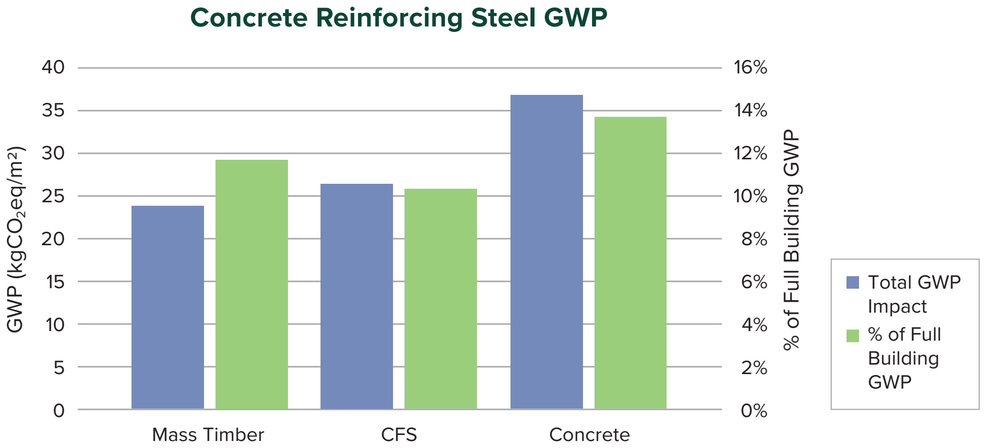


FIGURE 23: Concrete reinforcing steel GWP impact and percentage of reinforcing to full building GWP

Figure 23 shows the overall impact of reinforcing steel for each building. When compared to the mass timber building, the steel reinforcement GWP is 12% higher in the CFS building and 56% higher in the concrete building. However, the relative contribution of reinforcing steel to total building GWP is similar for all three buildings at 10%-14%.

An important consideration for biogenic carbon and its potential embodied carbon advantages are assumptions regarding the wood products' end-of-life disposition. The LCA results in this building study are based on TallyLCA's end-of-life mix allocation assumptions which presume that the majority of the biogenic carbon is released back into the atmosphere via incineration or decomposition at landfill, while 31.75% is permanently stored (Feitel & Kingsley, 2024). To illustrate the biogenic carbon content of the mass timber system, Figure 24 isolates the biogenic carbon entering the system at Stage A, which is termed "stored biogenic carbon."

The best-case scenario at end-of-life is that the mass timber material stores all of the biogenic carbon content indefinitely, through deconstruction, recovery, and direct reuse, or the building service life reaches 100 years, which also considers the biogenic carbon to be permanently stored (Biotechnology Industry Organization, n.d.).

Figure 24 shows the stored biogenic carbon of each mass timber component (at Stage A), per above-podium gross floor area. The CLT's stored biogenic carbon is roughly 162 $kgCO_2eq/m^2$, which is significant when compared to Figure 15, structural above-podium GWP impact, which has values ranging from 28 $kgCO_2eq/m^2$ to 164 $kgCO_2eq/m^2$ for the three structural systems.

GWP is the impact category discussed primarily in this building study as it represents all greenhouse gas emissions (GHGs) in proportion to their relative influence in creating the conditions for global temperature rise. GHG emissions "can be reported with clarity, as they have a high degree of global agreement on reporting methods [...] The emissions of GHGs anywhere in the world results in the same global impact on climate change" (Simonen, 2014). In contrast, the effects and risks of other environmental impacts are locally and regionally dependent. Table 3 shows all impact categories calculated in the LCAs. Results of this study show that the mass timber building has the lowest impact related to GWP and the use of non-renewable energy, but the CFS and concrete buildings have a lower impact in all other categories.

