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The Impact of Connections on the Embodied Carbon of Mass Timber Buildings

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ABSTRACT

While full LCA studies of mass timber buildings quantify the embodied carbon (EC) of every individual component, some of these components have significant variability in early design when their characteristics are unknown. Consequently, many early design tools omit the contribution of structural connections. To address this gap in early design analysis of EC, this research investigates the EC impact of connections relative to the total gravity structural system. An interior bay of the gravity system provided the framework for analysis across both case study reviews and the development of parametrically driven design spaces for both mass timber systems and steel systems. When looking at mass timber beam to girder pre-engineered connections, they account for an average of 0.43 lbs CO_2 / sqft. When including column connections and deck fasteners, connections are found to account for up to 40% of the total gravity system EC. Accounting for mass timber connections during LCA studies can be significantly more relevant as compared to more traditional system types when considering the EC contributions.

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Chapter 1

Introduction

1.1 Introduction

The building industry accounts for 37% of total global carbon dioxide (CO_2) emissions [1]. As operational carbon use and costs decrease, embodied carbon (EC) becomes more relevant. The two primary structural systems in mid-rise commercial buildings – steel and concrete – significantly contribute to EC emissions. Substituting mass timber structural elements or systems can reduce emissions overall to provide a more sustainable option. Because of this reduction in EC, individual contributions from components carry greater importance to the overall emissions [2]. One of these components that few early design studies include is the impact of the connections relative to the entire model in terms of EC. Therefore, the purpose of this research is to establish a parametric model to measure EC for mass timber connections.

Life-cycle assessment (LCA) provides an internationally recognized methodology for determining the energy and emissions associated with the production and construction of materials. These studies can be evaluated through full life-cycle assessments ("cradle-to-grave") or a selected portion of the life cycle ("cradle-to-gate" or "gate-to-gate") [3]. When these studies are completed, most do not include the EC impact of connections because the models rely on reference cases that do not have adequate detail to perform connection related material takeoffs or the case study is simplified to exclude such details [2]. Additionally, ISO 14044:2006 provides guidance on input selection criteria and if one component, like connections, is low enough in mass compared to the total system it may be omitted, however this standard does also caution that this may result in omissions of relevant data.

To explore this gap in the EC contributions of connections relative to the total building, this research addresses the following questions:

- How does the contribution of connections compare to the EC associated with mass timber gravity systems?
- Do connections pose greater relevance to EC conscious gravity systems compared to more traditional systems?

1.2 Methodology

To address these questions, this research performs case study analyses coupled with model generated design space exploration. As seen in Table 1, this research is broken into case study analyses for both mass timber and steel gravity systems. These case studies utilize drawing sets from three real buildings for each material type to complete material take-offs and EC analysis. The parametric study involves using a design space of possible bay layouts with beam to girder connections to analyze trends related to the EC of these shear connections.

Table 1: Scope Matrix

Study Type	Mass Timber	Steel
Case Study	Analyze an interior bay of existing mass timber buildings to quantify the EC of the gravity system per square foot.	Analyze an interior bay of existing buildings with joists, non-composite W-shape beams, and composite W-shape beams to quantify the EC of the gravity system per square foot.
Parametric Study	Analyze an interior bay of mass timber buildings across the design space considering beam length, bay aspect ratio, and number of beams to quantify the EC of the gravity system per square foot.	Analyze an interior bay with joists and non-composite W-shape beams across the design space considering beam length, bay aspect ratio, and number of beams to quantify the EC of the gravity system per square foot.

The scope is limited to a single interior bay across all four areas of study. The total EC is determined by considering elements within the bay; for example, in Figure 1, two girders, four infills, eight connections, and the deck within this bay are all elements counted in the total EC of this bay. No columns are considered contributions as this research focuses on the EC of the gravity system on one floor for one bay.

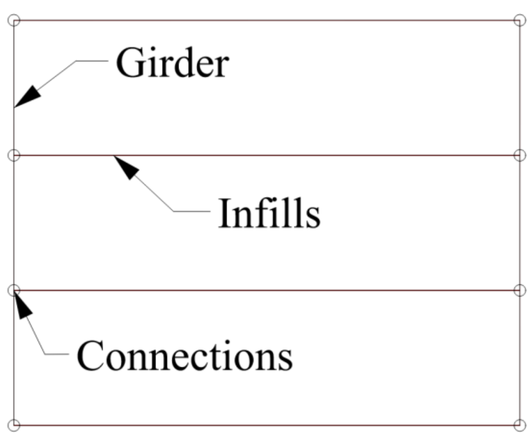
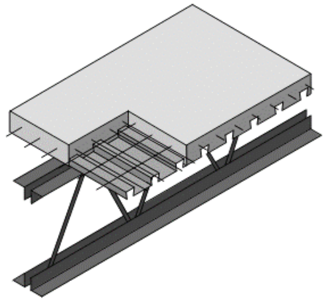
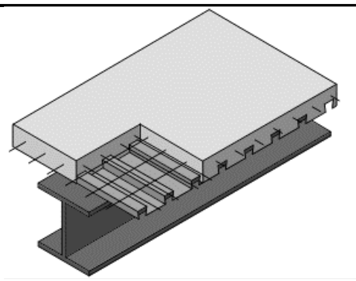
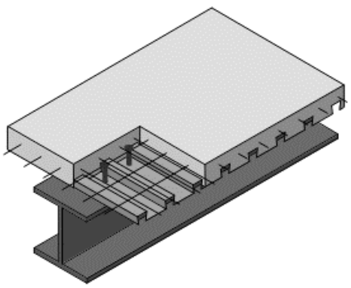
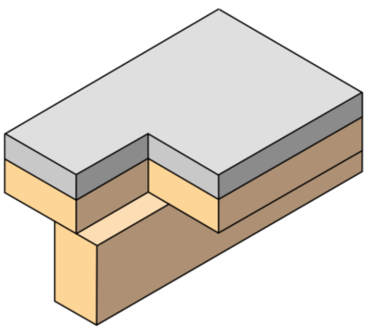


Figure 1: Typical Bay EC Analysis

Two mass timber connection types are analyzed to cover typical designs within a gravity structural floor system: beam to girder and girder to column. Grasshopper (GH), a 3-D parametric modeling program, generates the floor system geometry with integrated Python scripts to size timber components and connection types based on sizing guides from connection manufacturers based on a variety of bay design inputs. The EC of the connections is calculated and compared to the full bay design using material takeoffs from the final design. The case studies explore this type of connection as well as girder to column connections. The mass timber floor system is composed of glulam beams and girders, a CLT floor, and 1.5” normal weight concrete (NWC) topping with spans ranging from 10-40 ft. While this range goes beyond typical spans for mass timber glulam beams, it is included for analysis, understanding that most designed would be unable to adequately fit such deep beams in the plenum space between floors.

This process is also completed for several steel systems: open web steel joists (OWSJ), non-composite (NC), and composite. Similarly, a parametric model sizes the beams or joists, girders, and beam to girder connections for each of the steel systems. Case studies are selected for analysis of the beam to girder connections and girder to column connections to give a baseline for the parametric study as well as to provide a comparison for the mass timber results. All of these systems use W-shape beams or joists, W-shape girders, and 1.5VLI-36 deck with 4 ½” NWC topping. All of these systems can be seen in Table 2 for additional clarity.

Table 2: System Types

Assembly Icon	System Name	System Components
	Steel Joists	Composite metal deck and NWC topping with regularly spaced joists and W-shape girders. No camber included.
	Non-Composite Steel	Composite metal deck and NWC topping with regularly spaced W-shape infill beams and W-shape girders. No camber included.
	Composite Steel	Composite metal deck and NWC topping with regularly spaced composite W-shape infill beams and composite W-shape girders. No camber included.
	Timber Floor with Timber Girders and Beams	CLT floor panels and NWC topping with regularly spaced glulam infill beams and glulam girders. Gypsum is installed directly against the underside of the CLT panels and wraps the girders and beams.

1.3 Scope Definition

This research focuses on the embodied carbon factors (ECF) developed from cradle-to-gate for all system types across both the parametric and case studies. This includes A1-A3 categories of the life cycle, as seen in Figure 2, which fall under production and include the extraction and upstream production, transportation to the factory, and the manufacturing process. This partial life cycle assessment is selected due to the early design nature of the parametric study where determining the transportation onsite and other factors from A4-D have much higher variability.

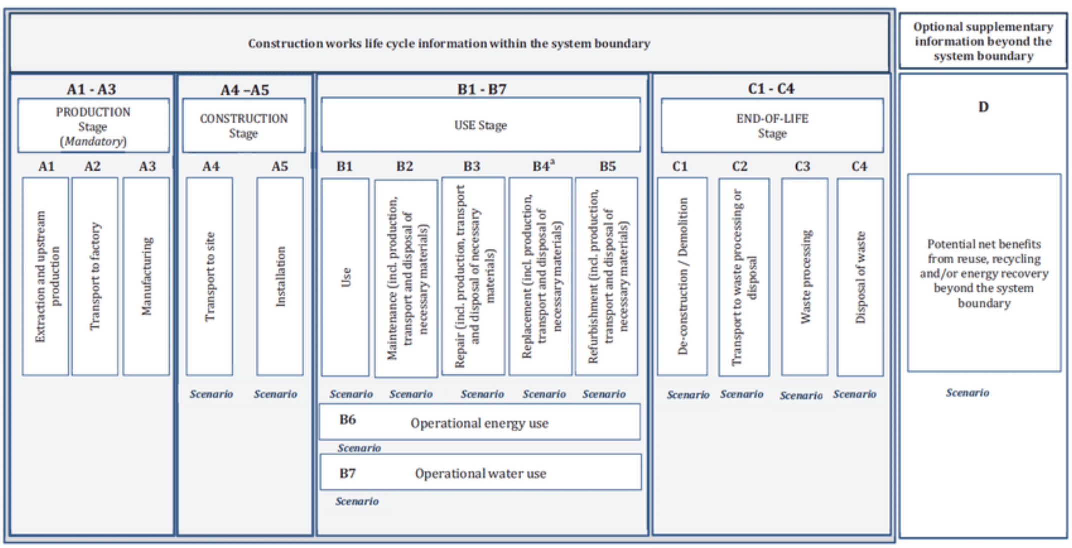


Figure 2: Life Cycle Analysis Boundaries [4]

In terms of occupancy, this research focuses on multifamily residential and business types as these encompass a large portion of commercial buildings being constructed. These occupancies also have similar live loads (LL): the multifamily residential buildings require 40 psf with 20 psf partition LL for private rooms and corridors serving them while office spaces require 50 psf load with 20 psf in addition for partitions [5]. Live load reduction is considered in the drawing sets used for the case study analysis, while it is not considered for the parametric analysis to simplify the constraints. The superimposed dead load (SDL) is assumed to be 20 psf when not explicitly stated in case study drawing sets and is used for the parametric studies. The International Building Code (IBC) Construction Types for all of the buildings varies between IB and VB.

Chapter 2

Literature Review

2.1 Introduction

In this chapter, a review of existing literature and research is analyzed and provided to give context surrounding mass timber buildings and their related connections. Key concepts of focus include mass timber buildings, timber connections, life cycle analysis with particular interest in EC, comparative analysis to traditional gravity systems and components, and parametric design space exploration. This literature will provide the basis for this research by showing the current gap in knowledge for the effect that connections have on EC of mass timber gravity systems.

2.2 Full Building LCA Studies

With mass timber buildings becoming increasingly popular and the 2021 IBC code allowing for tall mass timber buildings with a height of up to 18 stories, research related to mass timber buildings becomes progressively more relevant [6]. One of the largest benefits to mass timber buildings includes a significant reduction in EC; one such study provides a comparative LCA analysis between traditional building types and mass timber buildings in the Pacific Northwest, Northeast, and Southeast regions of the United States. Within each of these regions, three buildings are designed to cover the new construction types developed in the 2021 IBC to accommodate tall mass timber buildings: 18 story buildings for type IV-A, 12 story buildings for type IV-B, and 8-9 story buildings for type IV-C. When comparing the mass timber buildings to concrete buildings, total EC reduced by between 22% and 50%. Because all of the mass timber case studies discussed in Chapter 3 are in the Pacific Northwest, the results from this study for this region are of particular interest. The total EC for the 8-story building in the Pacific Northwest is 113.4 kg CO_2 / m^2 which is equivalent to 23.2 lbs / sqft where 43% or 9.98 lbs / sqft is from the floor system – CLT deck and glulam beams. This provides a good measure of comparison when both the mass timber case studies and parametric studies are evaluated. This study does not however include connections or details beyond glulam, 3/8” acoustic mat, CLT, concrete, and gypsum concrete in terms of material assembly [3].

While the previous study developed results by designing and modeling six different mass timber buildings with LCAs, another option is to draw conclusions from relationships developed in a parametric design space of mass timber buildings. Hens is more focused on early-stage tall timber design for post-beam-panel and post-and-platform and uses GH with a component, Karamba3D, for structural analysis. This model develops three-dimensional structural layouts based on user-defined variables and parameters. The primary elements in consideration when measuring EC include glulam beams and CLT deck, however an approximation is offered for concrete toppings, steel connections, and concrete foundations. The ECFs to calculate EC are used from the Inventory of Carbon and Energy (ICE) open-source database which is one of the primary sources for ECFs in this research as well, however when possible environmental product declarations (EPD) are used instead because they provide more specific product data and are more current than most of the data in the ICE database. The approximations for EC due to connections are from Strobel who analyzed mass timber connections and their EC impact relative to the rest of the building. Hens specifically states that while detailed connection design is out of scope for this paper, further investigation carries merit because its impact on EC, member sizes, and fire safety are not yet well understood [7].

2.3 Connection Related Studies

Strobel uses parametric modeling of mass timber office buildings at various scales to measure the environmental impact of the structural system and subsystem components. The primary contributors of EC are facades and floor slabs, however shear wall connections are also considered in the EC accounting. These connections are composed of steel plates and fasteners and designed to resist the combined shear and bending from seismic forces at the shear wall base. Based on this research, the steel volume of connections is 0.25% of the timber volume of the building and EC of connections can then be determined [8]. While this research does begin to explore the EC impact of connections relative to other building components, there lacks a level of detail in the shear connections between glulam beams, girders, and columns which this research begins to examine in greater depth to bridge the gap in understanding.

In addition to parametric studies that recognize the gap in knowledge regarding mass timber connections, Lukic compiles 14 life cycle studies of multi-story timber buildings. A majority of these studies omit the EC contribution of connections and most studies that do consider the impact of connections do so because they are analyzing a real building.

The study uses a base case study building with a central core and four residential units per floor from the Building Systems Manual for multi-story residential units by Stora Enso. From this base architecture the building is broken into four cases ranging between one and four stories maintaining the same plan on each floor. For all of these cases, a timber-frame panel system is used where connections and fasteners are designed between the horizontal and vertical elements of the building: angle brackets for tensile and shear loads, staples for attaching sheathing boards to the timber frame, countersunk screws for timber frame and frame elements, full thread connectors with cylindrical head for the timber beams, and screws for attaching the oriented strand board (OSB) to the timber beams. All of these products then use an ECF for chromium steel to determine the EC associated with connections and fasteners. Based on this methodology, the connectors and fasteners can account for up to 25.66% of the loading-bearing timber structure [2]. While Lukic provides a detailed methodology and analysis for connections associated with residential buildings using a timber-frame panel system, these results and trends cannot necessarily be assumed to carry over to tall mass timber buildings like those described in the research performed by Puettmann and Hens. In this sense, this thesis is novel because in the following chapters, connections are considered for mass timber systems composed of glulam beams and girders with CLT deck. In addition, this methodology provides a more detailed list of ECFs for separate elements of connections between timber elements.

Chapter 3

Mass Timber Case Study

3.1 Introduction

In this chapter, three mass timber buildings are selected as case studies to review the EC associated with their gravity systems. All of these case studies focus on the same mass timber gravity system type: glulam beams, girders, and columns with timber floor deck and NWC topping. The connections, however, are different for each building and are specifically designed for the project rather than a pre-engineered connection from a manufacturer as done for the mass timber parametric connection study, which is further discussed in Chapter 4. Unlike for steel buildings, mass timber connections are far less standardized which is why multiple case studies are reviewed. Figure 3 provides a general overview of the case study analysis methodology.

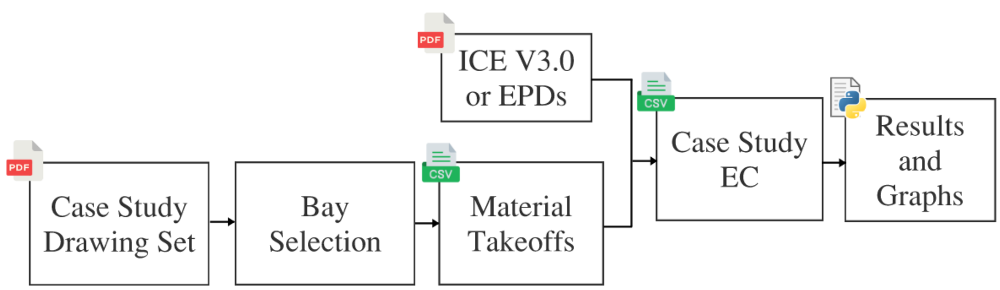


Figure 3: Mass Timber Case Study Analysis Methodology

The purpose of this chapter is to develop a better understanding of how EC varies across mass timber gravity systems and to provide a baseline for the mass timber parametric study completed in Chapter 4. For each case study, one bay is selected for analysis and when possible, an interior bay with no openings or associated shear walls is selected. Avoiding these types of irregularities allows for a better comparison to the mass timber parametric study and the steel studies. To keep the accounting of EC consistent across systems, EC is tracked for the gravity system including the beams, girders, decking and connections between beams, girders, and columns. Elements not included are the columns, fire protection elements that are not directly structural elements, and edge condition elements including hardware and connections associated with façade systems and concrete pour stops.

