COST EFFECTIVENESS OF BEAM-COLUMN GRAVITY SYSTEMS
FOR MASS TIMBER BUILDINGS

by
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ABSTRACT

Mass timber construction (MTC) has grown in popularity in recent decades, leading to the adoption of new construction types for MTC to be included in the 2021 International Building Code (IBC). Estimating the cost of mass timber construction is uniquely different and less understood than the cost estimation of concrete, steel, and light-framed wood buildings. This thesis will provide a better understanding of cost estimation of mass timber construction by investigating the cost sensitivity of key design features for a mass timber gravity system. An algorithm consisting of automated design and cost estimation is used. The algorithm implements strength and serviceability limits and the building type requirements defined by the IBC. The major system components and design choices that significantly affect cost are found and discussed.
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CHAPTER 1

INTRODUCTION

Cross laminated timber (CLT) is an engineered wood panel product invented in Europe in the early 1990s (Brandner et al., 2016). It consists of boards placed side-by-side to create layers (laminations) that are then glued orthogonally to create dimensionally stable solid wood panels. CLT panels can be used as a floor, roof or wall in buildings. Initially, CLT was manufactured manually on a small scale. In the early 2000s, CLT manufacturing facilities began to automate on an industrial scale (Brandner et al., 2016). Over the last decade, standardization of the CLT product was established around the world, which resulted in the publication of ANSI/APA PRG 320 in 2012 for North American (Brandner et al., 2016). CLT has many advantageous characteristics for building design, including the product’s capability of bearing in-plane and out-of-plane loads, its high in-plane shear resistance, and strong tension capacity. Building components made from CLT can be prefabricated before arriving on site which allows for fast erection of mass timber buildings (Brandner et al., 2016). The low density of CLT (relative to traditional construction materials) allows for CLT structures to be constructed on soil with low bearing strength and as additions to existing buildings (Brandner et al., 2016). Due to its volume, CLT allows for fire design of wood components to achieve higher fire rating than what is possible with light framed wood. Additionally, CLT and other mass timber materials such as glue-laminated members are also regarded by environmentally conscious users as an effective way to create a “carbon sink” in permanent building infrastructure (Churkina et al., 2020). Research has shown that timber emits less carbon and stores more carbon than concrete and steel and so mass timber buildings are potentially better for the environment and combating climate change (Churkina et al., 2020).

Historically, the use of timber was mainly for light-frame wood construction in the United States. Now, the invention of CLT has played a large part in timber replacing mineral-based materials for construction of mainly multi-residential and commercial buildings (Brandner et al., 2016). Mass timber construction (MTC) has been relatively slow in the United States compared to Europe, Australia, and Canada (A. Scouse et al., 2020). It is estimated that the
current CLT manufacturing capacity in the United States is approximately 7% that of production in Europe in 2012 (A. Scouse et al., 2020). However, the MTC market is growing in the United States and there are reasons to believe that this trend will continue. People are moving from rural communities to the city, which will increase the demand of multi-residential and commercial construction (A. Scouse et al., 2020). MTC also has the potential to help the economy of rural communities, such as in Oregon, where wood production has declined from 1980 to 2010 (A. Scouse et al., 2020). As of June 2020, there are 921 mass timber projects that have either been constructed or are in the design process in the United States (WoodWorks, 2020). This growing interest in MTC led to three new construction types being approved by the International Code Council (ICC) to be a part of the 2021 International Building Code (Breneman et al., 2019). The three new construction types, namely Type IV-A, IV-B, and IV-C, are based on the previous construction type for heavy timber (now called Type IV-HT) (Breneman et al., 2019). The new construction types have fire-resistance ratings and required protection from noncombustible materials. These new code provisions allow for a mass timber building to have up to 18 stories.

The new code requirements are discussed in greater detail in Chapter 2.

There is a need to better understand the cost of mass timber buildings and the structural and architectural implications of design on cost. One of the market barriers for MTC is the upfront cost (Mallo & Espinoza, 2015). It is understood that fast construction results in economic benefits, such as a faster return on investment (Mallo & Espinoza, 2014). And there are some case studies of the cost of mass timber to other structural systems (Mallo & Espinoza, 2016, Burback & Pei, 2017). The purpose of this thesis is to provide some insight on the cost of the structural system of mass timber buildings in the context of the newly introduced IBC building types and NDS design requirements. Specifically, the cost of the structural materials for a mass timber gravity system was estimated based on building grid geometry and configurations. The methodology for design and cost estimation used for this thesis was described in Chapter 2, along with some examples to illustrate how the methodology works. A sensitivity analysis was conducted in Chapter 3 in order to reach some conclusions about the cost of different mass timber building types and the repercussions on cost of various design choices, such as architectural considerations, fire design, and building construction type. Gravity systems where the primary structural member is made of another material, such as reinforced concrete or light-framed wood, are not included in this analysis. Major conclusions and the needed future work on
MTC cost was summarized in Chapter 4. Chapters 2 and 3 are drafts of journal manuscripts submitted to peer-reviewed journals.
REFERENCES


CHAPTER 2

COST EFFECTIVENESS OF MASS TIMBER BEAM-COLUMN
GRAVITY SYSTEMS

Included with permission from coauthors Shiling Pei¹, Gregory Kingsley², and Erin Kinder³.

Abstract

The cost of mass timber buildings is a major point of interest to building developers and architects because it often dictates the fate of proposed mass timber projects. Cost estimation for mass timber construction has several unique aspects that differ from that of steel, concrete, and light-framed wood buildings. With the new building categories (Types IV-A, B, and C) introduced to the 2021 International Building Code (IBC), it is important to look at cost implications of both the new and existing types (III-A and B and IV-HT) and cost sensitivity to key design features. An automated design and cost estimation algorithm for mass timber gravity systems was developed. The algorithm includes an automated member selection and design procedure that implements strength and serviceability checks. Fire rating and design requirements defined by the IBC were included. The final cost calculation includes material costs of wood, connection hardware, fire protection, and an estimation of installation cost. The details of the proposed algorithm are presented in this paper, together with scenario analyses on archetype design using different IBC mass timber categories.