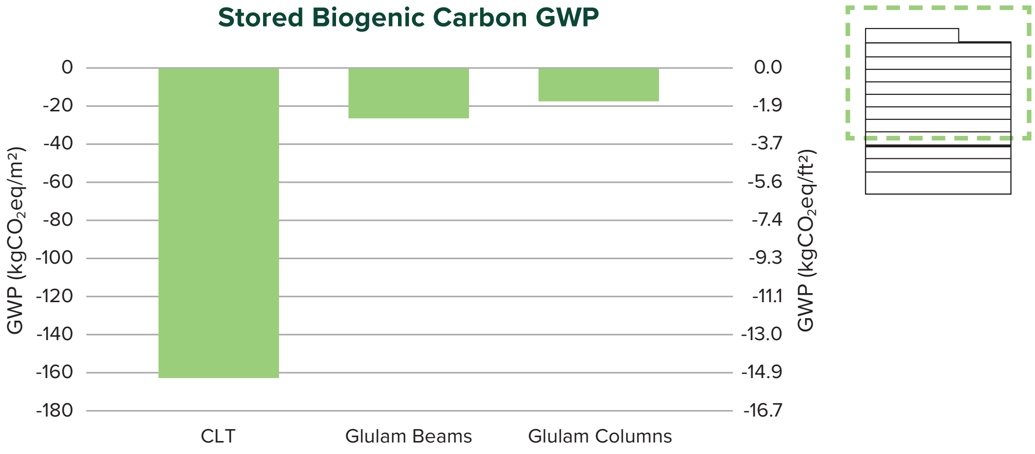


FIGURE 24: Stored biogenic carbon GWP of the mass timber building

Environmental Impacts							
Impact Category	Unit	Mass Timber		CFS		Concrete	
Acidification Potential	$kgSO_2eq/m^2$	1.20E+00	100%	7.98E-01	67%	7.51E-01	63%
Eutrophication Potential	$kgNeq/m^2$	1.47E+01	100%	5.58E-02	38%	5.22E-02	36%
Global Warming Potential	$kgCO_2eq/m^2$	2.03E+02	100%	2.56E+02	127%	2.70E+02	133%
Ozone Depletion Potential	$CFC\text{-}11eq/m^2$	5.10E-06	100%	1.21E-06	24%	4.05E-07	8%
Smog Formation Potential	kgO_3eq/m^2	1.67E+01	100%	1.46E+01	87%	1.45E+01	87%
Primary Energy Demand	MJ/m^2	3.35E+03	100%	2.79E+03	83%	2.67E+03	80%
Nonrenewable Energy Demand	MJ/m^2	2.54E+03	100%	2.59E+03	106%	2.51E+03	102%
Renewable Energy Demand	MJ/m^2	8.96E+02	100%	2.00E+02	22%	1.64E+02	18%

TABLE 3: Total Stages A-C plus Module D environmental impact categories for all three buildings

Supplemental Life Cycle Assessment Results

As discussed in the *Mass Timber Comparative Life Cycle Assessment Series Introduction,* results of the three LCAs discussed in this building study are dependent on the data available within the TallyLCA database and its methodology at the time of the analysis. The purpose of this section is to compare some of TallyLCA's data with currently available industry information and discuss potential effects on the comparative LCA results.

Concrete Mixes

Concrete as an industry has many strategies to reduce the embodied carbon intensity of its products (GWP impact per volume). The strategy employed for the LCAs compared in this study is to replace cement with supplemental cementitious materials (SCMs), specifically fly ash, as discussed in the section, Concrete Mix Designs. This is a standard approach in the Denver market. It is possible to achieve a lower embodied carbon-intensive mix design with a potential cost premium. Lower carbon-intensive mix designs would benefit the concrete building system the most, but it would also reduce the GWP impact of all three building systems. Compared to the concrete building, the mass timber building has 23% less concrete volume and the CFS building has 11% less concrete volume.

If TallyLCA referenced the NRMCA's 2022 *Concrete Industry-Average EPD* instead of the 2019 EPD, the effects on the total GWP would be a 5.6% reduction for the mass timber building, a 5.0% reduction for the CFS building, and a 5.7% reduction for the concrete building.