3.2 Mass Timber Case 1

This case study highlights a 16,000 sqft office building in the Northwestern region of the United States. It is a type IIIB three-story building with the primary occupancy classified as Business. The LL is 80 psf including 15 psf for partition loading and is based on office loading. Because the building is relatively small, there are no fully interior bays available for analysis. Therefore, as seen in Figure 4, the selected bay includes an exterior side of the building. This did affect the size of the exterior girder changing it from a 6 ¾ x 24 to a 6 ¾ x 18 glulam beam. The pour stop edge conditions and façade attachment connections were also not considered for takeoffs.

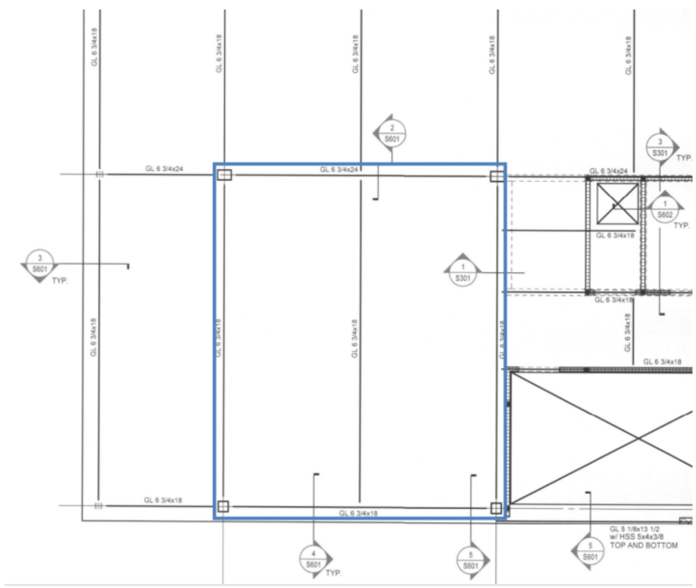


Figure 4: Mass Timber Case 1 Partial Second Floor Framing Plan, with Analyzed Bay

Generally, this system includes glulam 6 ¾ x 18 beams and 6 ¾ x 24 girders with a three ply CLT deck with 2” NWC topping. The connections associated with diaphragm design are included in the EC calculations. As seen in Figure 5, the beam to girder connections use pipe which the beams bear on with a tie-strap at the top.

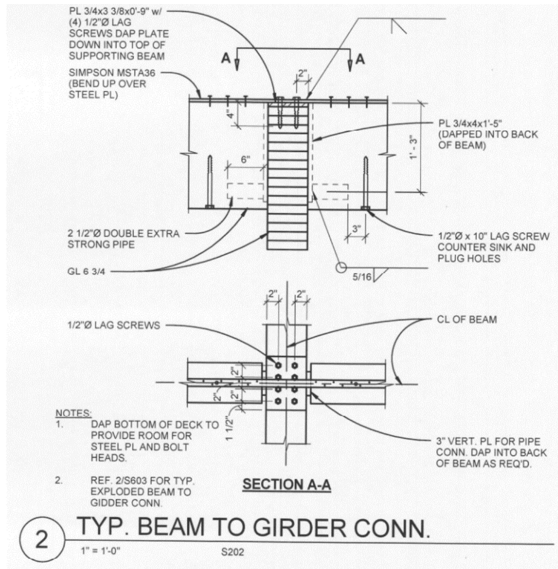


Figure 5: Mass Timber Case 1 Beam to Girder Connection

As seen in Figure 6, the column connections primarily use plates and bolts to provide enough bearing capacity for the beams and girders. This connection type requires a column splice at every floor.

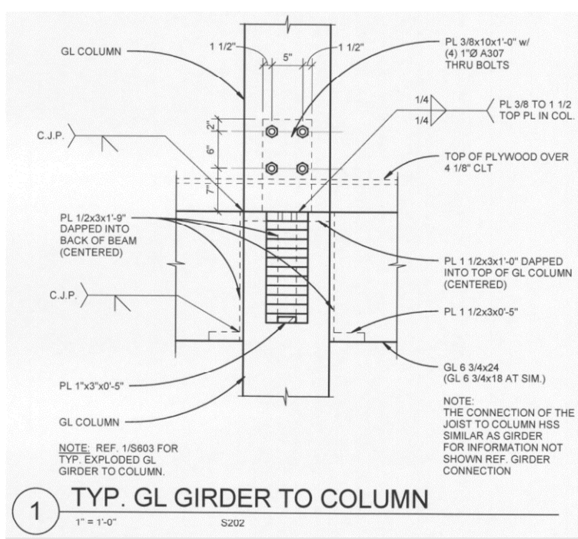


Figure 6: Typical Exploded Girder to Column Connection

The ECFs used in this analysis are shown in Table 3 where each considered element, the assumed ECF, and the source of the ECF are listed.

Table 3: Mass Timber Case 1 ECFs

Unit	Component	ECF (lbs CO_2 eq/lbs)	Notes
Beam to girder	PL ¾" x 3 3/8" x 9"	1.73	AISC Industry-Wide Steel Plate EPD [9]
	PL ¾" x 4" x 1'-5"		
	½" DIA, 4 ½" Lag Screw	1.27	ICE V3.0 Engineering Steel [10]
	½" x 10" Lag Screw		
	0.148" x 2 ½" Fastener		
	MSTA 36 (SST)	2.76	ICE V3.0 Hot-Dip Galvanized Steel [10]
	2 ½" DIA x 6" Double Extra Strong Pipe	2.35	Goodluck India Limited Pipe EPD [11]
Beams and Girders to Column	PL 3/8" x 10" x 1'	1.73	AISC Industry-Wide Steel Plate EPD [9]
	PL 1 ½" x 3" x 1'		
	PL ½" x 3" x 1'-9"		
	PL ½" x 3" x 1'-6"		
	PL 1" x 3" x 5"		
	PL 1 ½" x 3" x 5"		
	1" ϕ A307 Thru Bolts	1.27	ICE V3.0 Engineering Steel [10]
Beam	GL 6 ¾ x 18	0.25	AWC North American Glulam EPD [12]
Girder	GL 6 ¾ x 24		
Decking	3/8" DIA x 11 7/8" ASSY KOMBI Screws	1.27	ICE V3.0 Engineering Steel [10]
	5/16" DIA x 3 1/4" ASSY ECO Screws		
	½" Plywood	0.39	AWC North American OSB EPD [13]
	1" x 8" Plywood Spline		
	CLT SLT 3 Deck	0.26	Structurlam CLT EPD [14]
	2" Concrete Topping	0.13	NRMCA EPD [15]

3.3 Mass Timber Case 2

This case study showcases a 35,000 sqft mixed use building with retail and office spaces in the Northwestern part of the United States. It is a type IIIB four story building with the primary occupancy of Business. The LL is 65 psf with partition loading included. As seen in Figure 7, this structure includes a glulam timber frame with two concrete cores. The deck system includes 3” tongue and groove (T&G) lumber with 2 ½” NWC topping with #5 rebar in both laterally and longitudinally.

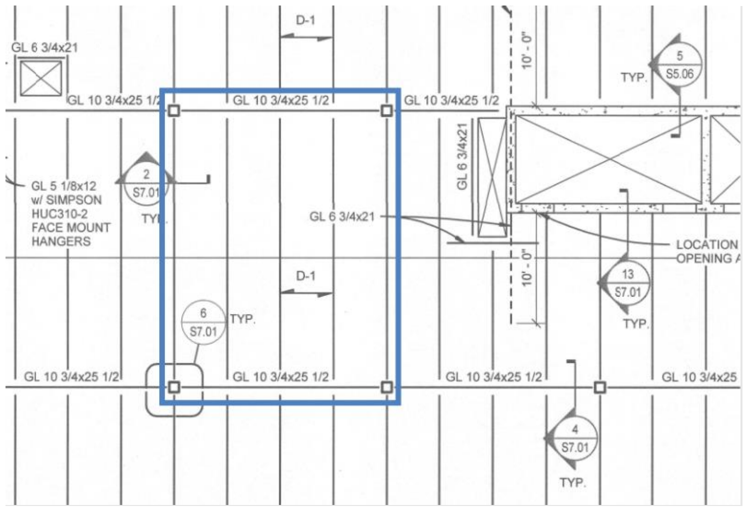


Figure 7: Mass Timber Case 2 Partial Third Floor Framing Plan, with Analyzed Bay

The beams are 6 ¾ x 21 ½ and girders are 10 ¾ x 25 ½ in the analyzed and remain regular across the entire frame. As seen in Figure 8, the beam to girder connection uses a knife plate type connection with plates and screws.

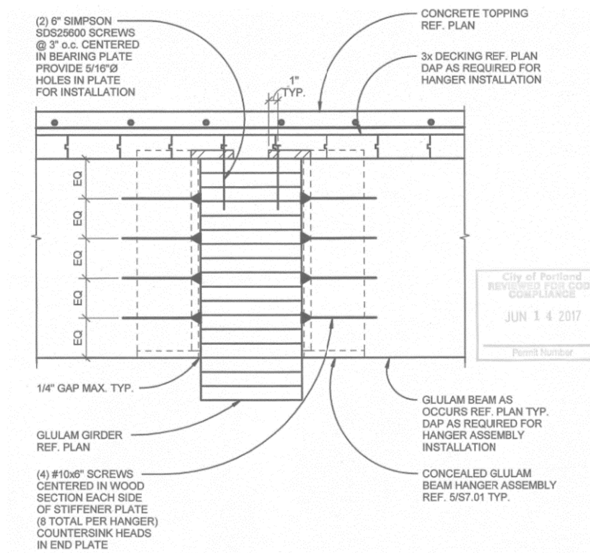


Figure 8: Mass Timber Case 2 Beam to Girder Connection

As can be seen in Figure 9, the column connections used are similar to the first mass timber case study although instead of one large plate, the connection for each beam or girder is more separate.

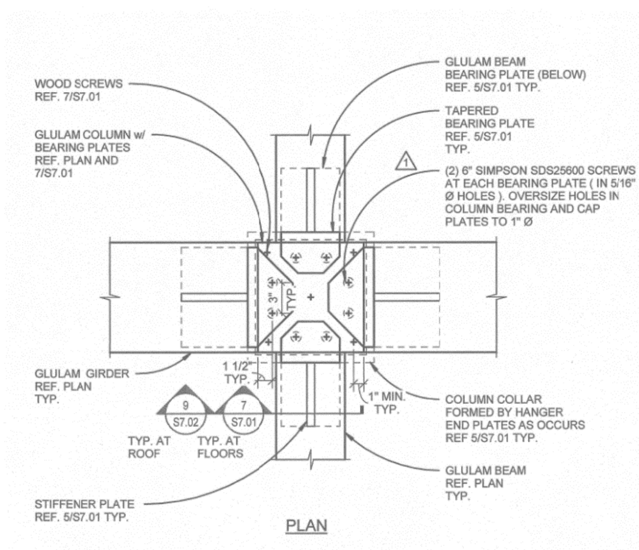


Figure 9: Mass Timber Case 2 Beams and Girders at Column

The ECFs used in this analysis are shown in Table 4 where each considered element, the assumed ECF, and the source of the ECF are listed.

Table 4: Mass Timber Case 2 ECFs

Unit	Component	ECF (lbs CO_2 eq/lbs)	Notes
Beam to girder	#10 x 6" Screws	1.27	ICE V3.0 Engineering Steel [10]
	3/4" DIA x 4 1/2" Studs		
	6" SST SDS 25600 Screws	2.76	ICE V3.0 Hot-Dip Galvanized Steel [10]
	Bearing PL 7/8" x 5 3/4" x 3 1/2" (Tapered)	1.73	AISC Industry-Wide Steel Plate EPD [9]
	Stiffened PL 1/2" x 6 1/2" x 21"		
	Beam Bearing PL 3/4" 6 1/2" x 5 3/4"		
	End PL 3/4" x 5 3/4" x 28 1/2" (Tapered)		
Beams and Girders to Column	3" SST SDS25300 Screws	2.76	ICE V3.0 Hot-Dip Galvanized Steel [10]
	6" SST SDS 25600 Screws		
	Column PL 1/2" x 10 3/4" x 10 1/2"	1.73	AISC Industry-Wide Steel Plate EPD [9]
	Bearing PL 7/8" x 5 3/4" x 3 1/2" (tapered)		
	Stiffened PL 1/2" x 6 1/2" x 21"		
	Beam Bearing PL 3/4" 6 1/2" x 5 3/4"		
	End PL 3/4" x 5 3/4" x 28 1/2" (Tapered)		
	Bearing PL 7/8" x 9 3/4" x 3 1/2" (Tapered)		
	Stiffened PL 1/2" x 6 1/2" x 25 1/2"		
	Beam Bearing PL 3/4" x 6 1/2" x 9 3/4"		
	End PL 3/4" x 5 3/4" x 33" (Tapered)		
	#10 x 6" Screws	1.27	ICE V3.0 Engineering Steel [10]
	3/4" DIA x 4 1/2" Studs		
Beam	GL 6 3/4 x 21	0.25	AWC North American Glulam EPD [12]
Girder	GL 10 3/4 x 25 1/2		
Decking	3" T&G Decking	0.306	ICE V3.0 Hardwood Timber [10]
	2 1/2" NWC Topping	0.13	NRMCA EPD [15]
	#5 @ 12" and #5 @ 24" Rebar	0.854	CRSI EPD [16]
	40d Common Nail	1.27	ICE V3.0 Engineering Steel [10]
	60d Common Nail		
	8" Wood Spikes @ 30", @ 10"	2.76	ICE V3.0 Hot-Dip Galvanized Steel [10]

3.4 Mass Timber Case 3

The third mass timber case study focuses on a 72,000 sqft mixed-use office and retail building in the Northwestern United States. It is a 6-story type IIA building with the primary LL being 80 psf for office space. As seen in Figure 10, it was not possible to select a bay for analysis without edge condition or an opening so an interior bay with a relatively small opening is selected. For this analysis, the opening and any structural elements associated with it will not be considered.

Figure 10: Mass Timber Case 3 Partial Fifth Floor Framing Plan, with Analyzed Bay

The structural gravity system is composed of glulam 8 ¾ x 34 ½ beams and glulam 8 ¾ x 42 girders. These sizes vary slightly throughout the building but maintain similar dimensions. The nail laminated timber (NLT) deck uses 2x6 dimensional lumber with and 1” of gypcrete topping. As seen in Figure 11, the beam to girder connection uses a knife plate connection type where a top plate bears on the girder and extends down to collect the shear force of the beams.

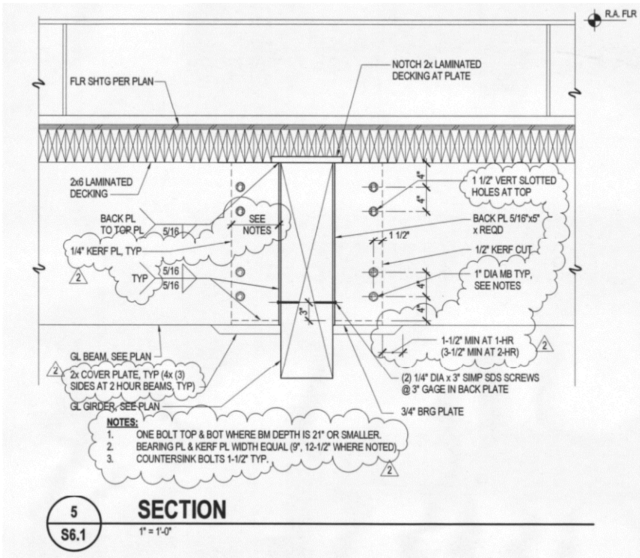


Figure 11: Mass Timber Case 3 Beam to Girder Connection

As seen in Figure 12, the column connection requires the glulam columns to be spliced at every floor by using an HSS at all beam and girder connection points. All of the plates that support the beams and girders are then connected to the HSS.

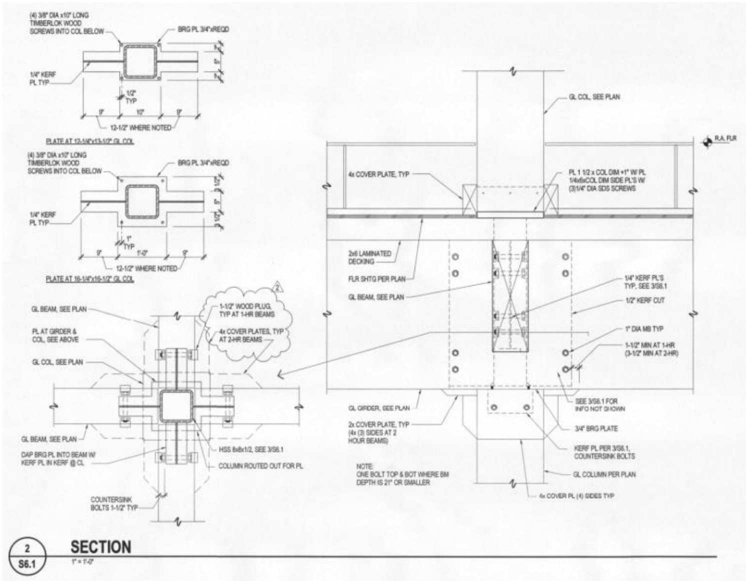


Figure 12: Mass Timber Case 3 Beams and Girders at Column

The ECFs used in this analysis are shown in Table 5 where each considered element, the assumed ECF, and the source of the ECF are listed.