Key words: Mass timber, Cost, Cross Laminated Timber, CLT, tall wood construction, Gravity frame

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2.1 Introduction

Before the 2000’s, modern engineered wood buildings in North America were predominantly constructed using light-framed wood systems which have stringent height and total area limits. The taller building categories in the current codes rely either on non-combustible structural materials or non-combustible protection (i.e. Gypsum board) to achieve required fire ratings. The 2~3 hour fire ratings needed for taller and larger buildings have historically been unrealistic, if not strictly prohibited for wood construction. Although it is well-known that heavy timber members have inherent fire-resistance due to their size and naturally protective charring, there has not been suitable planar massive wood elements (i.e. wall or floor) until the invention of cross laminated timber (CLT) panel in the 1990’s. CLT is an important addition to wood buildings because it enables the construction of building gravity systems to be made entirely of wood products that can be constructed rapidly. Development of CLT and other prefabricated mass timber elements eventually led to new mass timber building types in the 2021 International Building Code (IBC) that allow for wood buildings much taller and larger than in the past.

After about 30 years of development since its invention, CLT has grown in popularity worldwide. This new material gives engineers and architects an option to construct the entire building out of wood with relatively better fire resistance than light-framed wood systems. A recent full-scale compartment fire test revealed that full burn-out (i.e. to have a fire in a compartment to burn until it self-extinguishes) can be achieved with exposed CLT (Zelinka et al. 2018). Based on recent research advances in mass timber, a proposal successfully passed the voting process to change the IBC in the upcoming 2021 update. The new IBC provisions include dedicated Building Types (Types IV-A, B, and C) for mass timber construction which allow up to 18 story mass timber buildings to be constructed. Several local jurisdictions in the U.S. (e.g. states of Oregon and Washington, City of Denver) have already adopted provisions similar to the newly adopted IBC proposal into their local codes by 2020. Details on the new code changes related to tall wood buildings can be found in Breneman et al. (2019).

While significant advancement has been made regarding the height and area limits on mass timber buildings in regulatory space, one of the other major obstacles for the adoption of mass timber construction is the cost of these buildings. Pricing of mass timber building projects...
is quite different than steel and concrete options due to the price of the wood material and high level of pre-fabrication (which allows for low on-site labor requirements and fast construction process). Based on the authors’ experience, the cost of construction material itself contributes the largest portion of the total project cost of mass timber buildings relative to labor costs, which tend to be low compared to other construction materials. Limited suppliers of material and the lack of construction experience on these systems also tend to result in higher bidding prices than more mature building systems. To date, the implications on cost of key design choices such as building type and main structural grid dimensions are not well understood by designers and architects given the novelty of the system. Therein lies the motivation of this study to develop a procedure for estimating material cost of a commonly adopted mass timber gravity system, namely beam-column grid with CLT floor panels. The gravity system is the focus in this study because it consists of a significant portion of mass timber material use and thus dominates the overall cost.

The algorithm developed in this study includes an automated selection and design module that implements wood member design based on allowable stress design criteria in the American Wood Council National Design Specification for Wood Construction (NDS) and serviceability requirements on deflection and vibration. The fire design and protection requirements for different IBC mass timber categories were also implemented. The final cost calculation includes material costs of wood, connection hardware, fire protection, and a rough estimation of installation effort. The details of the algorithm are presented in the following sections, including scenario analyses on archetype designs using different IBC category constraints. The goal of this paper is to illustrate the effects of basic design choices (primarily grid size and fire rating requirements) on system cost for the benefit of architects and engineers not yet familiar with mass timber systems.

2.2 Mass Timber Gravity System

The mass timber gravity system used in this study consists of glulam beam-column grids and CLT panels as the floor and roof. This is a commonly adopted gravity system for mass timber commercial construction. This system provides the occupants with an open floor plan that is reconfigurable with non-structural partition walls. It is worth noting that there is another type
of all-mass timber gravity system that consists mainly of CLT bearing walls (sometimes termed as “honeycomb” style), which is more suitable for residential compartmentalized applications. In this beam-column grid system, the CLT panel spans with as few beams as possible for a given CLT thickness based on CLT strength and serviceability limit states or fire rating requirements. The connections at glulam beam and column joints are typically custom designed, with their costs differing significantly based on the design and load demands. Typical loads considered in this study in the design of gravity system include: roof live load, office live load, partition live load, dead load from self-weight, and a superimposed dead load of a 3 inch concrete floor topping and estimated mechanical loads.

Both the strength and serviceability limits are considered in this study for the gravity system design. The strength limit states are checked using allowable stress design (ASD) provisions of the NDS, which is currently the wood design code in the U.S. Where fire rating is required at exposed wood conditions, fire design of the mass timber components are also performed based on NDS. Note that currently ASD is the only available design format in NDS regarding wood member design under fire conditions, which is essential for design of an exposed mass timber system under new IBC provisions. In fire design, serviceability requirements are not checked as they are not required.

Based on the newly proposed IBC mass timber building types, the automated design program is set up to design all practical building types that could be implemented with mass timber construction, namely Types III-A, III-B, IV-A, IV-B, IV-C, and IV-HT. Within these categories, Types IV-A, IV-B, and IV-C are the recently adopted new construction types. Types III-A, III-B, and IV-HT (previously Type IV) are existing construction types that could be applied to enable mass timber buildings in practice. The primary difference between the building types is in the fire-resistance rating (FRR) which can have an impact on cost as a result of both member sizing and non-combustible protection if required. The FRR and non-combustible protection requirements for each building type are summarized in Table 1. Fire rating in connections are not explicitly considered in this study. A rough cost estimation based on connection classes is implemented instead (as presented in detail later).