Glued-Laminated Timber

Glulam data within TallyLCA is based on the American Wood Council and Canadian Wood Council's (AWC/CWC's) 2013 *Industry-Average EPD for Glued-Laminated Timbers*, which expired in 2019 and was selected to represent all glulam within the mass timber building LCA as described in the series introduction. The current AWC/CWC EPD, issued in 2020, is not available within TallyLCA.

The 2020 glulam EPD has roughly 30% lower A1-A3 GWP impact compared to TallyLCA and the 2013 EPD. The difference in stored biogenic carbon is less than 2% as this value is based on the dry weight of the wood products. Based on current industry average data, TallyLCA overestimates the GWP impact of the glulam material. If the TallyLCA A1-A3 GWP data is replaced with the 2020 EPD data, the GWP impact of the glulam beams and columns would decrease by 24,790 kgCO_2eq in the mass timber building system. This would result in an 11% reduction of the above-podium structural A-D GWP, and a 1% reduction of the total building A-D GWP impact.

Cross-Laminated Timber

There is no North American industry-average EPD for CLT products, and no North American manufacturer-specific EPDs are included within the TallyLCA database though many are publicly available. TallyLCA does, however, offer an LCI data set based on the AWC/CWC's outdated 2013 *Industry-Average EPD for Glued-Laminated Timbers*. TallyLCA uses a proxied method to ratio glulam impacts and biogenic carbon content to the density of a typical CLT product.

In support of this comparative LCA series, all current North American CLT manufacturer-specific EPDs were collected to determine the average and spread of the reported GWP impacts for structural CLT panel products and compared to TallyLCA's current data. For this data comparison, reference the *Mass Timber Comparative Life Cycle Assessment Series Introduction* section, Life Cycle Assessment Data Uncertainty and Limitations.

Using the manufacturers' average A1-A3 GWP impact, the GWP impact of the CLT is reduced by 83,689 $kgCO_2eq$. This results in a 36% reduction in the above-podium structural A-D GWP impact and a 3% reduction in total building A-D GWP of the mass timber building system. There is nearly four times as much CLT volume compared to glulam volume in the mass timber building system, which is why the CLT has a larger relative impact on the system GWP.

Acoustic Mat

As noted in the Life Cycle Assessment Material Scope section, the acoustic underlayment mat of the CLT floor assembly was excluded from the LCA due to lack of industry data and data available within TallyLCA. Pliteq's GenieMat FF rubber pad underlayment mat product has a published EPD and meets the reference building's acoustic performance requirements. It is considered directly comparable to the acoustic product specified in the Construction Documents in terms of functional equivalency. Their EPD states that their product has 92% recycled rubber content (Pliteq Inc., 2023).

KL&A Team Carbon performed a calculation outside of TallyLCA to better understand the potential GWP impacts of the acoustic underlayment mat, which is a common solution to meet acoustic performance requirements of mass timber floor systems. The calculations consider only the Stage A1-A3 impacts of the acoustic mat, referencing the Pliteq GenieMat FF EPD, and result in an increase of 6.4 $kgCO_2eq/m^2$, a 23% increase to the mass timber system's above-podium A-D GWP. Although the above-podium impacts seem large, the overall contribution of the above-podium mass timber system to the total building GWP is low. The effect on the building's total A-D GWP impact is a 3.2% increase. In lieu of available embodied carbon data, it seems reasonable to assume an acoustic mat product with high recycled content will have a lower A1-A3 GWP impact than a product that sources virgin material.

In general, this supplementary data has minimal effect on the overall trends of the building and system embodied carbon comparisons.

Cost and Speed of Construction Results

This building study focuses primarily on WBLCA and design implications on embodied carbon impacts. Building material and system selections have cost in terms of dollars and time. This section endeavors to answer the question: *What is the dollar cost of lower embodied carbon system and material choices?*

This cost study is based on the Return to Form reference mass timber building, and an actual cost comparison undertaken with a cast-in-place concrete alternative during the original schematic development stage. The general contractor, Swinerton, prepared an additional estimate for the cold-formed steel version described in this report. Although the mass timber building is yet to be constructed at the time of this writing, all costs are normalized to July 2023 costs of materials and labor.