Table 5: Mass Timber Case 3 ECFs

Unit	Component	ECF (lbs CO_2 eq/lbs)	Notes
Beam to girder	Cover PL 1-1/2" x 8" x 12"	1.73	AISC Industry-Wide Steel Plate EPD [9]
	BRG PL 3/4" x 5" x 9"		
	Back PL 5/16" x 5" x 33 1/2"		
	KERF PL 1/4" x 33 1/2" x 9"		
	Top PL 3/4" x 12" x 24"		
	1" DIA Machine Bolt	1.27	ICE V3.0 Engineering Steel [10]
	1/4" DIA x 3" SST SDS Screws	2.76	ICE V3.0 Hot-Dip Galvanized Steel [10]
Beams and Girders to Column	KERF PL 1/4" x 6" x 13 1/2"	1.73	AISC Industry-Wide Steel Plate EPD [9]
	BRG PL 3/4" x 5" x 9"		
	BRG PL 3/4" x 12" x 12"		
	KERF PL 1/4" x 11" x 41"		
	BRG PL 3/4" x 5" x 9"		
	KERF PL 1/4" x 33 1/2" x 9"		
	PL 1-1/2" x 15 1/2" x 18 1/4"		
	Side PL 1/4" x 15 1/2 x 6"		
	Angle Cover PL 1/4" x 16" x 12"		
	3/8" DIA x 10" Timberlok Screws	1.27	ICE V3.0 Engineering Steel [10]
	1" DIA Machine Bolt		
	HSS 8x8x1/2x 47 1/2"	2.39	AISC Industry Wide HSS EPD [17]
	1/4" DIA SDS Screws	2.76	ICE V3.0 Hot-Dip Galvanized Steel [10]
Beam	GL 8 3/4 x 30	0.25	AWC North American Glulam EPD [12]
	GL 8 3/4 x 34 1/2		
Girder	GL 8 3/4 x 42		
	GL 8 3/4 x 40 1/2		
Decking	1" Gypcrete	0.17	Levelrock Gypcrete EPD [18]
	2x6 Vert Lam Decking NO. 1	0.09	Softwood Lumber EPD [19]
	4x6 Sleeper DF-L		
	5/8" OSB Plywood Sheathing	0.39	AWC North American OSB EPD [13]
	10d @ 18" o.c.	1.27	ICE V3.0 Engineering Steel [10]
	10d @ 12" o.c.		
	0.148" x 3-3/4" Nails @ 18" o.c.		
	SST SDWS22800DB 0.220" x 8"	2.76	ICE V3.0 Hot-Dip Galvanized Steel [10]

3.4 Mass Timber Case Study Results and Analysis

When comparing the three case studies, there are several trends of interest in relation to the bay geometry and the EC of the systems. Significant contributions of EC come from the concrete topping, timber decking, glulam, and steel plates used in the connections. As seen in Table 6, the total EC of Case 2 is the highest, 15.5 lbs CO_2/ sqft, when compared to Case 1, 9.5 lbs CO_2/ sqft, and Case 3, 11.7 lbs CO_2/ sqft. The concrete topping in this case study uses #5 reinforcing bars which contribute 1.3 lbs CO_2/ sqft; this is an element that neither of the other case studies uses and contributes 8% to the total EC. Case 2 also has five infills while the other two case studies only use three. This increases the EC contribution of the glulam beams and connections.

Table 6: Mass Timber Case Study Results

Results	Case 1	Case 2	Case 3
Bay Area (sqft)	487.5	483.3	725.0
Aspect Ratio (unitless)	1.2	1.3	1.2
Total EC (lbs CO_2)	4638.6	7510.6	8496.3
Total Connection EC (lbs CO_2)	508.2	2143.4	3339.3
Beam to Girder Connection EC (lbs CO_2)	82.0	717.4	408.9
Total EC (lbs CO_2/sqft)	9.5	15.5	11.7
Total Connection EC (lbs CO_2/sqft)	1.0	4.4	4.6
Beam to Girder Connection EC (lbs CO_2/sqft)	0.2	1.5	0.6
Total EC (%)	100.0	100.0	100.0
Total Connection EC (%)	11.0	28.5	39.3
Beam to Girder Connection EC (%)	1.8	9.6	4.8

Compared to Case 1, Case 2 and 3 also have significantly higher EC contributions due to the more frequent use of steel plates in the connections. Case 1 uses steel tube shapes in the beam to girder connections and uses fewer thicker plates, while the other cases rely on a greater number of plates to build up the connections. The most common plate thickness for Case 1 ranges between 1” – 1 ½”, while Case 2 uses a common thickness that ranges between ½” – ¾” and Case 3 uses a common thickness that ranges between ¼” and ¾”. Decreasing plate thickness across case studies follows an increasing EC trend due to connections. The total connection EC of Case 3 is also higher due to the EC contribution from an 8x8x1/2 HSS member that is used in the column connection. This element contributes 1.3 lbs CO_2/ sqft or 7.4% EC to the total connection EC; without this element, the total connection EC would be more similar to the Case 2 value.

Even though there is variability in these cases study results, overall they are still comparable to Puettmann’s results. When considering only glulam beams, CLT deck, concrete topping, and acoustic mat, Puettmann found 9.98 lbs CO_2/ sqft. While this study does not consider any acoustic mat, on average the total EC carbon is slightly higher than the 9.98 lbs CO_2/ sqft because of the inclusion due to connection EC contributions. Other differences are likely a result of variability with the design of the building and of the ECFs.

Figure 13 graphically shows the EC breakdown of the three cases studies. The beam to girder connections contribute between 0.2 lbs CO_2/ sqft to 1.5 lbs CO_2/ sqft of the total EC of the gravity system analyzed. The EC contributed by all connections within the bay – beam to girder connections, beam and girder to column connections, and any fasteners associated with the timber deck – account for up to 39% of total EC of the gravity system with an average much closer to 26% or 3.3 lbs CO_2/ sqft.

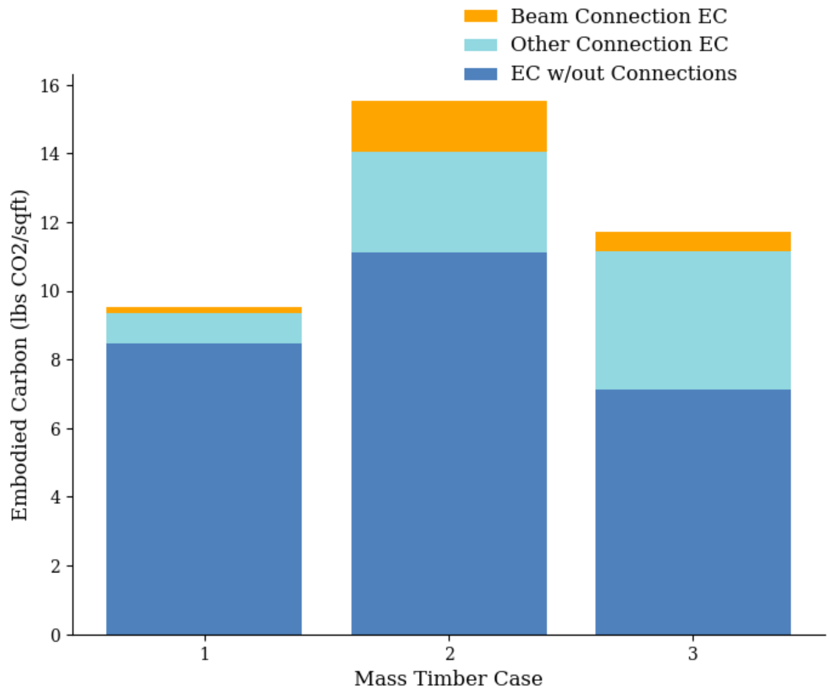


Figure 13: EC Comparison Across Mass Timber Case Studies

Chapter 4

Mass Timber Parametric Study

4.1 Introduction

In this chapter, the methodology involved in developing a mass timber beam to girder connection sizer is detailed using an endless bay configuration. Similarly to what is described in previous chapters, a single interior bay is considered with no openings or edge conditions. To focus on the relationships to EC of connections relative to their gravity system, the bay aspect ratio was limited to 1:1 and 1.3:1. These aspect ratios are selected for analysis because they can develop efficient structural bay systems. This gravity system includes glulam beams and girders, a CLT deck with 1 ½” NWC topping, and pre-engineered concealed beam to girder connections. Column connections and those relating to diaphragm are excluded from this design space due to research constraints and the variability associated with these types of connections. The required fire rating for this system is assumed to be developed through gypsum board encasement of structural beams, although this fire protection mechanism is not considered in the EC accounting.

4.2 Methodology

The beam, girder, and deck data are collected from a parametric model developed in “Parametrically-Informed Early-Design Guidance for Mass Timber Floors for Embodied Carbon and Structural Design” by Samantha Leonard [20]. To analyze trends, 1000 iterations are run to cover the entire design space while recording all relevant data for each iteration. For this study, as seen in Table 7, the variables considered included girder length, girder size, beam length, beam size, and CLT deck depth. The loading is kept constant where SDL is 20 psf and LL is 60 psf and the concrete topping depth is kept constant at 1 ½”.

Table 7: Mass Timber Beam and Girder Sizer Inputs

Inputs	Notes
Girder Length	Units: ft, Range: 10 ft – 40 ft
Beam Length	
Number of Beams	Units: unitless, Range: 2 – 6
Superimposed Deadload (SDL)	Units: psf, Used 20 psf
Live Load	Units: psf, Used 60 psf
Deck Depth	Units: in, Range: 4.14 in – 12.42 in
Concrete Topping Depth	Units: in, Used 1 ½ in
Beam Width	Units: in, Range: 5 1/8 in – 20 in
Beam Depth	Units: in, Range: 11 ¾ in – 56 ¾ in
Girder Width	Units: in, Range: 5 1/8 in – 20 in
Girder Depth	Units: in, Range: 11 ¾ in – 56 ¾ in

As seen in Figure 14, the beam to girder connections include three different types. Each of these connections has several sizes, but from left to right the capacity of each connection type increases. They were selected based on their applicability for mass timber gravity members and use in previous studies.

Figure 14: Lightweight (left), Medium Weight (middle), Heavy Weight (right) [21]

As seen in Table 8, the connection sizer used the beam size, girder size, and bay characteristics developed from the design space generated by the mass timber bay sizer to select the connection with the most efficient capacity compared to the required capacity for a given bay design.

Table 8: Concealed Hanger Connection Sizer

Inputs	Notes
Beam Size	Units: in, Range: 5 1/8” x 11 ¾” – 20” x 56 ¾”
Girder Size	
Girder Length	Units: ft, Range: 10 ft – 40 ft
Beam Length	
Number of Beams	Units: unitless, Range: 2 – 6

This design space is imported to the connection sizer, which is primarily written in Python, as a data frame. This allows the data to be stored while retaining a structure of rows and columns making this data easily callable for further calculations. The characteristics of the connection types, including capacity from a representative manufacturer’s technical design guide, and the ECFs for all required material types, from the ICE Database and EPDs, are also imported into the Python script. As shown in Figure 15, this process for developing the beam to girder connection sizer. Based on the bay dimensions, the shear reaction for the beam to girder connection is calculated, which is compared to all possible connection types and sizes available within the design guide and sized based on the connection's available capacity. The possible connections are sorted from lowest to highest capacity where lightweight connections typically have the lowest capacity and heavy weight connections have the highest capacity. The medium weight connection type can be used in a single or double configuration to add capacity when needed – this is considered in the design space. After connection selection occurs based on capacity, secondary checks are performed to ensure compatibility between the beams and the connection including minimum sizes.

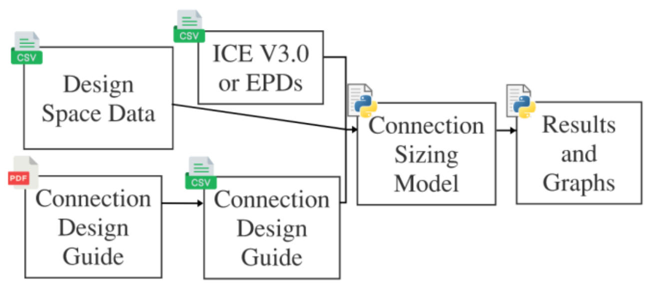


Figure 15: Glulam Beam to Girder Connection Sizer

Figure 16 shows a sample selection of connection sizes and their design capacity that are encoded into the Python script. It also includes the type and quantity of screws required to fasten the connection to both the beam and girder.

Item	Min. Beam Section	Specific Gravity [G]	Fasteners				Allowable Down Load [lbs]
			Primary Member		Secondary Member		
			Type	Qty.	Type	Qty.	
Single RICON S VS 140x60	3-15/16" x 11-5/16"	0.42	VG CSK 5/16" x 3-1/8"	10	VG CSK 5/16" x 6-1/4"	10	2,740
		≥ 0.50					3,780 ESR-4300
Double RICON S VS 140x60	6-11/16" x 11-5/16"	0.42	VG CSK 5/16" x 3-1/8"	20	VG CSK 5/16" x 6-1/4"	20	4,660
		≥ 0.50					6,410

Figure 16: Medium Weight Sample Connection Selection [21]

As seen in Table 9, the EC of all members and connections considered in this research is calculated with the ECFs.

Table 9: ECFs for Mass Timber Bays

ECFs	Notes
ECF of Glulam Beams	Value: 0.25 lb CO_2 / lb, Source: AWC North American Glulam EPD [12]
ECF of CLT deck	Value: 0.27 lb CO_2 / lb, Source: North American CLT Averaged EPD [20]
ECF of NWC	Value: 0.13 lb CO_2 / lb, Source: NRMCA EPD [15]
ECF of lightweight and medium weight connection	Value: 2.76 ICE V3.0 Hot-Dip Galvanized Steel [10]
ECF of heavy weight connection	Value: 3.82 lb CO_2 / lb, Source: Aluminum Association EPD [22]
ECF of Fasteners	Value: 1.27 lb CO_2 / lb, Source: ICE V3.0 Engineering Steel [10]

4.3 Mass Timber Parametric Study Results and Analysis

The design space sampled for the mass timber parametric study provides EC results across various bay geometries with a focus on the EC contributions of beam to girder connections. As can be seen in Figure 17, the selection of beam to girder connection types is reliant on beam length due to its linear relationship to beam loading and support reactions. The lightweight connection is primarily used for smaller bays where the beams are under 20ft in length. The single medium weight connection can be used for these smaller bay layouts, however it is more efficient for bays where the beams range in length between 15ft and 25ft. The double medium weight connection and the heavy weight connection have similar capacities however, the heavy weight connection does have higher capacity sizes for large bays. When the beam length is greater than 40ft, the frequency of double medium weight connections decreases and the heavy weight connections become more efficient.

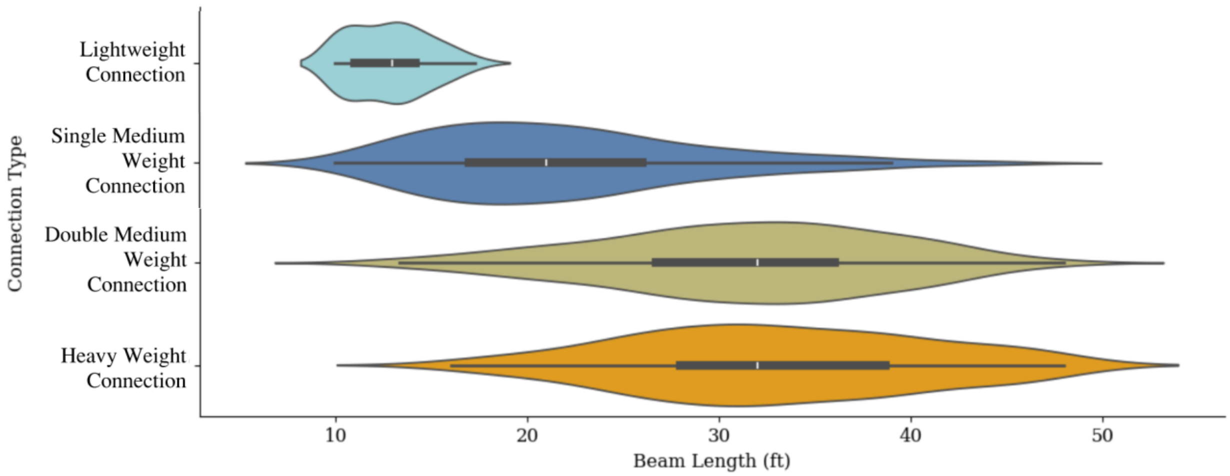


Figure 17: Mass Timber Connection Type Frequency Across Design Space

As seen in Figure 18, the EC of these connections is relatively consistent across the design space except for the heavy weight connections. The heavy weight connections have higher EC because they are manufactured with aluminum whereas the other connection types use steel. The ECF of aluminum is 3.82 lb CO_2 / lb while the ECF of steel is 2.76 lb CO_2 / lb. The production of primary aluminum uses approximately ten times more energy than steel meaning that the energy source in the largest contribution to the ECF [23]. Because the research is focused on cases within the United States, the aluminum ECF from a manufacturer in Virginia. Depending on the country, common energy sources, and the manufacturer, the ECF could vary further.