Among applicable construction types, Type III-A requires a FRR of 1 hour for the framing members, floor, and roof, without explicitly requiring non-combustible protection. This makes it possible to design a mass timber building with exposed wood. Type III-B does not
require any FRR for the primary structure, only the exterior envelope. Type IV-A requires members to be fully protected by non-combustible material. This requirement can be achieved using 3 layers of type X 5/8-in gypsum board on the exposed mass timber members in addition to 1 hour FRR of the mass timber members in the primary structural frame. Type IV-B requires partial coverage of the exposed mass timber elements by non-combustible material. It is permitted that the ceilings (including attached beams) can have an exposed area equal to 20% of the floor area. Columns that are not integral to the walls can be fully exposed. The detailed requirement can be found in Section 602.4.2 of the approved code changes for the 2021 IBC (G108-18). Type IV-C does not require any non-combustible protection, which means all FRR can come from mass timber sacrificial layers with wood exposed. Type IV-HT, previously known as Type IV, has specified minimum size requirements addressed in IBC Table 2304.11 (this requirement is also checked for all other categories). Type IV-HT does not require any non-combustible protection or explicit FRR checks. All construction types have their unique size and height restrictions that are very important for specific projects. For a given building height, such as a six-story mass timber building, there are multiple construction types that are theoretically viable. But the final decision on which type to adopt is largely dictated by first cost.

**Table 2.1** The FRR, Required Non-combustible Protection, Story Limit, and Maximum Height for each Building Type.

<table>
<thead>
<tr>
<th>Construction Type</th>
<th>FRR (hours)</th>
<th>Non-combustible Protection</th>
<th>Story Limit</th>
<th>Maximum Height (m (ft))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Primary Structural Frame</td>
<td>Floor</td>
<td>Roof</td>
<td></td>
</tr>
<tr>
<td>III-A</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Not Required</td>
</tr>
<tr>
<td>III-B</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Not Required</td>
</tr>
<tr>
<td>IV-A</td>
<td>3</td>
<td>2</td>
<td>1.5</td>
<td>Fully Covered</td>
</tr>
<tr>
<td>IV-B</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>Partially Covered</td>
</tr>
<tr>
<td>IV-C</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>Not Required</td>
</tr>
<tr>
<td>IV-HT</td>
<td>HT&lt;sup&gt;a&lt;/sup&gt;</td>
<td>HT&lt;sup&gt;a&lt;/sup&gt;</td>
<td>HT&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Not Required</td>
</tr>
</tbody>
</table>

<sup>a</sup>HT means that this member is required to meet the size prescribed in IBC Table 2304.11.
2.3 Cost Estimation for Mass Timber Gravity System

While the total cost of a construction project has many components, this study only focuses on the structural material and a rough estimate of installation cost of a mass timber gravity system. Thus, the scope of the discussion below only applies to the gravity system framing portion of a project. To calculate the gravity system cost, the cost for major system components is added together, namely glulam, CLT panels, connections, fire-proofing material, and labor for installation (labor is included approximately in the unit costs of materials). The examples in this study utilized hypothetical data estimated from the North American market at the time of the study for the unit cost of the CLT, glulam, and connections (details presented later). It is important to understand that these unit cost values are constantly changing based on market supply and demands for both finished products and commodity components. The cost estimation program developed in this study can be updated using newly available cost data. While the relative comparison of costs among different construction types is of good reference value, the actual costs in this study should not be used directly in real construction projects.

The CLT unit cost is dependent upon the species, grade, thickness, and the ratio of the pressed length to the required length. The pressed length varies with different manufactures of CLT. Because CLT panels need to be cut from a main press size (size varies depending on the manufacturer), and some cut lengths will have a larger associated waste, the unit CLT panel cost is not a simple linear function with its size but a function of the ratio between the pressed length to the needed panel length. When the final panel size gets closer to the press size, the unit cost decreases as the efficiency in material use increases. The relationship between panel length and cost assumed in this study is illustrated in Figure 1. The example data in Figure 1 represents the unit costs from one particular manufacturer at one point in time. The cost curve for other manufacturers with different production equipment and press size may be different, but a relationship between unit CLT cost and panel length will always exist.

Similarly the unit cost of the glulam depends on efficiencies associated with each manufacturer. In this study, this is captured by using a unit cost per wood volume that depends on the width of the member (beam, girder, or column). The assumed unit cost relationship to width used in this study is depicted in Figures 2 and 3.
The connection unit cost can vary greatly depending on the design and detailing. There is currently no uniform or standardized mass timber connection cost data available for the U.S. market. In this study, we assume the cost for column to column, beam to column, and beam to girder connections is a function of connection capacity, which is divided into several discrete categories and will be discussed later.