The comparative analysis performed for this study includes all substructure, superstructure, architectural and structural components.[12] The exterior vertical enclosure was important to capture in the cost analysis due to the variation in floor-to-floor and total building heights. The fire-rated assemblies and requirements were also important to capture as their design, installation, and material volumes vary across the three structural systems. Special systems used to install the structure and protect it from the elements during construction, such as concrete formwork, steel deck shoring, mass timber ultraviolet light and moisture protection, were included in the estimates.

It is typical for the initial pricing of mass timber systems to show a dollar cost premium over conventional systems; this building was no different (Figure 25). Similar to the LCA results, the above-podium residential structure (Level 5 through the roof) is isolated for comparison; the structural raw material cost is least expensive for the concrete system, with a striking 42% premium for the mass timber system, and a 7% premium for the CFS system. Considering structural raw material for the entire building, the premiums reduce to 19% for the mass timber system and 1.1% for the CFS system.

Larger and multi-story buildings can often be constructed in less time with mass timber systems than with concrete or steel. For Return to Form, Swinerton estimated the mass timber building could be built in 16.5 months, the CFS building in 18.5 months, and the concrete building in 20.7 months. This means the mass timber building could be completed two months faster (11% faster) than CFS, and 4.2 months faster (20% faster) than concrete. The dollar cost analysis took this into account by considering general conditions (labor), general requirements (equipment and waste), crane costs, urban site logistics, and variations in finishes such as topping slabs, interior walls, and gypsum covering and is termed "total structure construction." With these compounding considerations, the CFS system becomes the least expensive and the cost premium for the mass timber system reduces from 19% to 7.5%, which is only a 0.7% premium over concrete. Isolating the dollar costs of logistics and schedule (no hard material costs), the mass timber system is the least expensive, the concrete system has a 140% premium, and CFS a 67% premium.

When considering the "whole building construction cost"[13] to the owner, the mass timber building has a 1.8% premium over CFS, and only a 0.2% premium over concrete. These relative cost comparisons and premiums are illustrated in Figure 25.

The exposed mass timber in Return to Form will be a market differentiator in the River North Art District neighborhood of Denver, Colorado, which generally has an industrial aesthetic. Real estate sales data in Denver suggests that mass timber spaces can command market premiums; such premiums are not included in this analysis. Developer's liability insurance premiums, any financial benefits or losses to the developer associated with the time-value of money, such as interest premiums, financial benefits or losses to the developer associated with the lease or sale market value of the building, and potential carbon credits or carbon taxes are excluded from the cost analysis.

The authors of this building study speculate that consumer demand for sustainable buildings, including a desire for biophilic aesthetics, is the reason for potential market premiums. This market demand will likely increase over time, leading building developers and owners to consider, measure, and report the sustainability of their building products.

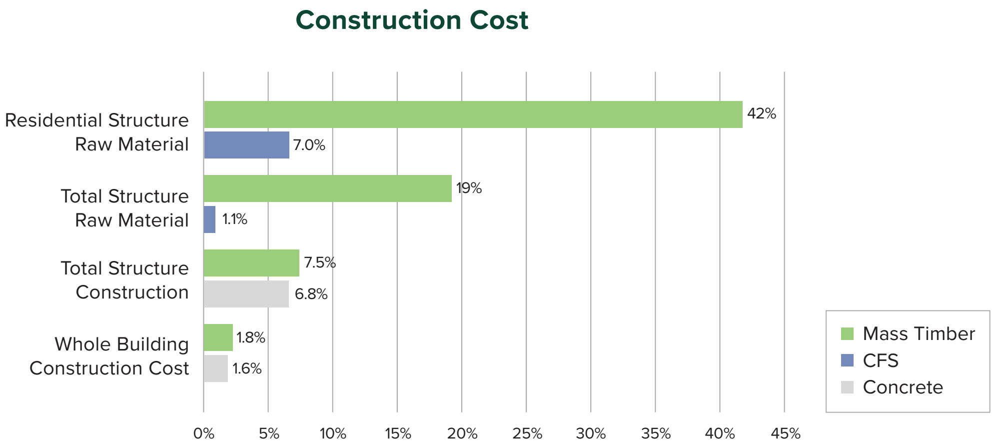


FIGURE 25: Construction cost premiums of the three building systems, relative to the lowest cost (illustrates progression of the cost analysis)