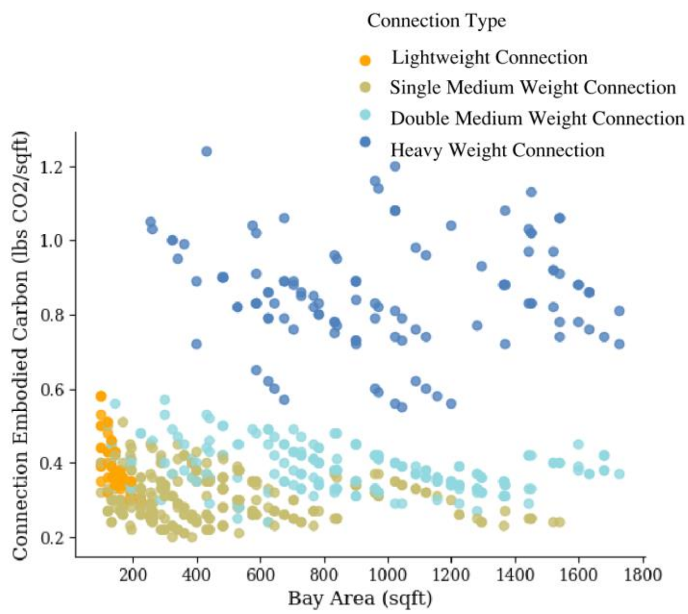


Figure 18: Mass Timber Beam to Girder Connection EC

As seen in Figure 19, the connection EC does not change significantly between the two bay aspect ratios. As beam spacing increases, the connection EC does increase slightly where the lowest EC for a given beam spacing changes from 0.2 lbs CO_2 / sqft to 0.35 lbs CO_2 / sqft.

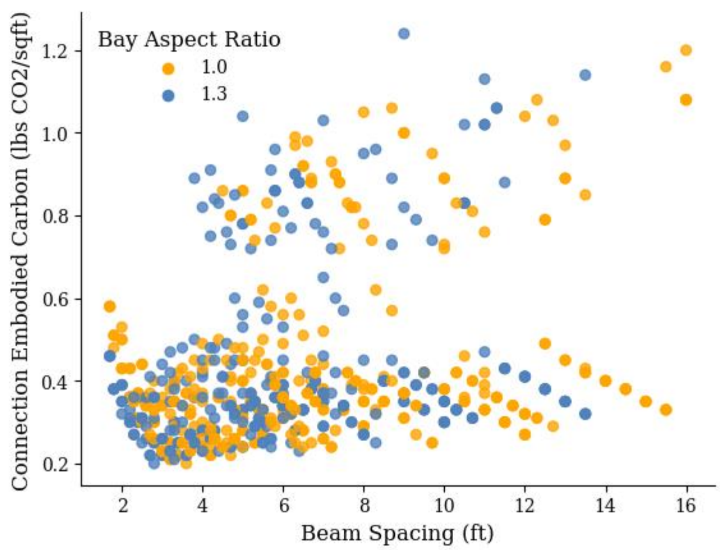


Figure 19: Bay Aspect Ratio Effect on Connection EC

As seen in Figure 20, the total EC per sqft rises significantly and becomes less efficient in terms of material usage when bay sizes are under 200 sqft. Similarly to Figure 19, the EC per sqft increases linearly as bay area increases when bay size is between 600 sqft and 1400 sqft. Beyond 1400 sqft, increasing bay size no longer increases the EC per sqft as significantly, however the size of these bays is less feasible considering the required glulam beam depth that would be required; to achieve a bay size of 1681 sqft, the required girder depth is 52 ¼” and beam depth is 50 ¾”.

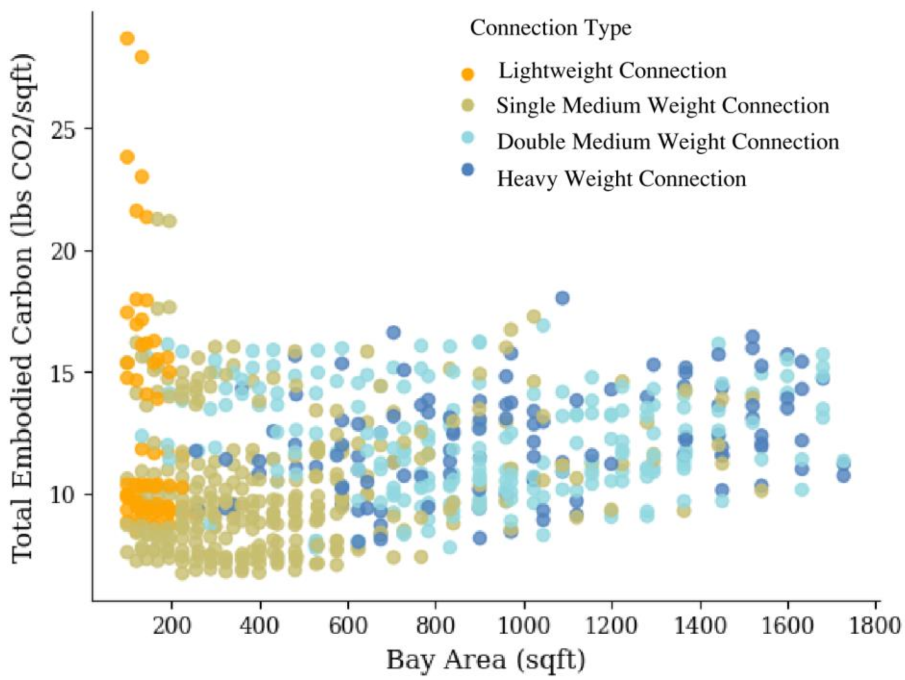


Figure 20: Total EC Across Design Space Bay Areas

Figure 21 provides the averaged embodied carbon of the mass timber gravity system per infill length across the design space. EC contributions are split into EC from beam to girder connections and EC from all other system components included in this analysis: glulam beams and girders, CLT deck, and concrete topping. Across the entire design space, the average connection related EC is 0.43 lbs CO_2 / sqft and the average total EC is 11.8 lbs CO_2 / sqft.

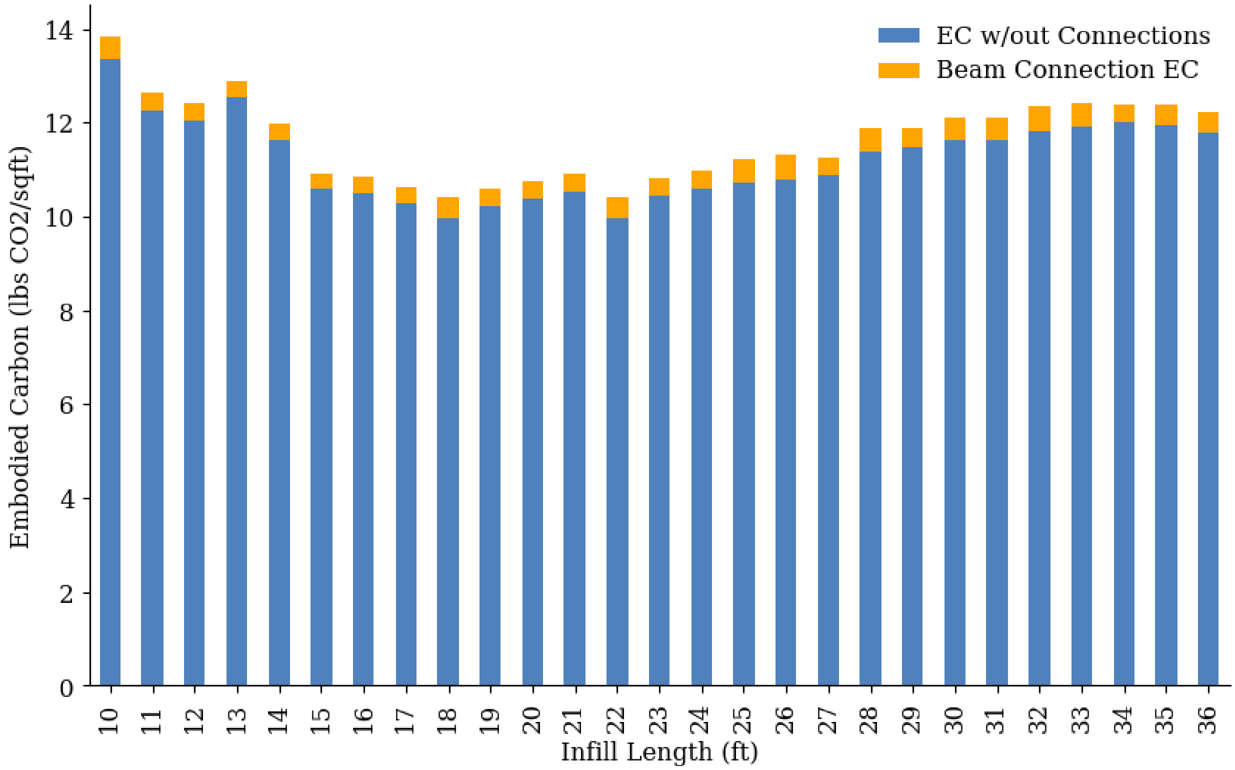


Figure 21: EC Comparison Across Mass Timber Parametric Design Space

Chapter 5

Steel Case Study

5.1 Introduction

In this chapter, three buildings are selected as case studies to review the EC associated with their gravity systems. All of these buildings are grouped based on their materiality – steel gravity systems – however each is selected for its unique subsystem: OWSJ, NC steel W-shapes, and composite steel W-shapes. Figure 22 provides a general overview of the case study analysis methodology.

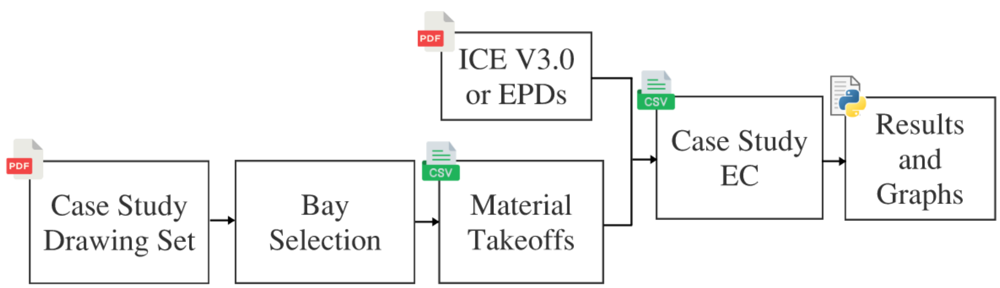


Figure 22: Steel Case Study Analysis Methodology

System selection requires consideration of multiple different factors; however, this study is primarily focused on the EC trends for each system. To allow for the consideration of multiple systems and because this study is focused on decision making in the early design stages, a typical bay for each of these buildings is selected and analyzed rather than conducting a full building EC life cycle analysis. When possible, each selection is an interior bay without openings or shear walls to avoid skewing the results based on façade loading or required framing around openings and shear walls that may force a bay to become more irregular. This provides a more accurate baseline for the steel parametric study following in Chapter 6. Similarly, this study provides a baseline comparison for the mass timber gravity system and its associated connections discussed in Chapters 3 and 4. For each of these case studies, there are some limitations to the EC accounting; because the primary focus of this research is to review the effect of EC related to the gravity system, moment connections are excluded as their purpose lies in resisting lateral forces. Column elements and edge conditions are also not included because the study is limited to a single bay. This includes pour stops for concrete toppings and related elements. The welded wire reinforcement (WWR) chairs are not included because quantities were not well documented in drawing sets. Similarly, most connections are not explicitly designed and detailed meaning the analysis for this study followed the connection types to the degree which was stated in the drawings and designed to completion for material takeoffs.

5.2 Steel Joists and Non-Composite W-Shape Girders

The first case study is a 20,000 sqft childcare center located in the northeastern region of the United States. It is a VB construction type two story building with the primary occupancy classified as Education. The LL is 40 psf with 15 psf partition live load, which is equivalent to the primary loading being analyzed for both of the parametric studies as discussed in Chapter 1. This loading, however, does take live load reduction into consideration when possible. As seen in Figure 23, the building primarily utilizes K series and LH series joists as infills with W-shape beams and hollow structural section (HSS) columns. The roof framing uses a pre-engineered joist product with tubular steel webs and laminated wood chords. There are also limited bays that use W-shapes as infills.

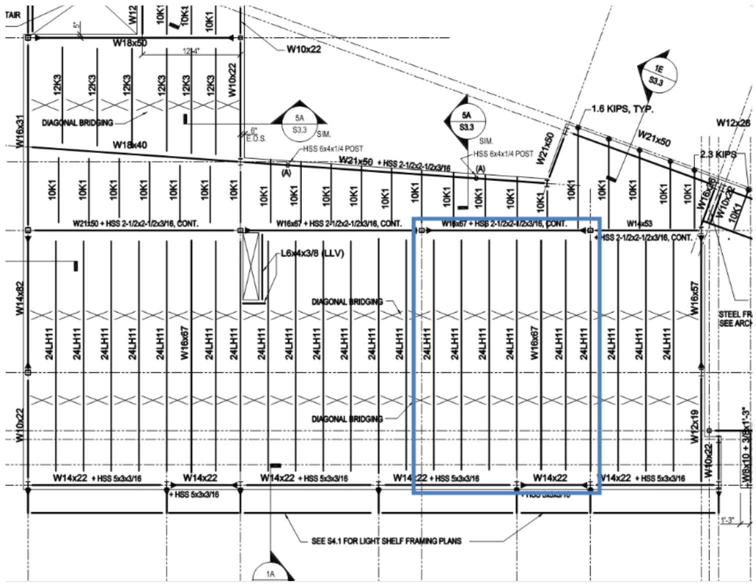


Figure 23: Joist Case Partial Second Floor Framing Plan, with Analyzed Bay

Due to the overall irregular and triangular shape of the building, the largest regular bays were selected as the focus of this case study. With the larger bays, bridging is required for the joists and is included in the total EC calculated. The bridging is not explicitly designed or detailed, therefore the bridging described in 2020 Vulcraft Steel Joist and Joist Girder Systems Manual is used and is assumed to be welded to the joists [24]. While the columns are not included in the analysis, as seen in Figure 24 the HSS columns required different moment connections compared to the W-shape columns. These connections are designed as shear connections for the purpose of this study. Along the W16x67, an additional HSS member is combined for additional stiffness; while this is not typical, it is included in the accounting of EC.

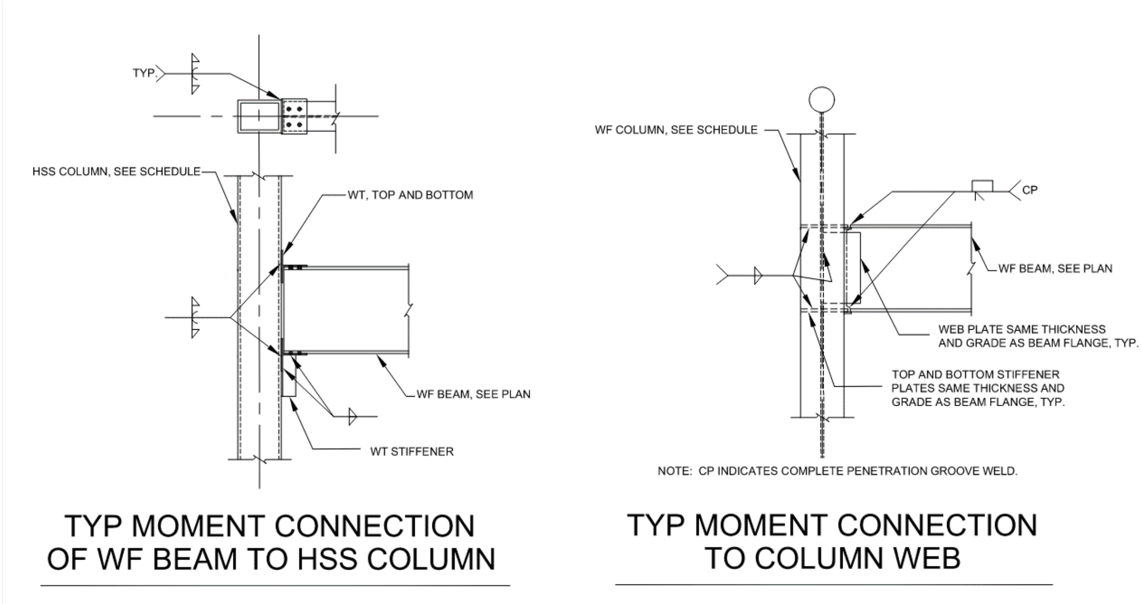


Figure 24: Joist Case Typical Moment Connections

As seen in Figure 25, the joist to girder connections follow industry standards with welding and the column connection uses a bolted welded stiffened seated connection. As described in Chapter 1, EC for all elements in the selected bay are calculated and included in the EC total.

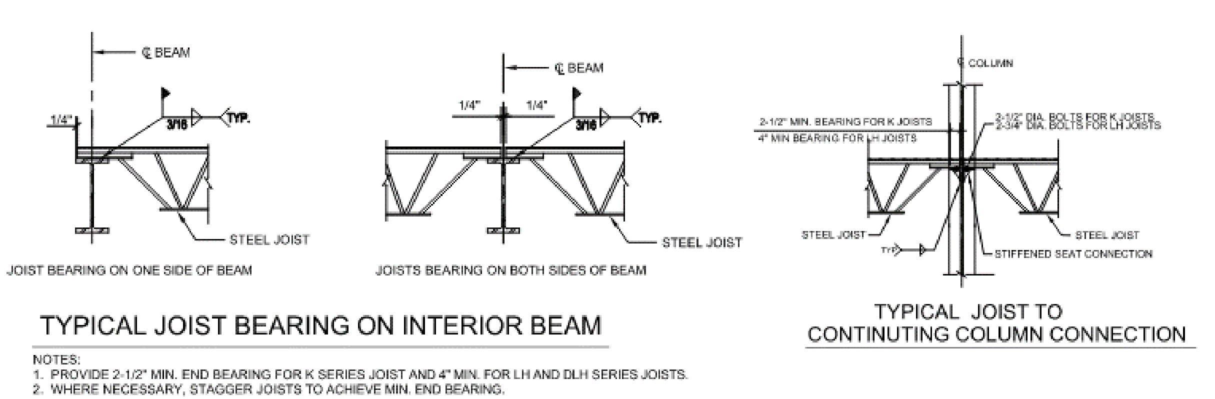


Figure 25: Joist Case Typical Shear Connections

The ECFs used in this analysis are shown in Table 10 where each considered element, the assumed ECF, and the source of the ECF are listed.