Figure 2.1 The unit cost of CLT (1 ft = 0.3048 m, 1 ft\(^2\) = 0.0929 m\(^2\))
2.4 Methodology for Automated Cost Estimating

The automated design and cost estimation procedure for mass timber gravity systems is summarized in Figure 4. This process includes five (5) major modules, namely Strength and
Serviceability Limit States Design (Module 1), HT Size Limits Implementation (Module 2), IBC Building Type Implementation (Module 3), Limit States Re-check (Module 4), and Cost Estimation (Module 5). Module 1 produces preliminary designs for each structural member for a given set of grid dimensions and loading conditions, with a first estimate of the mass timber member self-weight (this will be refined and iterated later considering dead load adjustment due to the HT size requirements). The design is based on ASD procedure following NDS specifications and IBC serviceability requirements. The FRR requirements are also considered and the non-combustible gypsum board coverage is added when needed. The program adopts a type X 5/8-in gypsum board as equivalent to a FRR of 40 minutes, as defined in 2021 IBC Table 722.7.1(2). Multiple design options with different CLT panel thickness values are conducted in parallel because different CLT thicknesses will dramatically change other parts of the design, including the need for intermediate beam supports. Three design options are produced corresponding to three thickness options for a given CLT grade (3-ply, 5-ply, and 7-ply). Module 2 enforces the minimum member sizes specified in IBC Table 2304.11 for Types IV-A, IV-B, IV-C, and IV-HT. The size of any member smaller than the HT requirement will be increased to the minimum member size specified. Module 3 checks the story height and number of stories against the IBC building size limits. Module 4 conducts another limit states check (repeat Module 1) with the updated self-weight from Module 2. Module 5 calculates the cost of each gravity system using the unit costs for materials and outputs the results in a per-square-foot basis. The details for each module and key assumptions are explained in the following sections.

**Figure 2.4** Schematic of the program used in this study.
2.4.1 Input Building Parameters

The proposed procedure requires specific input parameters for a typical gravity frame unit to perform automated design. The design is based on a typical column grid that is assumed to be extended to the entire building floor area, as it is shown in Figure 5. The input parameters include: IBC building category, number of stories, column grid width \((d)\) and length \((b)\), floor to floor height \((h)\), glulam properties (bending design stress, modulus of elasticity, shear design stress, compression design stress), the CLT properties from the manufacturer (or design values from PRG320), the desired grade of CLT, cost data, and connection class for columns, girders, and beams. The program assumes that a girder will always be installed along the length direction \((b)\) and smaller beams will be installed along the width direction \((d)\) when needed (i.e. when CLT cannot achieve the required span). The CLT panel will span along the length direction \((b)\) if beams are present. Otherwise, the CLT will span along the width direction \((d)\). The spacing between beams \((c)\) is not specified by the user, but calculated based on CLT maximum spanning capacity. The user can also specify a “no-beam” configuration that is common in CLT office floor plan designs. This option will select CLT panels with enough thickness to span the width direction without the need for beams.

![Diagram of Mass timber gravity system and associated grid dimensions.](image)

**Figure 2.5** Mass timber gravity system and associated grid dimensions.
2.4.2 Module 1: Strength and Serviceability Limit States Design

This module will conduct design of beams and columns based on CLT panel selection. By default, the program is designed to automatically design for three different CLT panel thicknesses (from 3 ply to 7 ply panels) with layer directions alternating. Each design is conducted in parallel in the subsequent modules (in the end the user can elect to use a particular design based on cost comparison, or the program will automatically output the least expensive design). The design limits checked for the CLT panel are bending, shear, deflection from live load, deflection from total load, vibration, and creep. The design limits for the column are compression axial load and buckling. (This is actually a simplification, because in reality, column sizes can be selected based on connection requirements.) The dimensions “b”, “d”, and “h” are always fixed because they are likely a given architectural constraint for a real project. If intermediate beams are a part of the bay, then the CLT design choice will dictate the number of beams needed for the bay (i.e. spacing “c”). Once the beam spacing is determined, the load demands on the CLT panels, beams, girders, and columns are calculated based on ASD load combinations. In this study, to limit the beam and girder sizes to relatively common choices, the width to depth ratio for the bending member cross-section is limited to a range of 1:3 to 2:3. The program automatically runs through the different beam size options to find which options meet the limit state requirements, starting with the beam size with the least volume.

A fire design function is also implemented to conduct fire design of the members based on NDS. Reduced cross-sections for members and panels are calculated based on required FRR char depth and checked against strength limit states (serviceability limits are not required or checked for fire design). In addition to explicit IBC fire requirements, an additional constraint imposed in this study is that exposed CLT floor should maintain at least two strong direction laminations after charring (even if one of them is partially charred) regardless of the strength calculation. This is done to ensure fire-fighting safety and post-fire floor access.

Module 1 also calculates the weight from the required gypsum board to design each member. The programs designs for type X 5/8-in gypsum board that has a FRR of 40 minutes. Type III-A does not require any non-combustible protection, but the floor and roof are designed with 1 layer of gypsum board that completely covers it. If the gypsum board was not used, then the exposed 3-ply CLT would not meet the self-imposed requirement of having more than one strong layer without the char layer. This would make a 3-ply gravity system ineligible. By
adding the gypsum board coverage, a 3-ply gravity system is possible which is cheaper than a 5-ply option. Construction Type IV-A is designed with 3 layers of gypsum board for the primary framing members and 2 layers for the floor and roofing. The surface area covered by the gypsum board includes all four sides of the columns, three sides of the beams and girders, and the bottom side of the CLT floor. Type IV-B designs with 2 layers of gypsum board that partially covers the mass timber elements. In this study, the program simply accounts for 100% of the CLT ceiling area to be covered with 2 layers of gypsum board. The beams, girders, and columns are fully exposed. For Types IV-C and IV-HT, there is no non-combustible coverage required or used in the calculations.

2.4.3 Module 2: HT Size limits Implementation

This module checks the member sizes for building Types IV-A, IV-B, IV-C, and IV-HT. If member sizes do not meet the minimum heavy timber (HT) member sizes specified in IBC Table 2304.11, then that member size will be increased to the minimum size required.

2.4.4 Module 3: IBC Building Type Implementation

Module 3 confirms that the building height and number of stories does not exceed the limits specified in the IBC. If the building height and number of stories meet the IBC restrictions, then the program continues to module 4. If the IBC restrictions are not met, the program outputs an error message and the design stops.