Conclusion

This building study endeavors to answer the questions: *How does mass timber compare to traditional structural systems? Is mass timber sustainable? What are the associated dollar cost premiums?*

The LCA and dollar cost results presented in this study have illustrated that a mass timber system, for a building of this construction type and occupancy, can have significant embodied carbon savings, minimal total cost premium, and construction schedule benefits when compared to functionally equivalent conventional structural systems—i.e., cold-formed steel and concrete (Figure 26 and Figure 27).

Specifically:

- Considering only the structure above the Level 4 podium, the mass timber system GWP is 73% less than the CFS system and 83% less than the steel system.
- Considering all structural and architectural systems above the podium, the mass timber system GWP is 47% less than the CFS system and 59% less than the concrete system.
- The mass timber system would be constructed two months faster than the CFS system (11% faster) and 4.2 months faster (20%) than the concrete system.
- Comparing only the structural material costs of the residential floors above the podium, the mass timber showed a 7% premium over CFS and striking 42% over concrete. However, when considering the whole building construction cost, including cost savings associated with the shorter duration of construction, the mass timber premium is 1.8% over CFS and only 0.2% over concrete.

Despite clear material cost premiums, cost-competitive mass timber solutions are achievable with thoughtful design, material optimization, designing for (de)constructability, and thorough, holistic cost estimating that includes the schedule and labor savings as a real component of construction cost.

The building industry has a significant opportunity and responsibility to address climate change and environmental impacts, due to its outsized global emissions impact. This study explores mass timber structural systems as one potential embodied carbon reduction strategy, due to the material's relatively low manufacturing GWP impacts and its natural ability to store biogenic carbon, although the industry will also need to consider bolder, innovative, multifaceted reduction opportunities for all systems—including both design and material strategies. The implementation of mass timber systems should be considered as a viable approach to minimize a building's embodied carbon impact with the understanding that building life expectancy, sustainable material sourcing,[3] and end-of-life pathways[4] for the mass timber material influence its ultimate embodied carbon impact.

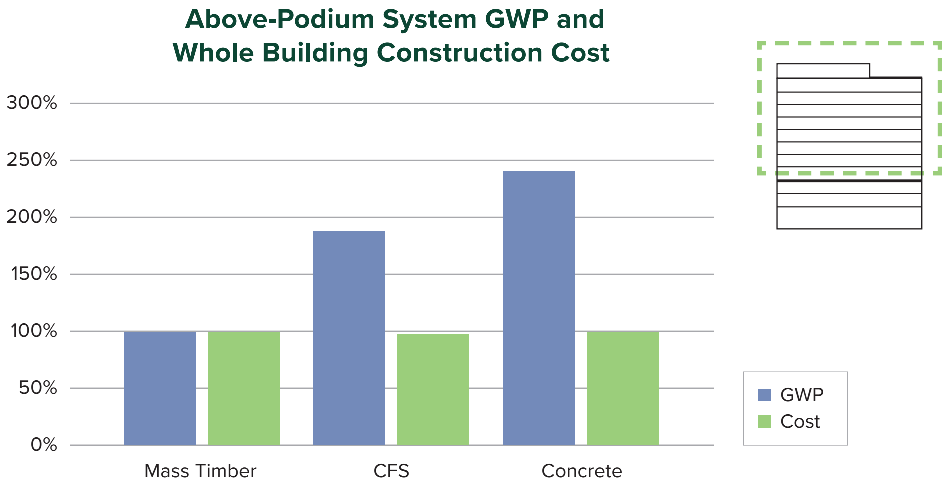


FIGURE 26: Above-podium system GWP (structure and architecture, including enclosure, fire-resistance rated assemblies, acoustic assemblies, and interior ceiling finishes) and whole building construction cost comparison of the three building systems, normalized to the GWP and cost of the mass timber system