Table 10: Joist Case ECFs

Unit	Component	ECF (lbs CO_2 eq / lbs)	Notes
Beam to Girder	2" x 2" x 5/16" x 4 3/4" L	2.28	ICE V3.0 Hot Rolled Coil Steel [10]
Beams and Girders to Column	2" x 2" x 5/16" x 4 3/4" L	2.28	ICE V3.0 Hot Rolled Coil Steel [10]
	2" x 2" x 3/8" x 4 1/2" L		
	3" x 3" x 3/8" x 14 1/2" L		
	1 3/4" x 1 3/4" x 3/8" PL	1.73	AISC Industry-Wide Steel Plate EPD [9]
	2 3/4" DIA Bolts	1.27	ICE V3.0 Engineering Steel [10]
	A325N Bolts		
Beam	24LH11	0.839	Vulcraft Joist EDP [25]
	Horizontal Bridging (1 1/4"x1 1/4"x7/64"x21"L)	2.28	ICE V3.0 Hot Rolled Coil Steel [10]
	Diagonal Bridging (1" x 1" x 7/64" x 3' 8" L)		
Girder	W14x22	1.22	AISC Industry-Wide Steel Section EPD [26]
	W16x67		
	HSS 5x3x3/16	2.39	AISC Industry-Wide HSS EPD [17]
	HSS 2 1/2 x 2 1/2 x 3/16		
Decking	Type C Metal Deck (24 ga.)	1.74	Vulcraft Steel Deck EPD [27]
	4x4 W2.9 x W2.9 WWF	1.45	INSTEEL WWR EDP [28]
	2 1/2" Concrete Toping	0.13	NRMCA EPD [15]

5.3 Steel Non-Composite W-Shape Beams and Girders

This case study features a 90,000 sqft office building located in the Northeastern region of the United States. It is a type IIB four story building with the primary occupancy classified as Business. The LL is 50 psf with 15 psf partition live load, and these loads may use LL reduction, similarly to the joist case study. Further, the office LL is not significantly higher than the residential LL discussed in Chapter 1. The project uses a NC steel system on all floors with the fourth floor being renovated to become a composite system and adding several openings throughout all floors. The columns use W-shapes with moment connections in the strong axis of the column; similarly to the joist case, only the shear connection is included for this study. The infill beams are consistently W16x31s across floors one through three including the selected bay used for analysis on the first floor, as seen in Figure 26. The girder sizes are less consistent but vary between W21s and W24s.

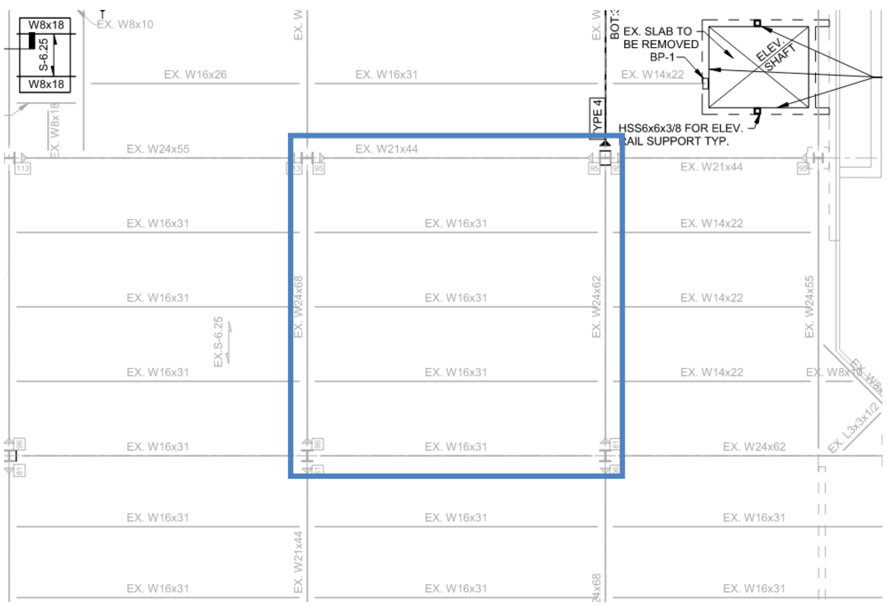


Figure 26: NC Case Partial First Floor Framing Plan, with Analyzed Bay

The moment connections, Figure 27, use bolted plate connections with stiffener plates along the web of the column. Shear connections are not detailed, but the general notes reference AISC Steel Construction Manual Chapter 10, Tables 10-1 to 10-3, which provide capacities of bolted-bolted double angle connections [29]. Additionally, when reactions are not called out in drawings as with most of the beams in the selected bay, the loading is determined using the DL and LL previously described. While A325N or A490N are allowed, the typical bolts used in some of the connection details are A325N and therefore is the bolt type assumed for shear connections. Shear beam to column connections are assumed as single angle connections when the beam is connecting to the column web to allow for beam connections on both sides of the web.

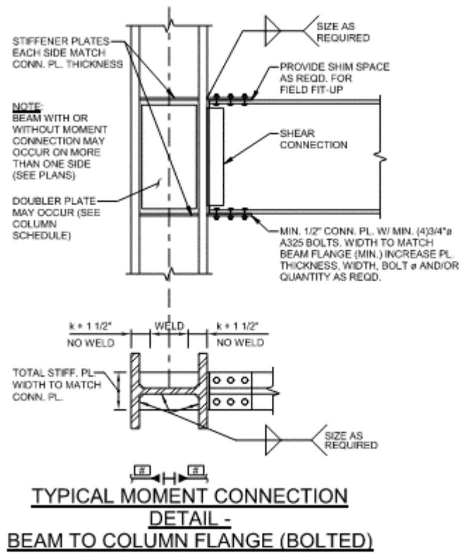


Figure 27: NC Case Typical Moment Connections

The ECFs used in this analysis are shown in Table 11 where each considered element, the assumed ECF, and the source of the ECF are listed.

Table 11: NC Case ECFs

Unit	Component	ECF (lbs CO_2 eq / lbs)	Notes
Beam to girder	3 1/2" x 3 1/2" x 5/16" x 8 1/2" L	2.28	ICE V3.0 Hot Rolled Coil Steel [10]
	A325N Bolts	1.27	ICE V3.0 Engineering Steel [10]
Beams and Girders to Column	3 1/2" x 3 1/2" x 5/16" x 11 1/2" L	2.28	ICE V3.0 Hot Rolled Coil Steel [10]
	3" x 3" x 3/8" x 8 1/2" L		
	3" x 3" x 3/8" x 11 1/2" L		
	A325N Bolts	1.27	ICE V3.0 Engineering Steel [10]
Beam	W16X31	1.22	AISC Industry-Wide Steel Section EPD [26]
	W21X44		
Girder	W24X68		
Decking	S-6.25 Deck (20 ga.)	1.74	Vulcraft Steel Deck EPD [27]
	6x6 W2.9 x W2.9 WWF	1.45	INSTEEL WWR EDP [28]
	4 1/4" Concrete Toping	0.13	NRMCA EPD [15]

5.4 Steel Composite W-Shape Beams and Girders

This case study is a 170,000 sqft medical center in the Midwestern region of the United States. It is a type IB six-story building with a primary Business occupancy classification for the analyzed bay. The LL is 80 psf which includes a 15 psf partition load and is based on hospital corridors above this first floor. This loading is higher than that used in both the parametric steel design chapter as well as the mass timber chapters, however this building has very regular bays, providing an acceptable baseline for the EC of composite gravity systems. The building is split into two areas and area B is more consistent with member sizes and has fewer openings and other irregularities, therefore the analyzed bay is selected from area B. As seen in Figure 28, the typical beam sizes in this area are W18x40s and the girders are W24x68s.

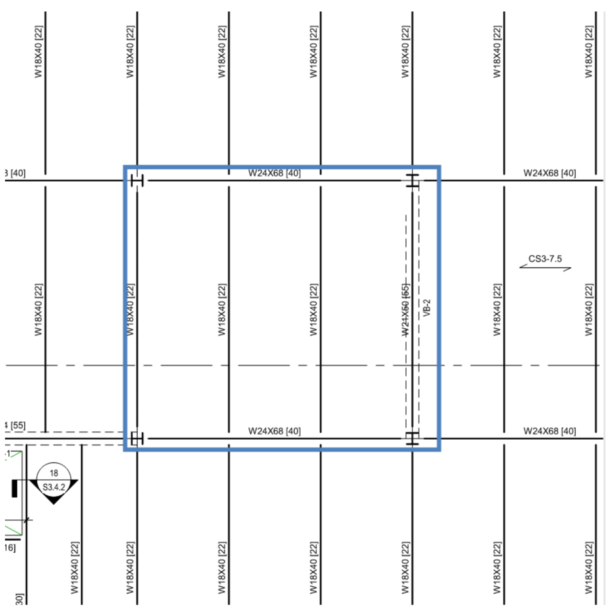


Figure 28: Composite Case Partial Second Floor Framing Plan, with Analyzed Bay

As seen in Figure 29, typical shear connections at columns are double angle connections at column flanges and single angle connections are used at the column web. These details provide the option for welded or bolted, but bolts are used for consistency with the NC case study.

Because these details are not fully detailed, however reactions of 83 k are given in the drawings for W18x40s and 150k for W24x68s. In the general structural notes, beam to girder shear connections are called out to be either single plate or double angle connections; to keep the connection type as uniform as possible, double angle connections are assumed.

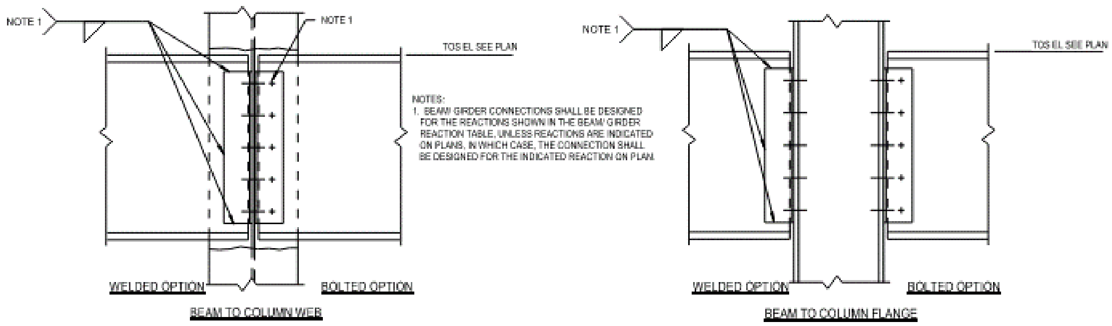


Figure 29: Composite Case Typical Beam to Column Connections

The ECFs used in this analysis are shown in Table 12 where each considered element, the assumed ECF, and the source of the ECF are listed.

Table 12: Composite Case ECFs

Unit	Component	ECF (lbs CO_2 eq / lbs)	Notes
Beam to girder	3 1/2" x 3 1/2" x 5/16" x 8 1/2" L	2.28	ICE V3.0 Hot Rolled Coil Steel [10]
	A325N Bolts	1.27	ICE V3.0 Engineering Steel [10]
Beams and Girders to Column	3 1/2" x 3 1/2" x 5/16" x 8 1/2" L	2.28	ICE V3.0 Hot Rolled Coil Steel [10]
	3 1/2" x 3 1/2" x 5/16" x 14 1/2" L		
	3" x 3" x 3/8" x 14 1/2" L		
	6" x 3 1/2" x 3/8" x 14 1/2" L		
	A325N Bolts	1.27	ICE V3.0 Engineering Steel [10]
Beam	W18X40 [22]	1.22	AISC Industry-Wide Steel Section EPD [26]
Girder	W24X68 [40]		
Decking	CS3-7.5 Deck (18 ga.)	1.74	Vulcraft Steel Deck EPD [27]
	6x6 W2.9 x W2.9 WWF	1.45	INSTEEL WWR EPD [28]
	4 1/2" Concrete Toping	0.13	NRMCA EPD [15]
	3/4" x 6 1/2" Shear Studs	2.73	ICE V3.0 Finished Cold-Rolled Coil Steel [10]

5.5 Steel Case Study Results and Analysis

Through these three case studies, trends relating to the EC of the different steel gravity systems and their related connections can be seen. The primary sources of EC are the joists or beams, concrete topping, girders, and steel deck. As can be seen in Table 13, the OWSJ case has the smallest total EC followed by the NC case. The EC contributed by joists and girders in the OWSJ case is 13.5 lbs CO_2/ sqft compared to 16.5 lbs CO_2 / sqft for the NC case and 16.3 lbs CO_2 / sqft for the composite case. Per linear foot, OWSJs are both lighter and have a lower ECF than W-shapes allowing for a decreased EC for the overall bay. The OWSJ case also only uses a 2 ½” concrete topping while the NC case uses 4 ¼” and the composite case uses 4 ½”. The difference in EC from the steel deck is less significant across all cases, however the deck depth and thickness does increase from 1” and 24 ga. for the OWSJ case to 2” and 20 ga. for the NC case to 3” and 18 ga. for the composite case. All of these factors contribute to the trend in total EC seen across these three cases.

Table 13: Steel Case Study Results

Results	OWSJ Case	NC Case	Composite Case
Bay Area (sqft)	679.4	784.0	960.0
Aspect Ratio (unitless)	1.5	1.0	0.9
Total EC (lbs CO_2)	12693.9	20710.4	26236.8
Total Connection EC (lbs CO_2)	193.5	478.8	928.7
Beam to Girder Connection EC (lbs CO_2)	77.9	214.5	143.0
Total EC (lbs CO_2/sqft)	18.7	26.4	27.3
Total Connection EC (lbs CO_2/sqft)	0.3	0.6	1.0
Beam to Girder Connection EC (lbs CO_2/sqft)	0.1	0.3	0.1
Total EC (%)	100.0	100.0	100.0
Total Connection EC (%)	1.5	2.3	3.5
Beam to Girder Connection EC (%)	0.6	1.0	0.5

In comparing the EC of the connections across all three of these cases, total connection EC contributes less than 4% of all gravity system components analyzed. Similarly to the trend with total EC, the OWSJ case has the lowest connection EC, 0.3 lbs CO_2/ sqft. The composite case has the highest EC related to connections and is largely due to the shear studs between the beams, girders, and deck being included; these account for 40% of the connection related EC. As can be seen in Figure 30, the connections do not account for a significant portion of the EC of steel gravity systems. OWSJs overall tend to produce less EC while NC and composite steel systems produce similar EC values.

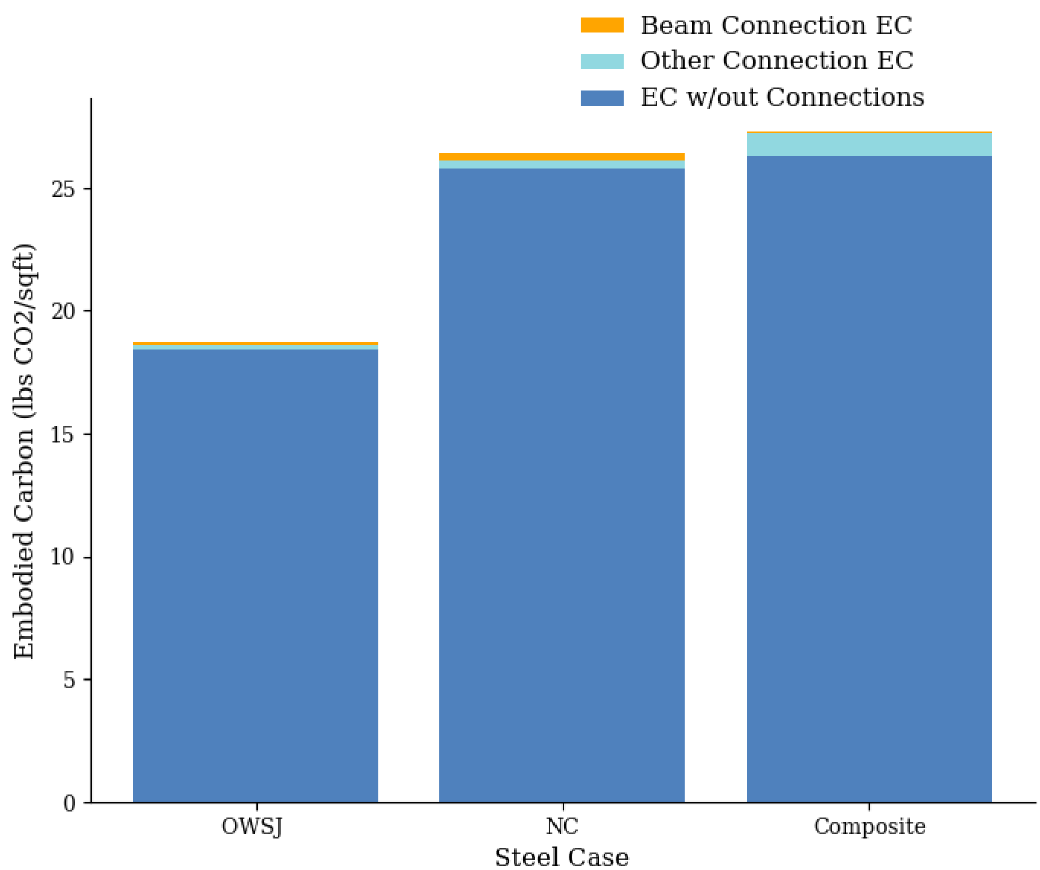


Figure 30: EC Comparison Across Steel Case Studies

Chapter 6

Steel Parametric Study

6.1 Introduction

In this chapter, parametric models have been developed for both OWSJ and NC steel systems using an endless bay configuration where one bay is analyzed and is assumed to be an interior bay. Although composite steel case studies were analyzed in Chapter 5, they were not included in the parametric model due to scope constraints. The composite system should have similar trends to the results from the NC system due to their similarities. The parametric study includes an accounting of the EC from all beams, joists, girders, and the beam or joist to girder connections. It does not explore the EC attributed to columns and any connections associated with columns. This is primarily to perform a more equally comparative study to the mass timber connection analysis to be discussed in Chapters 3 and 4. Column connections are significantly less standardized for mass timber buildings where glulam beams and columns are used – most designers provide custom connection details for each project – and it is therefore difficult to provide meaningful EC trends at early design stages, for additional information refer to Chapter 3.