2.4.5 Module 4: Limit States Re-check

In Module 4, all design checks in Module 1 are repeated using the updated member size (including possible size changes from Module 2). This step accounts for the true dead load from the gravity system. The demand-to-capacity ratio for each limit state of each member is calculated. If any of the limit states fails, that particular design option is not used and the program does not continue to module 5.

2.4.6 Module 5: Cost Estimation

Module 5 calculates the cost of each structural element and the average cost per square footage for each floor based on the typical interior bay. As was mentioned earlier, all material
costs are calculated based on unit-price and quantity. The unit prices used for each material also approximately included installation costs. The unit-price for CLT is not linear but reflects manufacturing limitations. In this study, a constant unit price of $3.9/sf for 1 layer of type X 5/8-in gypsum board is used. The connection cost per square footage is found by multiplying the unit cost (from Tables 2 and 3) by the number of pieces needed for each grid unit, and then dividing that cost by the area of the grid. Note that the connection unit cost is a rough estimation based on the author’s experience. A more accurate estimation of installation cost for each structural member can be added to the program when better cost data becomes available.

2.5 Connection Cost Considerations

Connection design is an extremely important component of mass timber system design and cost estimation. Unlike standardized connections such as joist hangers for light-frame wood construction, there is not yet a standard connection solution for mass timber components that is deemed universal in the U.S. market. To capture this variety in this study, the beam-to-column and beam-to-beam connections used in the gravity framing were categorized into three classes based on their load transferring mechanism and detailing. Class 1 includes bearing type connections, Class 2 includes custom bucket or knife plate connections, and Class 3 includes highly specialized connections which are often hidden, inherently fire-rated, high-capacity, and designed for constructability and low site labor. Some examples of these connection classes are shown in Figures 6-8. The estimated cost for connections used in this study is listed in Table 2. It should be noted that while cost increases as connection class increases from 1 to 3, the model does not incorporate cost that may be associated with fire protection for classes 1 and 2.
Figure 2.6 Example of a bearing type connection in Class 1.

Figure 2.7 Example of knife plate connection in Class 3.

Figure 2.8 Example of a concealed and high-capacity connection in Class 3.
**Table 2.2** Estimated unit cost of beam-column connections\(^a\).

<table>
<thead>
<tr>
<th>Reaction (lbs)</th>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$15.00</td>
<td>$75.00</td>
<td>$270.00</td>
</tr>
<tr>
<td>5000</td>
<td>$30.00</td>
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<td>--</td>
</tr>
<tr>
<td>10000</td>
<td>--</td>
<td>$117.00</td>
<td>$325.00</td>
</tr>
<tr>
<td>15000</td>
<td>$35.00</td>
<td>--</td>
<td>$405.00</td>
</tr>
<tr>
<td>18000</td>
<td>--</td>
<td>$139.00</td>
<td>--</td>
</tr>
<tr>
<td>20000</td>
<td>$85.00</td>
<td>$141.00</td>
<td>$485.00</td>
</tr>
<tr>
<td>25000</td>
<td>$120.00</td>
<td>$163.00</td>
<td>--</td>
</tr>
<tr>
<td>30000</td>
<td>--</td>
<td>--</td>
<td>$565.00</td>
</tr>
<tr>
<td>40000</td>
<td>--</td>
<td>--</td>
<td>$645.00</td>
</tr>
<tr>
<td>&gt; 40000</td>
<td>$500.00</td>
<td>$500.00</td>
<td>$1,000.00</td>
</tr>
</tbody>
</table>

\(^a\)The cost data included in this table for connections are rough estimates and for this comparative study only. It is not reflective of the cost for any specific design.

Mass timber buildings also require column connections/splice details to transfer column compression loads between different stories. Column connections are relatively simpler than beam-column connection and are mostly bearing type. In this study, column connections are divided into three capacity classes. Class 1 is low strength, with a capacity ranging from 22 to 89 kN (5 kips to 20 kips). Class 2 is medium strength, ranging from 22 to 178 kN (5 to 40 kips), and Class 3 is high strength, ranging from 97 to 445 kN (20 to 100 kips). The three classes do not require CNC of wood column ends and thus will cost less. The cost of column connections used in this study is listed in Table 3.
Table 2.3 Unit cost of column connections\textsuperscript{a}.

<table>
<thead>
<tr>
<th>Col Square Dim (in)</th>
<th>Column-Column Connection Class</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
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<tr>
<td>8</td>
<td></td>
<td>$50</td>
<td>$100</td>
<td>$150</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>$75</td>
<td>$150</td>
<td>$250</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>$100</td>
<td>$200</td>
<td>$350</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>$125</td>
<td>$250</td>
<td>$450</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>$150</td>
<td>$300</td>
<td>$550</td>
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<tr>
<td>18</td>
<td></td>
<td>$175</td>
<td>$350</td>
<td>$650</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>$200</td>
<td>$400</td>
<td>$750</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>$225</td>
<td>$450</td>
<td>$850</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>$250</td>
<td>$500</td>
<td>$950</td>
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<td>26</td>
<td></td>
<td>$275</td>
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</tr>
<tr>
<td>28</td>
<td></td>
<td>$300</td>
<td>$600</td>
<td>$1,150</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>$325</td>
<td>$650</td>
<td>$1,250</td>
</tr>
</tbody>
</table>

\textsuperscript{a}The cost data included in this table for connections are rough estimates and for this comparative study only. It is not reflective of the cost for any specific design.