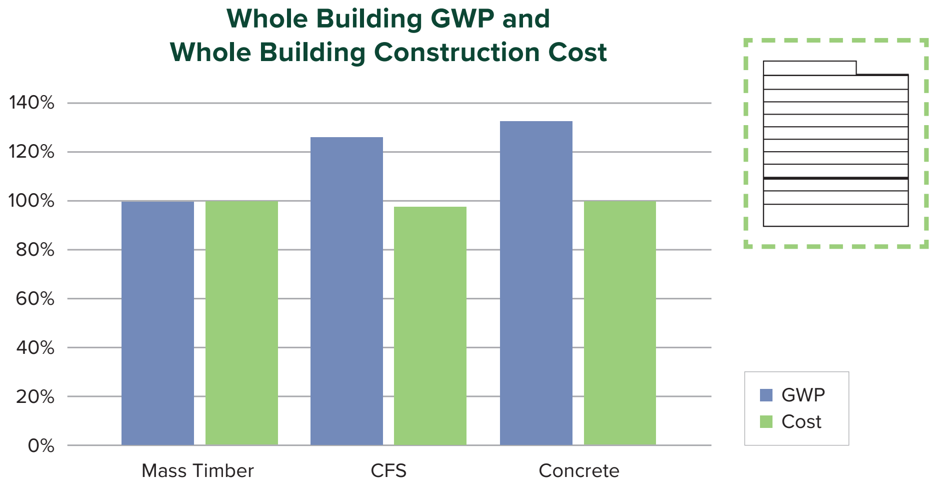


FIGURE 27: Whole building GWP and whole building construction cost comparison of the three buildings, normalized to the GWP and cost of the mass timber building

End Notes

1 Functionally equivalent means the same design criteria as the reference systems—i.e., equivalent floor area, site orientation, occupancy, general programmatic layout, geographic location, load criteria, and performance requirements, in accordance with ISO 14044 4.2.3.7 and ASTM E2921.

2 For more information on biogenic carbon, see the *Mass Timber Life Cycle Assessment Series Introduction*.

3 Wood products sourced from North American forests meet the definition of sustainable sourcing per ISO 21930 Section 7.2.11. For more information, see the *Mass Timber Life Cycle Assessment Series Introduction*.

4 End-of-life considerations are included in the cradle-to-grave LCA results and are based on TallyLCA's end-of-life allocation assumptions, as described in the *Mass Timber Life Cycle Assessment Series Introduction*.

5 This method of fire resistance is referenced in IBC Section 722.1, defined in NDS Chapter 16, and is allowed for fire-resistance ratings up to 2 hours. For more information see the WoodWorks paper, *Fire Design of Mass Timber Members*, available at www.woodworks.org.

6 Requirements for protecting concealed spaces in Type IV-B construction are covered in IBC Section 602.4.2.5. For more information, see the WoodWorks paper, *Concealed Spaces in Mass Timber and Heavy Timber Structures*, available at www.woodworks.org.

7 Note that these fire-resistance rating requirements match that of the Type IV-B construction noted for mass timber.

8 Alternative fire protection strategies for the steel framing include coating it in spray-applied cementitious fireproofing or intumescent paint. These are not considered typical or cost-effective solutions in the Denver market for multifamily buildings.

9 Primary concrete-reinforcing steel such as typical mats and additional reinforcement in slabs and walls, vertical bars and ties in columns, and drilled piers are included. Secondary reinforcing steel such as lap splices, dowels, connections, drag bars, and corner detailing are excluded.

10 While steel reinforcing bar is inherent to both concrete and masonry elements, it is categorized as a metals division for the purposes of this study.

11 Avoiding a transfer condition at the Level 4 podium slab benefits the concrete building in both GWP and construction dollar cost.