The process used for both systems includes modelling a bay with a floor deck, infill beams, and girders, using line elements. Then, as seen in Figure 31, based on the geometry, the infills and girders are sized. The deck is held constant using 1.5 VLI-36 composite steel deck with 4 ½” NWC topping selected from Vulcraft’s Steel Deck Catalog where the gage of the metal deck changes to accommodate different span capacities. This deck was selected because it is an economical selection and has a 2-hr fire rating assuming unprotected deck. The geometry, member sizes, and uniform bay loading all become inputs to size the connections. After the bay has been designed, the EC is calculated for each element. To analyze trends, 1000 iterations are run to cover the entire design space while recording all relevant data for each iteration. To focus on the relationships to EC of connections relative to their gravity system, the bay aspect ratio was limited to 1:1 and 1.3:1. These aspect ratios are selected for analysis because they can develop efficient structural bay systems. This entire process is completed in GH with Python plugins to produce the sizer components and EC calculator.

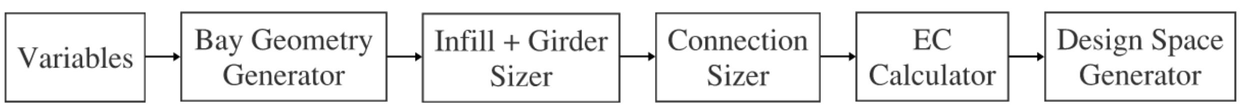


Figure 31: General Process of Steel Parametric Study

6.2 Open Web Steel Joists and Non-Composite W-Shape Girders

As seen in Table 14, The OWSJ were sized according to the 2020 Vulcraft Steel Joist and Joist Girder Systems Manual with the input variables [30]. Per Ruddy 1983, the aspect ratio that allowed for the lowest material weight, a factor that linearly relates to EC, was 1:1; based on this study and to provide more consistency across the design space, the girder length became a function of joist length to maintain the same 1:1 aspect ratio [31]. The SDL and LL were also kept constant at 20 psf and 60 psf respectively to meet the residential loading discussed in Chapter 1. The gage of the 1.5 VLI-36 deck was kept constant at 22 ga. to focus on the relationship between EC and other bay properties; the primary focus of this research is not to review how deck design impacts EC. While it was made possible to limit girder member depth, it was not necessary when sampling the design space.

Table 14: Joist and Girder Sizer Inputs

Variables	Notes
Girder Length	Units: ft, Range: 10 ft – 36 ft
Joist Length	
Number of Joists	Units: unitless, Range: 2 – 8
SDL	Units: psf, Range: 20 psf
LL	Units: psf, Range: 60 psf
Deck Type	Units: psf, Range: 62.4 psf, steel deck and NWC weight
Girder Min Depth	Units: unitless, Range: W4 – W44
Girder Max Depth	

The member sizing process started with calculating the loads applied to the joists at both strength and serviceability levels. Based on the length of the required joist, the list of possible joists is sorted and then strength and serviceability checks are performed. From the Vulcraft Manual, as seen in Figure 32, this table was imported into a Python script where once the joist length is defined, there is a list of possible solutions with their properties in respective lists. Each of these lists are checked against the calculated ultimate load.

JOIST DESIG.	TOTAL LOAD (ASD)	LOAD for L/360 DEFL.	TOTAL LOAD (LRFD)	JOIST WEIGHT (lbs/ft)	MAX CHORD WIDTH (IN)	BRIDG. (H/X/EX)
19' LENGTH (continued)						
16K5	550	455	825	7.7	5	1/0/0
18LH02	748	748	1122	9.7	5	1/0/0
18LH03	833	833	1250	10.5	5	1/0/0
18LH05	1093	1093	1640	12.9	5	1/0/0
18LH06	1329	1329	1994	15.2	6	1/0/0
18LH07	1414	1414	2121	16.3	6	1/0/0
18LH08	1598	1500	2397	18.1	6	1/0/0
18LH09	1831	1601	2747	20.1	7	1/0/0
18LH10	2054	2054	3081	21.9	7	1/0/0
18LH11	2291	2291	3437	26	7	1/0/0
18LH12	2533	2533	3800	28.5	8	1/0/0

Figure 32: Sample Joist Selection Table [24]

As shown in Figure 33, the checks include LL and DL deflection, flexure, and shear starting with the most economical member and increasing until the member meets all required checks. All joists in a single bay are designed to be identical.

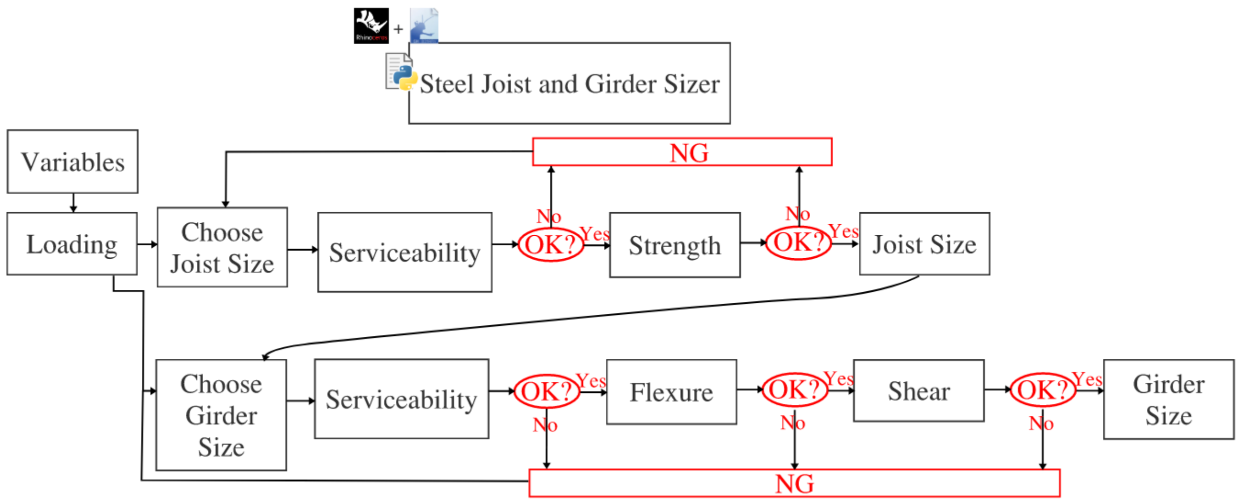
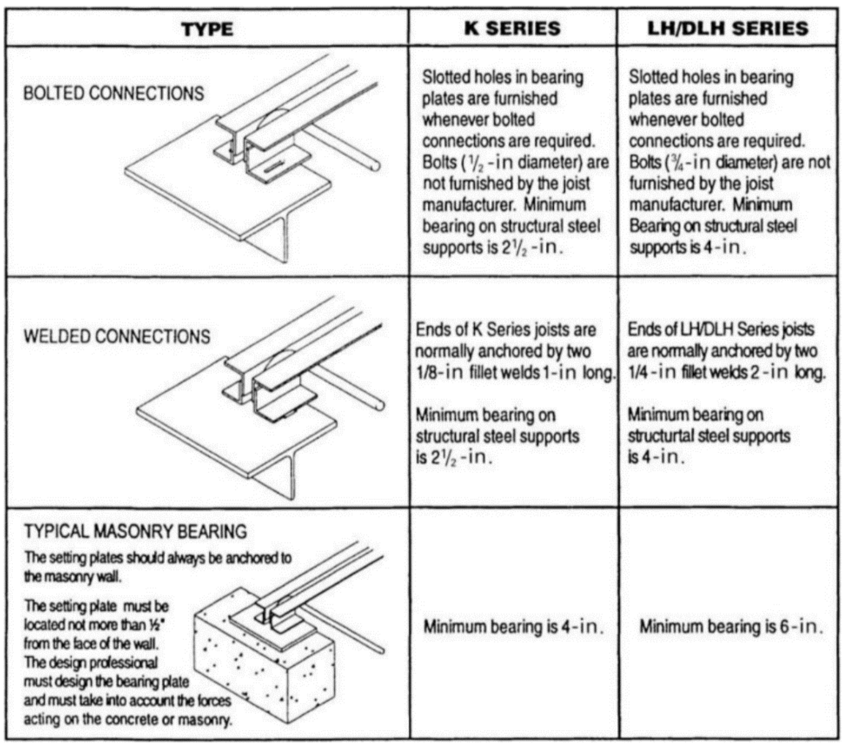


Figure 33: Joist and Girder Sizer

A W-shape girder is then designed in a similar manner with point loads calculated at each joist location and an assumed self-weight of 5plf is applied as a uniform linear load to start the sizing process. A list of all possible W-shapes is sorted based on member weight, then strength and serviceability checks are performed. If a member fails any of these checks, the member is upsized, and checks will start over. Once a member meets all checks with the assumed self-weight, they will be rechecked with the actual self-weight. If the member passes all checks, then the beam sizer ends and provides outputs for designing the connection and calculating EC of the bay. If there are any errors of the code to size either the joist or girder, member size outputs will remain empty or at minimum, a failure output will be present. The most common cause of a failure within the design space is if the joist spacing has exceeded the deck span, but other failure types are possible. The total failure rate is ~10% of iterations.

Once a joist has been sized, this information can be used to help design the related connections. As a reference point, the Handbook of Structural Steel Connection Design and Details provides some typical shear connection details for joist to W-shape girder connections while also referencing the Steel Joist Institute (SJI) for minimum design dimensions as can be seen in Figure 34 [32]. The handbook presents typical bolted and welded connections, however welded connections are used for this design tool as they are more common practice in industry. Table 5.4-1 and Table 5.7-1 from SJI was also referenced for more specific minimum weld thicknesses and bearing lengths [24].



TYPE	K SERIES	LH/DLH SERIES
BOLTED CONNECTIONS	Slotted holes in bearing plates are furnished whenever bolted connections are required. Bolts ($1/2$-in diameter) are not furnished by the joist manufacturer. Minimum bearing on structural steel supports is $2\,1/2$-in.	Slotted holes in bearing plates are furnished whenever bolted connections are required. Bolts ($3/4$-in diameter) are not furnished by the joist manufacturer. Minimum Bearing on structural steel supports is 4-in.
WELDED CONNECTIONS	Ends of K Series joists are normally anchored by two 1/8-in fillet welds 1-in long. Minimum bearing on structural steel supports is $2\,1/2$-in.	Ends of LH/DLH Series joists are normally anchored by two 1/4-in fillet welds 2-in long. Minimum bearing on structurtal steel supports is 4-in.
TYPICAL MASONRY BEARING The setting plates should always be anchored to the masonry wall. The setting plate must be located not more than ½" from the face of the wall. The design professional must design the bearing plate and must take into account the forces acting on the concrete or masonry.	Minimum bearing is 4-in.	Minimum bearing is 6-in.

Figure 34: Joist Bearing Details [32]

Similarly to the joist and beam sizer, the joist to girder connection sizer has several inputs as can be seen in Table 15. To start the sizing process, the minimum weld thickness and length of the angle (using the minimum bearing length) is determined using the joist size. Per AISC Steel Construction Manual Specification Section J2.2b, the minimum angle thickness is equal to the weld thickness plus 1/16”[29]. Based on these preliminary dimensions, the angle is checked for shear yielding and shear rupture limit states. The girder flange thickness is expected to be larger than angle thickness and therefore does not control. Because this study focuses on EC from stages A1-A3, the EC associated with wielding is not included and therefore not designed. If an increase to the weld length was needed to reach the required capacity, the increase would be possible without changing the dimensions of the angle due to the minimum weld lengths falling below the total length of the angle. Additionally, early studies indicate that weld limit states are not likely to control. After limit states are checked, the connection sizer provides outputs to be used in the EC calculator.

Table 15: Joist to W-Shape Connection Sizer Inputs

Inputs	Notes
Joist Size	Units: unitless, Range: 10K1 – 28LH19
Girder Size	Units: unitless, Range: W4X13 – W44X408
Connection Load	Units: K, Range: 8 K – 40 K

The EC calculator uses inputs from the joist and girder sizer, the connection sizer, and ECF factors for all material types, shown in Table 16. EC is primarily calculated by multiplying the ECF by the weight of the material. When weight is not available, the volume of the material is multiplied by density and EFC. Total EC per square foot of the bay is calculated excluding EC contributions from beam to column connections and columns. EC of the connections is also calculated and includes the material required for the angle.

Table 16: EC Calculator Inputs for Joist Bays

Inputs	Notes
Joist Weight	Units: plf, Range: 5.1 plf – 62.9 plf
Joist Length	Units: ft, Range: 10 ft – 36 ft
Number of Joists	Units: unitless, Range: 2 – 8
Girder Weight	Units: plf, Range: 13 plf – 408 plf
Girder Length	Units: ft, Range: 10 ft – 36 ft
Angle Leg Length	Units: in, Using 2 in
Angle Length	Units: in, Range: 2.5 in – 7.25 in
Angle Thickness	Units: in, Range: 3/16 in – 5/16 in
Total Deck Weight	Units: psf, Range: 62.4 psf, steel deck and NWC weight
ECF of Concrete	Value: 0.13 lb CO_2 / lb, Source: NRMCA EPD [15]
ECF of Steel Deck	Value: 1.74 lb CO_2 / lb, Source: Vulcraft Steel Deck EPD [27]
ECF of W-shape	Value: 1.22 lb CO_2 / lb, Source: AISC Industry-Wide Steel Section EPD [26]
ECF of Angle	Value: 2.28 lb CO_2 / lb, Source: ICE V3.0 Hot Rolled Coil Steel [10]
ECF of Joist	Value: 0.839 lb CO_2 / lb, Source: Vulcraft Joist EPD [25]

6.3 Steel Non-Composite W-Shape Beams and Girders

The NC bay was parametrically designed similarly to the OWSJ bay. The beam and girder sizer begins the automated design process with the variables discussed in Table 17. The SDL and LL were kept the same for residential loading. The gage of the 1.5 VLI-36 deck was kept constant at 20 ga.; this is slightly thicker than the 22 ga. selected for the joist system, allowing for greater infill spacing. This is more efficient for W-shape members as compared to OWSJs. The range for beam length is slightly larger and the minimum girder depth is set to be one size larger than the designed beam depth.

Table 17: NC Beam and Girder Sizer Inputs

Inputs	Notes
Girder Length	Units: ft, Range: 10 ft – 40 ft
Beam Length	
Number of Beams	Units: unitless, Range: 2 – 8
Superimposed Deadload (SDL)	Units: psf, Using 20 psf
Live Load	Units: psf, Using 60 psf
Deck Type	Units: psf, Using 62.8 psf, steel deck and NWC weight
Beam Min Depth	Units: unitless, Range: W4 – W44
Beam Max Depth	
Girder Min Depth	Units: unitless, Range: W4 – W44, one size larger than beam
Girder Max Depth	Units: unitless, Range: W4 – W44

As can be seen in Figure 35, the general sizing process in the Python module to size beams and girders is similar to the overall process for selecting girders previously discussed. All design checks were performed in accordance with AISC's 15th ed. Steel Construction Manual and unlike the Vulcraft design guide where ultimate loads are compared to allowable loads in tables, the allowable shear and moment capacities are calculated using equations for limit states in the specifications section rather than importing the existing tables that have been developed through the rest of the manual into readable data frames in Python.

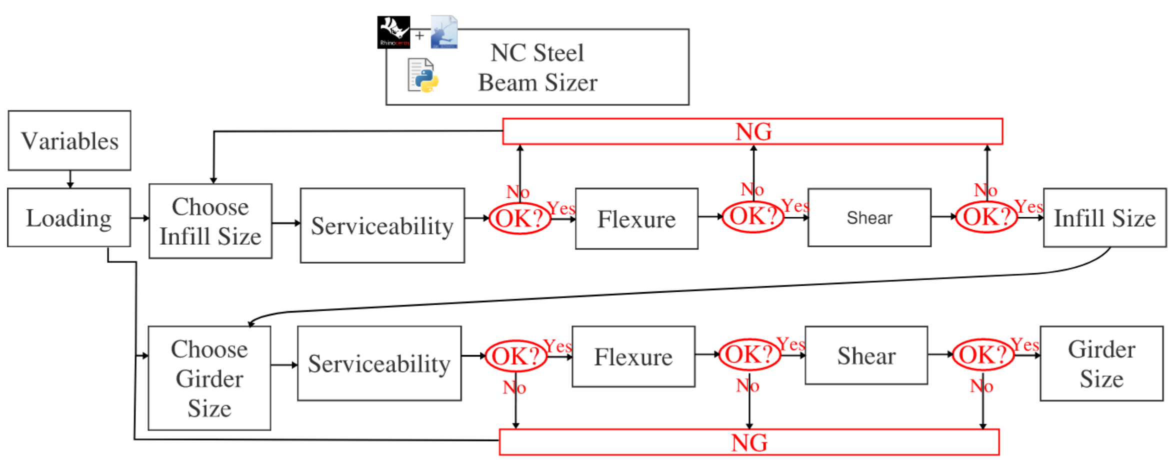


Figure 35: Beam and Girder Sizer Process

After both the beam and girder designs are completed, those member sizes and the ultimate shear force become input for the double angle connection sizer, see Table 18. Double angle connections were selected because both the NC and composite case studies called out double angle connections. This allows for a more equal comparison between the case studies and the parametric study.