2.6 Estimated Costs for a Typical Column Grid

The automated design and cost-estimation procedure described above is implemented using Matlab. The algorithm was applied to a typical column grid of 9 x 9 m (30 x 30 ft) to evaluate cost effectiveness of different CLT panel thickness options and IBC construction types. The selected column grid was applied to a typical 6-story office building with a 60 x 90 m (200x300 ft) floor plan.
The design loads for the example building include a roof live load of 1 kN/m² (20 psf), a floor live load of 2.4 kN/m² (50 psf), a superimposed dead load of 0.7 kN/m² (15 psf) for the roof and 2.3 kN/m² (47.5 psf) for the floor. The CLT panel is grade V2 based on APA-PRG 320. The glulam is a 24F-1.8E grade. The girders and beams are assumed to be an integrated part of the ceiling. The total building height is 22 m (72 ft) with 6 stories and a floor-to-floor height of 3.7 m (12 ft). The IBC building types analyzed in this study are: III-A, IV-A, IV-B, IV-C, and IV-HT (Type III-B was not included because it is not allowed for this building height). Type III-A is included because it is possible to classify a mass timber building of this height into this category within the existing IBC framework. In fact, that is how some of the early mass timber building projects in the U.S. were classified before the new IBC types. Within each building type, different CLT floor thickness options were considered. The connection class for column-beam connections and column-column connections is set to be class 2. In order to illustrate the automated design process, a detailed description of the Type IV-A design with different CLT panel thicknesses is presented here first, followed by comparisons with other building categories in IBC (with only the most cost effective CLT panel option for each category).

### 2.6.1 Example Results from the Type IV-A design

In this section, the three viable gravity systems for Type IV-A are observed. For Type IV-A, there is a gravity design option for 3-ply, 5-ply, and 7-ply CLT. Each of these gravity systems have different costs as they have different member sizes, a different CLT thickness, different gypsum board coverage, and can have a different number of beams.

Based on IBC requirements, gravity framing members in Type IV-A need to be fully covered by 3 layers of type X 5/8-in gypsum board in order to achieve 120 minutes of FRR. The floor CLT requires 2 layers of gypsum board, resulting in 80 mins of the FRR. Sacrificial charring layer of wood members are designed to contribute to the rest of the required FRR. Based on the automated design, the beam, girder, and column sizes for the different CLT options are listed in Table 2.4.
Table 2.4 Member sizes for each CLT option for Type IV-A.

<table>
<thead>
<tr>
<th>Level</th>
<th>CLT Ply</th>
<th>Column Width(^a) mm (in) [from 5(^{th}) story to 1(^{st}) story]</th>
<th>No. of Beams</th>
<th>Beam width [mm] x depth [mm] (in x in)</th>
<th>Girder width [mm] x depth [mm] (in x in)</th>
<th>Average Wood Volume m(^3) (ft(^3))</th>
<th>Final Cost USD/m(^2) (USD/ft(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>3</td>
<td>273 (10.75)</td>
<td>3</td>
<td>222x521 (8.75x20.5)</td>
<td>273x686 (10.75x27)</td>
<td>113.2 (23980)</td>
<td>547 (49)</td>
</tr>
<tr>
<td>Floor</td>
<td>[311 (12.25), 362 (14.25), 413 (16.25), 464 (18.25), 514 (20.25)]</td>
<td>4</td>
<td>222x610 (8.75x24)</td>
<td>311x965 (12.25x38)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>5</td>
<td>273 (10.75)</td>
<td>2</td>
<td>222x597 (8.75x23.5)</td>
<td>273x724 (10.75x28.5)</td>
<td>183.2 (38806)</td>
<td>616 (55)</td>
</tr>
<tr>
<td>Floor</td>
<td>[311 (12.25), 362 (14.25), 413 (16.25), 464 (18.25), 514 (20.25)]</td>
<td>3</td>
<td>273x660 (10.75x26)</td>
<td>311x965 (12.25x38)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>7</td>
<td>273 (10.75)</td>
<td>2</td>
<td>222x610 (8.75x24)</td>
<td>273x724 (10.75x28.5)</td>
<td>252.7 (53535)</td>
<td>697 (62)</td>
</tr>
<tr>
<td>Floor</td>
<td>[362 (14.25), 362 (14.25), 464 (18.25), (20.25), 514 (20.25)]</td>
<td>2</td>
<td>273x787 (10.75x31)</td>
<td>362x927 (14.25x36.5)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)All columns in this study have a square cross section.

It can be seen from Table 2.4 that the number of beams needed in a typical column grid decrease as the CLT ply increases. This is because the CLT maximum span capacity increases
for thicker panels. Beam and girder sizes also increase as CLT gets thicker. In fact, even though the number of beams generally decreases as the CLT plies increase, the overall wood volume increases significantly, which also leads to the increase in column size. The break-down of cost composition attributed to each member type is depicted in Figure 9 for 3-ply (most economical) and 7-ply (most costly) CLT options.

Figure 2.9 Cost of each structural component for the 3-ply and 7-ply CLT options for Type IV-A.
The main cost difference between the two CLT ply options in Figure 2.5 is the CLT cost. The 7-ply CLT costs more than the 3-ply CLT (the increase in thickness is if the entire floor area). For the 7-ply option, the most costly component is the CLT and for the 3-ply option, the most costly component is the gypsum board. Going from 3-ply to 7-ply, the beam cost decreases because the overall wood volume of the beams decreases. The girder, column, and connection cost increases (except for the girder connection cost, which remains the same) as the member sizes and reactions increase.

For all CLT options, the maximum span is controlled by creep-induced long-term deflection. The girder and column designs are controlled by member strength. The beam design is controlled by the fire design for flexure (considering reduced cross section due to charring with a modified allowable stress based on NDS).