12 The reported construction costs do not include the costs associated with the lower embodied carbon concrete mix designs described in the section, Concrete Mix Designs.

13 Whole building construction cost includes the material and installation of the foundation substructure, floor and roof superstructure; all architectural, mechanical, electrical, plumbing and civil costs; schedule-related costs like general conditions, labor, equipment and waste; and site logistics. As noted in the *Mass Timber Comparative Life Cycle Assessment Series Introduction*, costs such as developer liability insurance premiums, and financial gains or losses to the developer associated with time-value of money or any market value sale of the building are not included.

Revision History

March 21, 2024 – First release
March 25, 2024 – Revisions made to correct errors in Figures 20, 22 and 24

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Appendix

TallyLCA® Data Selection[1]	Total Mass (kg)		
	Mass Timber	Steel	Concrete
Adhesive, polychloroprene (neoprene)	225.37	232.43	222.75
Aluminum curtain wall system, YKK AP - EPD	16,751.43	15,701.83	15,972.69
Aluminum storefront system, YKK AP - EPD	132.34	127.13	120.67
CLT (Cross laminated timber)	750,367.41	--	--
Coated steel deck, SDI - EPD	--	107,369.98	320.43
Cold formed structural steel	42,872.19	132,927.44	40,245.54
Concrete masonry unit (CMU), hollow-core	133,170.02	132,524.79	132,021.63
EPDM, reinforced membrane, 60 mils, SPRI - EPD	4,754.52	4,903.26	4,699.19
Fasteners, stainless steel	22.04	21.37	21.56
Fluid applied synthetic polymer air barrier	6,834.39	5,971.18	6,180.43
Glass wool unfaced batt, Knauf, EcoBatt - EPD	7,727.90	12,773.03	7,113.91
Glazing, double, insulated (air)	48,690.60	44,405.05	45,451.22
Glue laminated timber (Glulam), AWC - EPD	217,333.40	--	--
Hot rolled structural steel, AISC - EPD	238.69	15,527.11	231.83
Lightweight concrete, 4000 psi, 0% fly ash and slag	11,566.52	11,563.48	11,563.48
Metal lath, for plaster	3,684.29	3,209.24	3,324.03
Mineral wool, low density, NAIMA - EPD	8,555.16	8,283.11	8,385.05
Mortar type S	13,490.28	13,339.98	13,289.33
PIR rigid foam insulation, roof, R=20.5, PIMA - EPD	32,410.28	32,858.15	31,560.52
Polyethelene sheet vapor barrier (HDPE)	742.91	647.12	670.27
Stainless steel sheet, Chromium 18/8	3,370.99	3,267.97	3,296.82
Steel tube, Bull Moose Tube - EPD	747.14	13,635.01	761.53
Steel, concrete reinforcing steel, CMC - EPD	207,427.10	231,786.91	323,229.01
Structural concrete, 4000 psi, 20% fly ash	1,706,615.36	2,907,063.41	247,241.28
Structural concrete, 4000 psi, 40% fly ash	745,238.58	745,238.58	813,094.12
Structural concrete, 5000 psi, 40% fly ash	1,830,155.47	1,761,121.99	2,134,151.25
Structural concrete, 6000 psi, 20% fly ash	3,093,918.84	3,167,679.42	6,550,569.38
Structural concrete, 6000 psi, 40% fly ash	473,305.72	473,305.72	540,920.83
Stucco, portland cement	133,038.24	115,884.27	120,029.54
Suspended grid	1,990.87	1,990.89	1,990.90
Thickset mortar	144,487.19	143,790.28	143,246.95
Wall board, gypsum, fire-resistant (Type X)	502,064.67	777,690.21	410,807.26
Wall board, gypsum, natural	50,989.69	47,108.64	47,374.91

1. The TallyLCA® Data Selection name reported is the TallyLCA® formal data entry terminology and represents the LCI and EPD data set for a given product type and specification

WW-LCA-02 - Return to Form Comparative Life Cycle Assessment Study

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