Table 18: Double Angle Connection Sizer Inputs

Inputs	Notes
Infill Size	Units: unitless, Range: W4X13 – W44X408
Girder Size	
Shear reaction	Units: kips, Range: 10 k – 100 k

There are some dimensions and overall properties of the connection that are constant throughout the entire design space. While they could fluctuate in order to accommodate large shear reactions, increasing the number of bolts is the primary response to failing any design checks. Figure 36 shows the base design before the number of bolts is calculated and all design checks are completed. These base dimensions were chosen because they are standard values in the AISC's Steel Construction Manual for double angle connections [29].

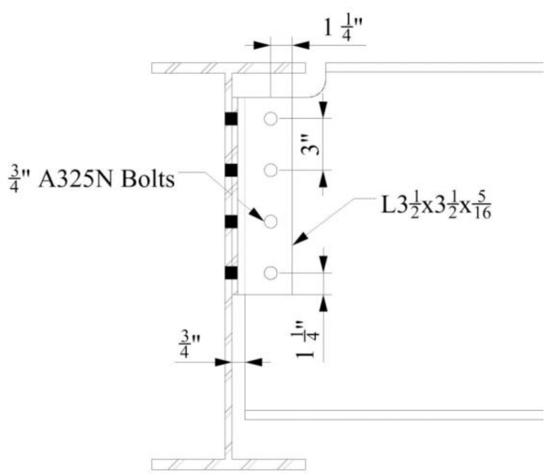


Figure 36: Double Angle Base Constraints

The only aspect of this base design that could change is the location of the angle relative to the beam. As seen in Figure 37, the primary reason for changing the angle location would be if the coped beam fails due to block shear, but passes all other checks; in this case, changing the angle location allows the number of bolts to remain the same, and no additional material is required to reach the ultimate capacity.

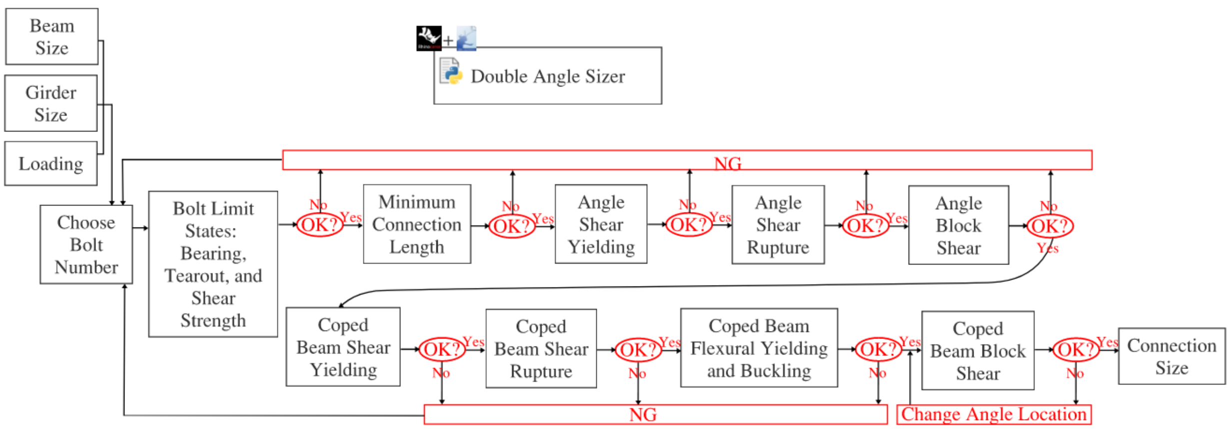


Figure 37: Double Angle Connection Sizer Process

The cope of the beam is determined based on the dimensions of the girder. In the horizontal direction, the cope is equal to half the length of the flange without the thickness of the web and then this value is rounded up to the nearest ½”. The cope in the vertical direction is equal to K_{des} rounded to the nearest whole number with a minimum value of 2”. Once the connection design is complete, the inputs shown in Table 19 are applied to the EC calculator to determine the total EC and EC due to the beam to girder connections.

Table 19: EC Calculator Inputs for NC Bays

Inputs	Notes
Beam Weight	Units: plf, Range: 13 plf – 408 plf
Beam Length	Units: ft, Range: 10 ft – 40 ft
Number of Beams	Units: unitless, Range: 2 – 8
Girder Weight	Units: plf, Range: 13 plf – 408 plf

Girder Length	Units: ft, Range: 8 ft – 32 ft
Angle Leg Length	Units: in, Using 3 ½ in
Angle Length	Units: in, Range: 5 ½ in – 11 ½ in
Angle Thickness	Units: in, Using 5/16 in
Bolt Number	Units: unitless, Range: 2 – 4
Total Deck Weight	Units: psf, Using Range: 62.4 psf – 64.1 psf, steel deck and NWC weight
ECF of Concrete	Value: 0.13 lb CO_2 / lb, Source: NRMCA EPD [15]
ECF of Steel Deck	Value: 1.74 lb CO_2 / lb, Source: Vulcraft Steel Deck EPD [27]
ECF of W-shape	Value: 1.22 lb CO_2 / lb, Source: AISC Industry-Wide Steel Section EPD [26]
ECF of Angle	Value: 2.28 lb CO_2 / lb, Source: ICE V3.0 Hot Rolled Coil Steel [10]
ECF of Bolt	Value: 1.27 lb CO_2 / lb, Source: ICE V3.0 Engineering Steel [10]

6.4 Steel Parametric Study Results and Analysis

In the following section, the design spaces for both the OWSJ and NC gravity systems are analyzed. Both systems show similar trends across their respective design spaces at different scales. The OWSJ gravity system has lower overall EC compared to the NC system.

As seen in both Figure 38 and Figure 39, bay aspect ratio, 1.0 and 1.33, does not significantly affect the EC of either system. These figures also show that as joist or beam spacing increases, the connection EC per square foot decreases until the spacing reaches 3’; when beam or joist spacing is greater than 3’, the EC contribution from the beam to girder connections remains more constant.

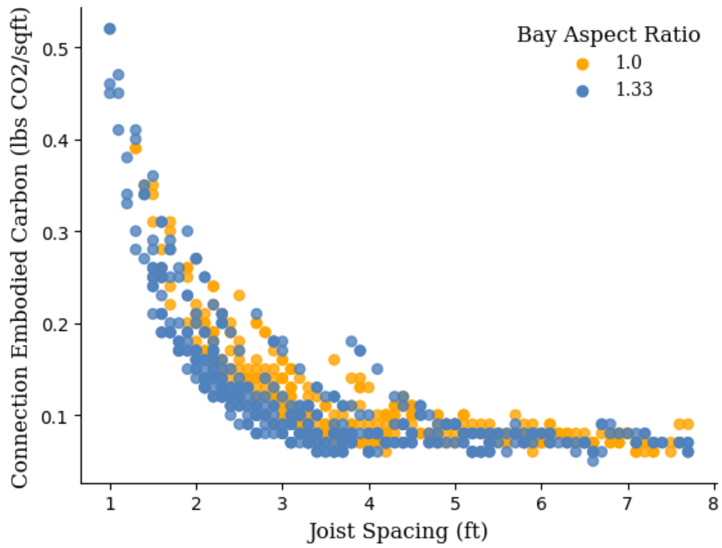


Figure 38: Bay Aspect Ratio Effect on Connection EC for OWSJ System

The connection EC is much higher for the NC gravity system, 1.15 lbs CO_2 / sqft on average, compared to the OWSJ gravity system, 0.12 lbs CO_2 / sqft on average. The OWSJ connections contribute significantly less EC because they are simpler and require less steel overall. The joist connections include smaller shorter welded angles compared to the double angle bolted-bolted connection that the NC system uses.

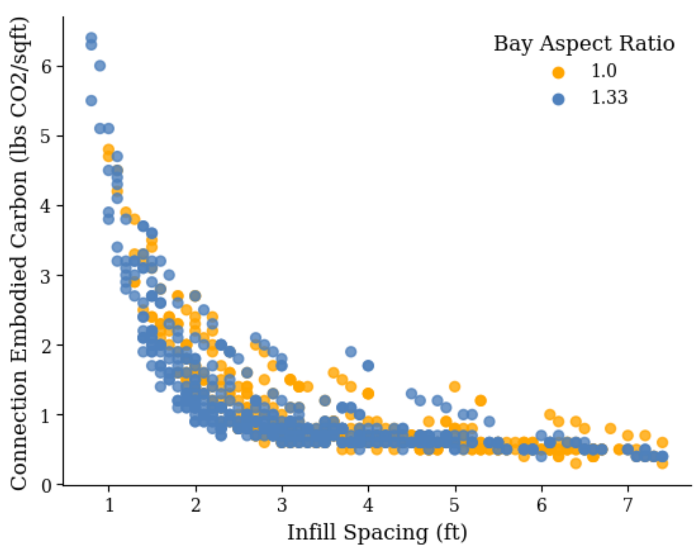


Figure 39: Bay Aspect Ratio Effect on Connection EC for NC System

Figure 40 and Figure 41 show the linear relationship between bay size and total EC: as bay size increases, the total EC also increases. The EC of the connections is most relevant when bay sizes are small less than 400 sqft; this is particularly relevant for the NC system where in some iterations when bay area is less than 200 sqft, the beam to girder connections account for 16% of the analyzed gravity system components.

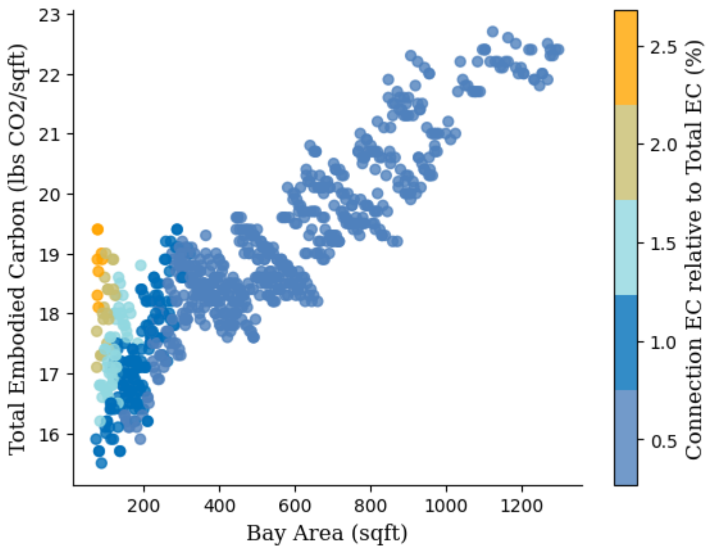


Figure 40: Total EC Across OWSJ Design Space Bay Areas

Most typical interior bays are closer to 1000 sqft and at this size [31], the percent contribution of the beam to girder connections to the total EC is relatively low. For the OWSJ system, the joist to girder connections contributed less than 0.75% to the total EC for 72% of iterations. For the NC system, the beam to girder connections contributed less than 3% to the total EC for 51% of iterations.

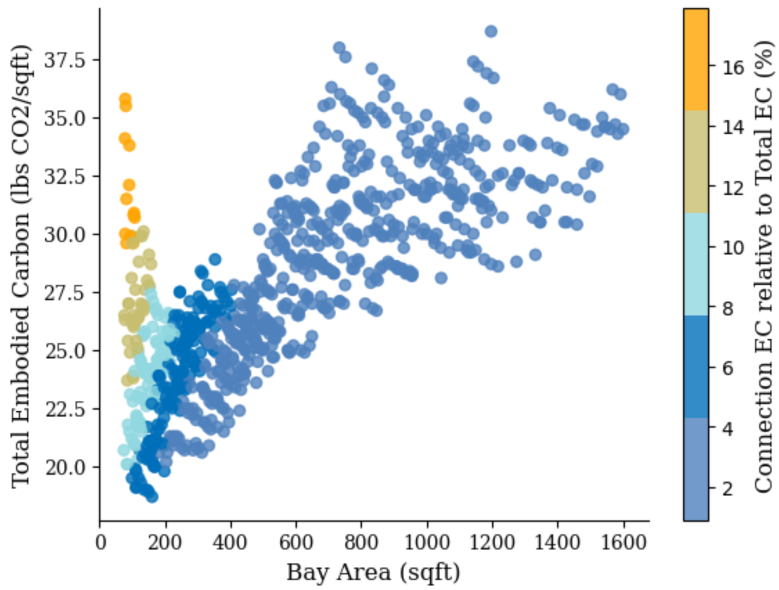


Figure 41: Total EC Across NC Design Space Bay Areas

As seen in Figure 42, the EC contributions from beam to girder connections for OWSJ systems are low compared to the contributions associated with the joists, girders, deck, and concrete topping.

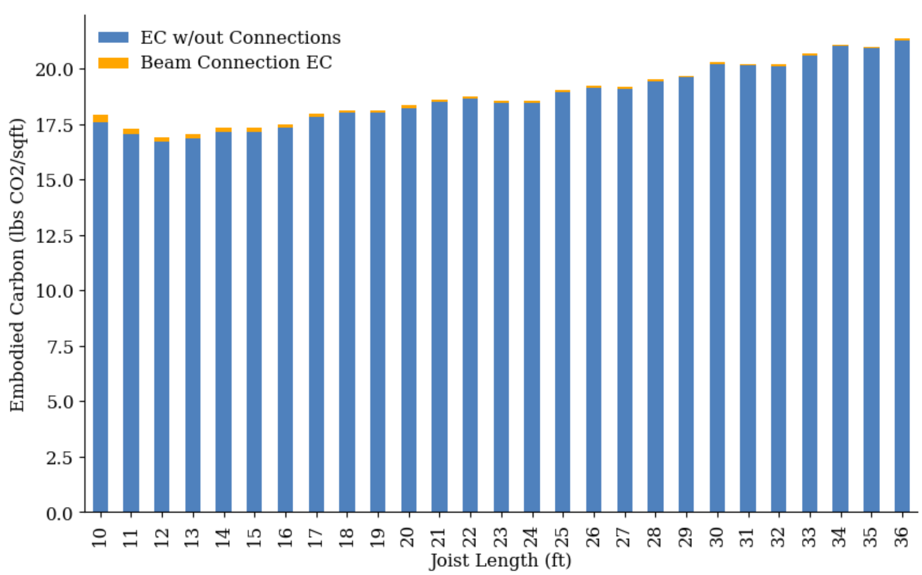


Figure 42: EC Comparison Across OWSJ Parametric Design Space

As seen in Figure 43, the EC contributions from beam to girder connections for NC systems are more relevant than for OWSJ systems, particularly for smaller bays with shorter beams; however, as bay size increases the connections become less impactful to the total EC of the bay.

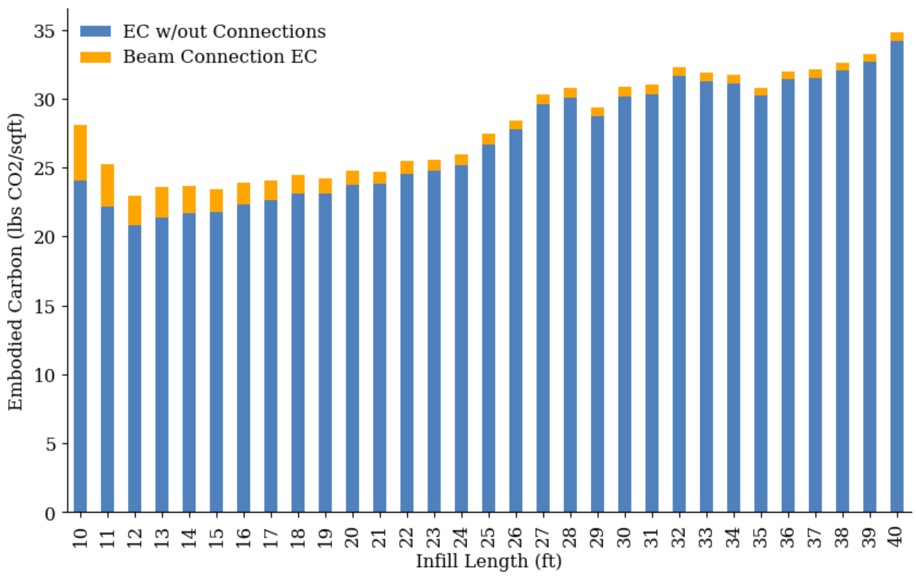


Figure 43: EC Comparison Across NC Parametric Design Space

Chapter 7

Results and Analysis

7.1 Introduction

In this chapter, the results developed across all four quadrants of research are compared to each other. Within each material type, mass timber and steel, the case study results are compared to the parametric studies. The mass timber studies are then compared to the steel studies for further comparison and analysis. These elements are not considered in the parametric studies and should be understood that for an even comparison these elements should be added to the parametric studies.

7.2 Comparative Analysis Between Mass Timber Case Study and Parametric Study

When comparing the mass timber case study results to the parametric study results, the parametric iterations have a similar total EC as well as EC related to connections. Figure 44 compares the EC of the case studies to the averaged EC value from the parametric case with the same beam length. The other connection EC from the case studies accounts for beam and girder to column connections and any fasteners associated with the timber deck which are elements not analyzed for the parametric study. When taking into account that these elements are not accounted for in the parametric study, the parametric study is showing total EC values. This is primarily due to the EC contributed by the beams and girders. For example, the beams in case study 1 account for 0.95 lbs CO_2 / sqft compared to the beams from the equivalent parametric study, P1, which account for 2.64 lbs CO_2 / sqft. This is significantly higher because the average number of infills is 4.8 compared to 3 infills for the case study. The average beam size is 7.11” x 26.5” compared to 6.25” x 17”, which is also larger and increases the EC. This difference in beam size is likely due to the LL not being reduced for the parametric study while they are being reduced for the case study. The girders follow a similar trend and also increase the total EC compared to the case study values.