2.6.2 Comparison among different IBC Types.

As is illustrated in the Type IV-A example, the automated design program actually generates a group of viable designs based on the selection of CLT material. Since these designs will have different costs, it is logical to assume that the most economic option will be selected in a real project. In this section, the most economical option from different IBC building types were compared. This will help provide a preliminary insight into the cost-effectiveness of these options for the 6-story example building.

Because of the self-imposed requirement to maintain at least two layers of parallel to grain CLT lamination in the span direction for fire design, the 3-ply CLT option is only viable for Types III-A and IV-A. For building Types IV-B, IV-C, and IV-HT, the 5-ply CLT option is the minimum thickness that can be used. Using a 3-ply CLT floor exposed to fire will result in the loss of the bottom strong direction lamination, leaving the entire floor being supported only by a single strong direction CLT lamination after a fire. This condition was not allowed in the design algorithm.

A comparison of the total cost for each building type is shown in Figure 10. Building Type IV-A turns out to be the most expensive building type and building Type III-A is the least expensive option. In every case except IV-A the majority of the cost is attributed to CLT material. This is consistent with the experience and observation of the authors on existing projects. For Type IV-A, the majority of the cost is attributed to the gypsum board fire
protection. There is a significant increase in the CLT cost for Types IV-B, IV-C, and IV-HT because a minimum of 5-ply CLT is used based on assumptions made in this study. The benefit of using 5-ply CLT is the ability to have exposed wood surface (although limited in Type IV-B). The value of exposed wood to the client is not explicitly considered in this study, although it can play a significant part in real projects. It is possible for a real project to adopt more expensive options due to aesthetics. It is also interesting to note that the self-weight of both CLT and gypsum board is significant, so the cost of the framing members and connections increases as the CLT and/or the amount of gypsum board used becomes larger.

Figure 2.10 Cost per square foot of each component for building Types III-A, IV-A, IV-B, IV-C, and IV-HT.
The final member dimension designs for each building category are listed in Table 2.5. Like the trend observed in building Type IV-A with different CLT options, the number of beams decrease as the CLT goes from 3-ply to 5-ply and the size of beams and girders increases. We also see that the overall wood volume increases for building types that require 5-ply CLT panels.

The design results of each IBC building type option also show that the column and girder sizes are larger for Types IV-B and IV-C, which use a 5-ply CLT, than Types III-A and IV-A, which use 3-ply CLT. However, the member sizes do not increase as much for Type IV-HT, which also uses a 5-ply CLT. This is because Types IV-B and IV-C use gypsum board, which also adds to dead load. Also, the columns in Type IV-B and IV-C were designed explicitly for 2 hour FRR, while Type IV-HT only needs to follow prescriptive minimum size requirements.

Table 2.5. Member sizes for each building category.

<table>
<thead>
<tr>
<th>Level</th>
<th>Building Type</th>
<th>CLT Ply</th>
<th>Column Width mm (in) [from 5th story to 1st story]</th>
<th>No. of Beams</th>
<th>Beam width [mm] x depth [mm] (in x in)</th>
<th>Girder width [mm] x depth [mm] (in x in)</th>
<th>Wood Volume m³ (ft³)</th>
<th>Final Cost USD/ m² (USD/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>III-A</td>
<td>3</td>
<td>273 (10.75)</td>
<td>3</td>
<td>222x508 (8.75x20)</td>
<td>273x686 (10.75x27)</td>
<td>112.9 (23928)</td>
<td>366 (34)</td>
</tr>
<tr>
<td>Floor</td>
<td></td>
<td>[311 (12.25), 362 (14.25), 413 (16.25), 464 (18.25), 464 (18.25)]</td>
<td>4</td>
<td>222x (8.75x24)</td>
<td>311x927 (12.25x36.5)</td>
<td>113.2 (23980)</td>
<td>547 (49)</td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>IV-A</td>
<td>3</td>
<td>273 (10.75)</td>
<td>3</td>
<td>222x521 (8.75x20.5)</td>
<td>273x686 (10.75x27)</td>
<td>113.2 (23980)</td>
<td>547 (49)</td>
</tr>
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</table>
Table 2.5 Continued

<table>
<thead>
<tr>
<th>Floor</th>
<th>Roof</th>
<th>IV-B</th>
<th>IV-C</th>
<th>IV-HT</th>
</tr>
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<tr>
<td>Floor</td>
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<td>2</td>
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<td>4</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
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<td>273x597 (10.75x2.5)</td>
<td>311x724 (12.25x2.8)</td>
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<td>273x648 (10.75x2.5)</td>
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<td></td>
<td>273x724 (10.75x2.8)</td>
<td>362x104 (14.25x4.1)</td>
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<td>311x927 (12.25x3.6)</td>
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<td>(10.75x2.5)</td>
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<td>(49)</td>
<td>(49)</td>
<td>(35)</td>
<td>(49)</td>
</tr>
<tr>
<td></td>
<td>311x673 (8.75x26.5)</td>
<td>311x699 (12.25x2.7)</td>
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<td>222x610 (8.75x24)</td>
<td>311x965 (12.25x3.8)</td>
<td>273x686 (10.75x2.7)</td>
<td>311x927 (12.25x3.6)</td>
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<tr>
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<td>(12.25x3.8)</td>
<td>(12.25x3.8)</td>
<td>(10.75x2.7)</td>
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<td>(39)</td>
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</table>
Overall, it can be seen from the comparison that for the specific example studied here, Type III-A is the most economical option based on material cost. If fully exposed wood is important to the developer, then Type IV-HT should be used. This example only explored a single building height (6-story) and column grid, thus it is possible that other building types will become more economical for different height and grid configurations. The cost composition and results from this example is reasonable and comparable to realistic projects based on authors’ experience, thus confirming the accuracy of the design cost estimation algorithm proposed.