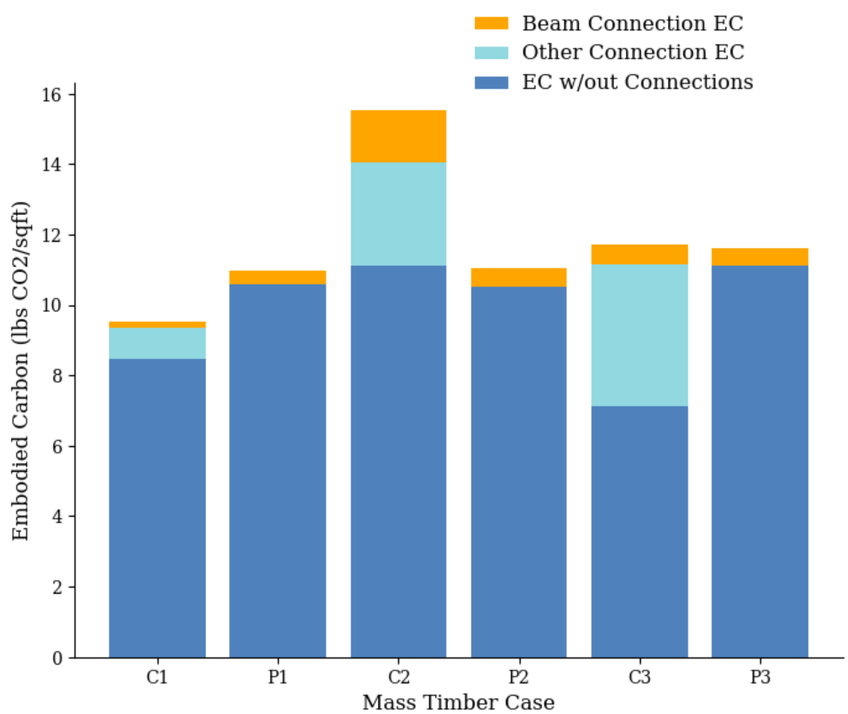


Figure 44: Mass Timber Case Study to Parametric Study Comparison

Even with these beam size increases, the case studies and parametric studies are similar because the case studies include other elements that are not considered like case study 1 including a double layer ½” plywood which contributes 1.26 lbs CO_2 / sqft in addition to the column connections and deck fasteners. Case study 2 is significantly higher than the parametric equivalent due to the rebar included in the concrete topping which contributes 1.32 lbs CO_2 / sqft and due to numerous plates being used in the column connection, refer to Chapter 3 for further discussion. Despite the use of pre-engineered connections for the parametric study as compared to more general connections using plates, angles, bolts, and screws in the case studies, both case study 1 and 2 provide similar results to the parametric results in terms of EC contributed by the beam to girder connections. The beam to girder connections in case study 2 are likely so much higher because there are more infills requiring more connections and a greater quantity of plates being used while the total area of the bay is relatively small.

7.3 Comparative Analysis Between Steel Case Study and Parametric Study

When comparing the steel case study results to the parametric results, similarly to the mass timber comparison, the parametric results are slightly higher. This can be seen in Figure 45, where the case studies for each steel system is compared to averaged parametric values from the design space when the beam length is equal to that of the case study. Because a parametric design space is not developed for the composite steel case study, the results are compared to averaged NC bays where the beam length is the same. Similarly to the mass timber, the reason behind the increase in EC for the parametric iterations is due to the joists and W-shapes having a higher count on average than the case study and on average the sizes selected parametrically are slightly heavier than those from the case studies.

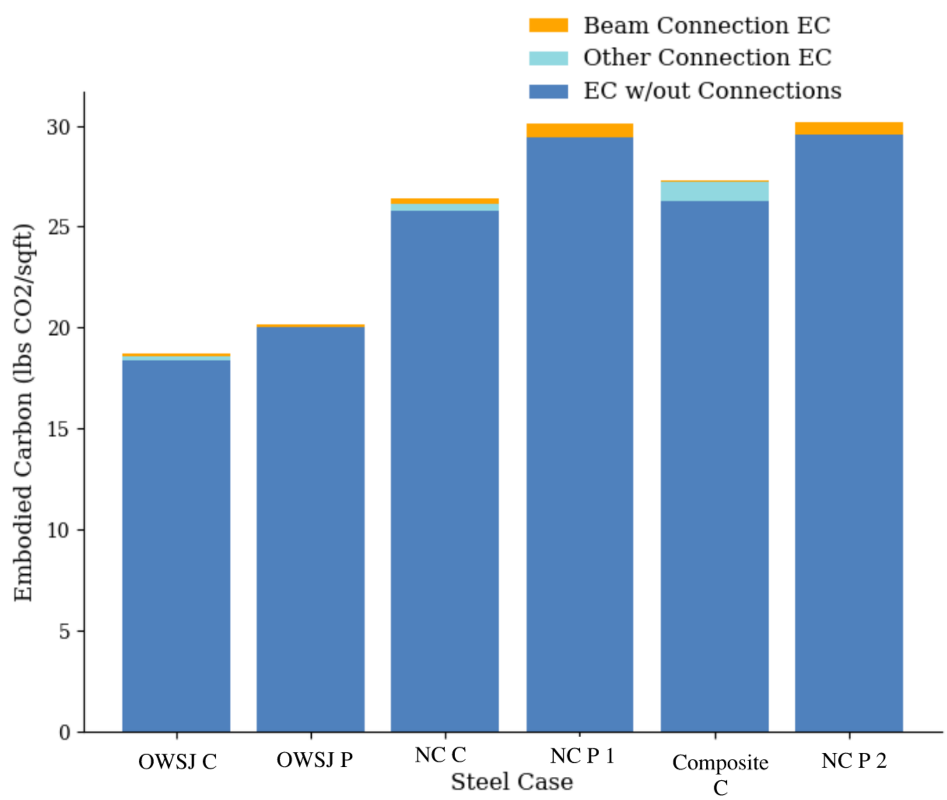


Figure 45: Steel Case Study to Parametric Study Comparison

7.4 Comparative Analysis Between Mass Timber and Steel Studies

The mass timber studies produce significantly less EC compared to more traditional steel gravity systems. As seen in Figure 46, the parametric studies for mass timber, OWSJ, and NC systems are compared across their common design space and are organized by infill length. The EC is averaged across all iterations within the design space for the given system type and infill length. Across systems, mass timber has the lowest total EC while NC has the highest total EC.

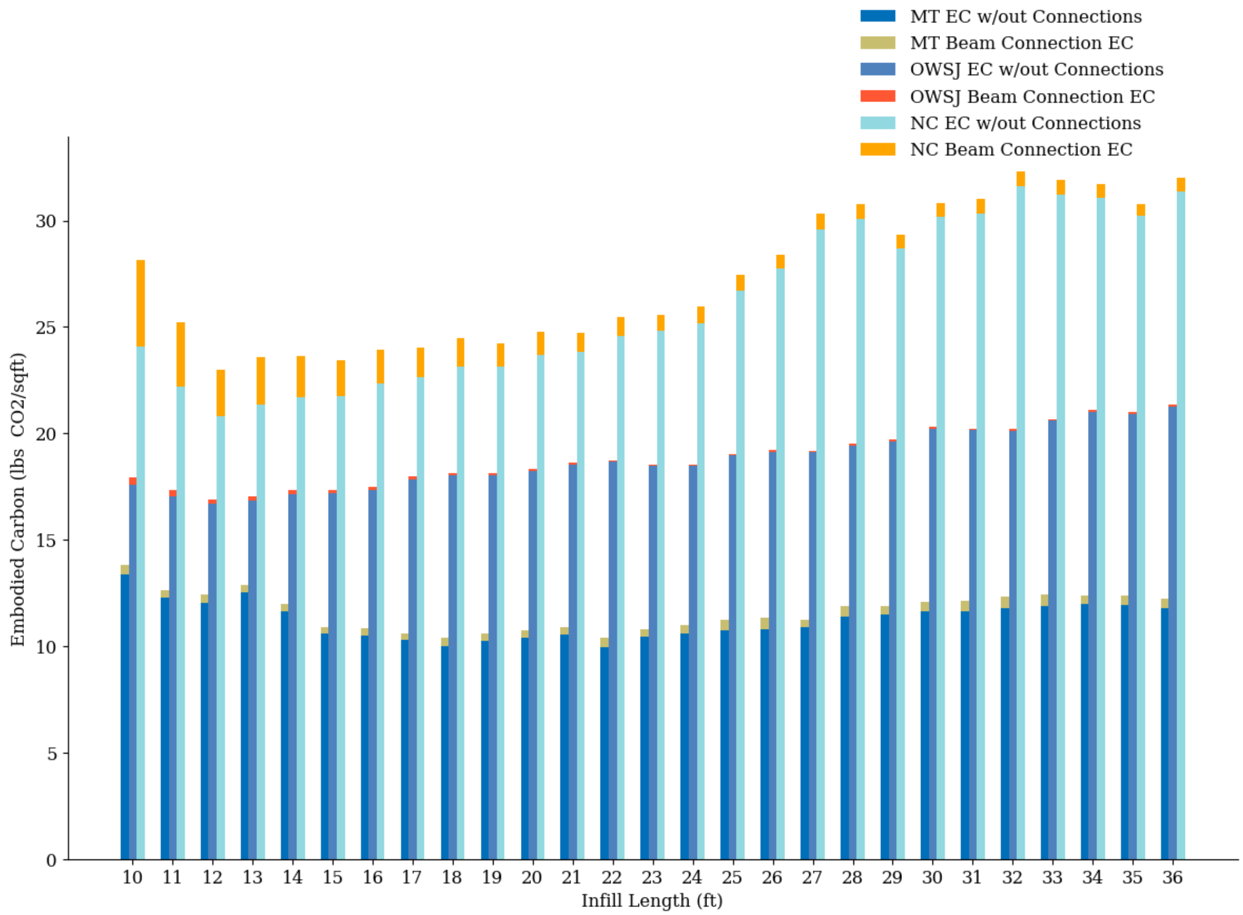


Figure 46: EC Comparison Across Mass Timber and Steel Parametric Studies

When comparing the EC of the connections for each system, the OWSJ system has the lowest absolute beam to girder connection EC values in units of lbs CO_2 / sqft. While mass timber does not have the highest absolute connection EC, its relative EC is the highest because the total EC of the system is so much lower compared to the other systems. On average, the connections from the OWSJ system contribute less than 0.75% of total EC for 72% of iterations completed in the design space. For the connections from the NC system, they contribute less than 3% of total EC for 50% of iterations completed. From 50%, this number drops to 35% for mass timber connections that contribute less than 3% of total EC. This means that a majority of the beam to girder connections for mass timber gravity systems are contributing more than 3% to the total gravity system elements analyzed in this study and this does not account for the column connections or the deck fasteners, which were shown to contribute an even greater percent of the total EC.

Chapter 8

Conclusion and Future Work

8.1 Summary of Contributions

Through this research the EC impact of mass timber connections is examined. When looking at mass timber beam to girder pre-engineered connections, they account for an average 0.43 lbs CO_2 / sqft or 3.7% of the analyzed parametric bay system described in this study. When including column connections and deck fasteners, connections are found to account for up to 40% of the total gravity system EC. When considering the EC contributions of connections to relative to the total gravity system, mass timber connections can be significantly more relevant as compared to more traditional systems types including OWSJ, NC, and composite steel gravity systems due to their primary components – beams, girders, timber deck – producing less EC compared to their equivalent steel components.

8.2 Limitations and Future Work

The scope of this research is limited to analyzing interior gravity bays with no edge conditions or irregularities. Full building LCAs are not performed as the focus of this research is to understand the early trends of the EC related to connections and begin to assess the relevancy of considering connections when performing LCAs. To this end, elements of the lateral system are not included in this study and even some of the gravity system elements are omitted including columns. In future work, these are areas that could be further explored to expand this understanding of the EC of connections throughout an entire building. In doing more research, more case studies could be completed to develop a database of building elements and their respective EC contribution. The types of connections analyzed could also be expanded upon to better understand how connection type impact EC. It is also important to recognize the impact that accurate ECF have on this research. While EPDs were used when possible, most fastener manufacturers do not perform LCAs on individual screws or bolts. As EPDs become more and more of an industry standard, the EC of smaller system elements will also become increasingly accurate.

8.4 Concluding Remarks

This research is particularly relevant to those continuing to pursue mass timber research, especially when developing models to understand the EC trends of these buildings. Industry professionals seeking to reduce EC may also find these results of interest when making design decisions because knowing that developing connections with fewer thicker plates can reduce EC or knowing that aluminum connections have a higher ECF due to the manufacturing process may allow a designer to make simple changes in their design that multiply throughout the building.

BIBLIOGRAPHY

[1] United Nations Environment Programme, *2022 Global Status Report For Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector*. 2022. [Online]. Available: www.globalabc.org.

[2] I. Lukić, M. Premrov, A. Passer, and V. Žegarac Leskovar, "Embodied Energy and GHG Emissions of Residential Multi-Storey Timber Buildings by Height – A Case with Structural Connectors and Mechanical Fasteners," *Energy Build*, vol. 252, Dec. 2021, doi: 10.1016/j.enbuild.2021.111387.

[3] M. Puettmann *et al.*, "Comparative LCAs of Conventional and Mass Timber Buildings in Regions with Potential for Mass Timber Penetration," *Sustainability (Switzerland)*, vol. 13, no. 24, 2021, doi: 10.3390/su132413987.

[4] International Organization for Standardization, "Sustainability in Buildings and Civil Engineering Works Core Rules for Environmental Product Declarations of Construction Products and Services," 2017.

[5] American Society of Civil Engineers, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. Reston, VA: American Society of Civil Engineers, 2022. doi: 10.1061/9780784415788.

[6] S. Breneman, M. Timmers, and D. Richardson, "Tall Wood Buildings in the 2021 IBC," 2022.

[7] I. Hens, R. Solnosky, and N. C. Brown, "Design Space Exploration for Comparing Embodied Carbon in Tall Timber Structural Systems," *Energy Build*, vol. 244, 2021, doi: 10.1016/j.enbuild.2021.110983.

[8] K. Strobel, "(Mass) Timber Structurally Optimized Timber Building," 2016.

[9] American Institute of Steel Construction, "Environmental Product Declaration Fabricated Steel Plate," 2021.

[10] C. Jones and G. Hammond, "Inventory of Carbon & Energy." 2019.

[11] Goodluck India Limited, "Environmental Product Declaration ERW Bare Steel Pipes," 2022. [Online]. Available: www.environdec.com/contact.

[12] American Wood Council, "Environmental Product Declaration North American Glued Laminated Timber," 2020. [Online]. Available: https://spot.ul.com/

[13] American Wood Council, "Environmental Product Declaration North American Oriented Strand Board," 2020.

[14] Structurlam, "Environmental Product Declaration for Cross Laminated Timber," 2020. [Online]. Available: www.astm.orgwww.structurlam.com

[15] National Ready Mixed Concrete Association, "Environmental Product Declaration NRMCA Member Industry-Average for Ready Mixed Concrete," 2022. [Online]. Available: www.nsf.org

[16] Concrete Reinforcing Steel Institute, "Environmental Product Declaration Steel Reinforcement Bar," 2022.

[17] American Institute of Steel Construction and Steel Tube Institute, "Environmental Product Declaration Fabricated Hollow Structural Sections," 2016. [Online]. Available: www.aisc.org/epd.

[18] American Society for Testing and Materials, "Environmental Product Declaration USG Levelrock Brand 2500 Green and 2500 Green FR Floor Underlayments Baltimore, MD and Gypsum, OH," 2020.

[19] Roseburg Forest Products Company, “Environmental Product Declaration Softwood Lumber,” 2018.

[20] S. Leonard, “Parametrically-Informed Early-Design Guidance for Mass Timber Floors for Embodied Carbon and Structural Design,” The Pennsylvania State University, 2023.

[21] MTC Solutions, “Beam Hanger Design Guide,” 2020. [Online]. Available: www.mtcsolutions.com

[22] The Aluminum Association, “Environmental Product Declaration Industry-Average Aluminum Sheet Manufactured in North America,” 2022.

[23] A. Pak, “Embodied Carbon: Key Considerations for Key Materials.”

[24] Nucor Vulcraft, “Steel Joist & Joist Girder Systems ,” 2020.

[25] Nucor Vulcraft, “Environmental Product Declaration Fabricated Open-Web Steel Joists and Joist Girders,” 2022.

[26] American Institute of Steel Construction, “Environmental Product Declaration Fabricated Hot-Rolled Structural Sections,” 2021.

[27] Nucor Vulcraft, “Environmental Product Declaration Fabricated Steel Roof and Floor Deck,” 2023.

[28] Insteel Wire Products, “Environmental Product Declaration Welded Wire Reinforcement,” Feb. 2024. [Online]. Available: https://www.astm.org/

[29] American Institute of Steel Construction, *Steel Construction Manual,* 15th ed. 2017.

[30] J. M. Fisher and J. Van De Pas, “The 3rd Edition of: Steel Joist & Joist Girder Systems,” 2020.

[31] A. Wolf and K. W. Kramer, “Parametric Analysis of Economical Bay Dimensions for Steel Floor Framing,” 2016.

[32] A. Tamboli, *Handbook of Structural Steel Connection Design and Details, Third Edition*. 2017.

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