2.7 Conclusions

An automated design and cost estimation procedure was proposed and implemented in this study for mass timber gravity system consisting of beam-column grid with CLT floors. The method used in this study provides a way to quickly assess the cost of different design layouts for gravity mass timber systems. While only one simple illustrative example was analyzed, several general conclusions can be drawn from this study:

- The automated algorithm can provide a reasonable and accurate estimation for material cost for mass timber gravity system if accurate unit cost data is given. The cost data used in this study is a rough estimation of unit costs proposed by the authors based on their experience of the current mass timber market.

- Wood material cost (and thus wood volume) is the major contributing factor to overall gravity system cost for this type of mass timber system. A change in CLT floor thickness will greatly increase building cost. When non-combustible fire protection is required, the added gypsum board and installation cost will also contribute greatly to building cost, especially for Type IV-A construction.

- For a six-story mass timber building, it is most economical to adopt Type III-A in terms of gravity system material costs. If fully exposed wood is desired, both Type IV-C and Type IV-HT are viable options.

The scope of the example investigated in this paper is limited. Conclusions specific to the illustrative example should not be generalized to all building configurations and conditions. With the proposed cost estimation tool developed, a future study can be undertaken to study sensitivity of costs to other important design parameters such as grid geometry and building height.
2.8 Data Availability Statement

All data, models, and code that support the findings of the study are available from the corresponding author upon reasonable request.
REFERENCES


CHAPTER 3

IMPLICATIONS ON COST OF MASS TIMBER BEAM-COLUMN
GRAVITY SYSTEMS

Included with permission from Shiling Pei, Gregory Kingsley, and Erin Kinder

Abstract

Interest in mass timber construction is growing and understanding the cost of mass timber buildings is important as mass timber projects are typically dependent on the cost. The growth of the mass timber industry has led to new building types (Types IV-A, B, and C) to be adopted into the 2021 International Building Code (IBC). The estimation of cost for mass timber buildings differ from that of traditional building materials (steel, concrete, and light-framed wood). An algorithm with automated design and cost estimation was developed to study the cost sensitivity for mass timber gravity systems. The algorithm implements strength and serviceability limits for the automated design. The fire rating requirements by the IBC were also implemented. The cost estimation includes the material costs of wood, connection hardware, fire-proofing materials, and an approximation of installation cost. This paper presents the implications on cost from grid configurations, the IBC building types, and other design features.

Key words: mass timber, cost, cross laminated timber, CLT, tall wood construction, gravity frame

3.1 Introduction

The invention of cross laminated timber (CLT) in Europe in the 1990’s led to the large growth of mass timber construction (MTC) globally. CLT is an engineered wood product that allows for gravity systems to be made completely out of wood. The growing interest in MTC also led to new building types, namely Type IV-A, IV-B, and IV-C, to be approved by the
International Code Council (ICC) for the 2021 International Building Code (IBC). These new code provisions allow for mass timber buildings to be constructed up to 18 stories. More information on these new code changes can be found in Breneman et al. (2019).

Strides in regulations and manufacturing of CLT and MTC have been made in the United States recently. Estimating the cost of mass timber buildings remains to be a challenge. Some cost trends are understood, such as MTC being economically advantaged in that the speed of construction is much faster than that of concrete and steel because mass timber is prefabricated. However, upfront costs of mass timber is more expensive than traditional building materials such as concrete and steel. The effects on cost from architectural and structural design choices are not well understood for the novel system of mass timber. This paper will provide insights on how the cost of the system is affected by design choices, such as the grid size, building type, and fire design.

The method for estimating cost of mass timber gravity systems includes an algorithm with an automated design selection based on allowable stress design criteria in the American Wood Council National Design Specification for Wood Construction (NDS). Serviceability requirements and the fire-resistance rating (FRR) for the different building types were also included based on the IBC. The cost estimation includes the cost of materials (timber, connection hardware, non-combustible protection) and an approximation of installation costs. The cost estimation results are analyzed to compare different mass timber gravity systems. Gravity systems utilized other materials as the primary structural frame, such as reinforced concrete, light-frame construction, etc., are not a part of the study.

3.2 Mass Timber Gravity System

The mass timber gravity system in this study is represented by a typical bay of glulam beam-column grids with CLT panels as the floor and roof. The bay dimensions are typically determined by the architectural design for real projects. When possible, a minimum number of intermediate beams are used since the CLT panel is designed to span as long as possible, based on the strength and serviceability limits and the fire rating requirements. The strength limits used in this study are based on allowable stress design requirements in the NDS (the current wood design code in the U.S.). The serviceability limits and fire resistance requirements are based on
the corresponding IBC provisions. This system uses column to column connections, beam to girder connections, and girder to column connections. These connections are typically custom and the cost depends on the capacity and design of the connection. The loads used in this study include: roof and office live load, partition live load, a superimposed dead load from a 3-in concrete floor topping and mechanical loads, and dead load from the self-weight of the materials. The program only designs for an interior bay and not for an exterior or corner bay.

The IBC building types implemented in the algorithm for this study include Types III-A, III-B, IV-A, IV-B, IV-C, and IV-HT. The newly adopted building types for the 2021 IBC are Types IV-A, IV-B, and IV-C. The main differences between the building types are the FRR, the story limit, and the maximum height. These requirements for each building type are summarized in Table 2.1. Type III-A requires 1 hour for the FRR and no non-combustible protection is required. Type III-B does not require any FRR or non-combustible protection but has a lower height limit. Type IV-A requires a FRR of 3 hours for the primary structural frame, 2 hours for the floor, and 1.5 hours for the roof. Type IV-A also requires for the primary structural frame, floor, and roof to be fully covered by non-combustible protection. Type IV-B requires a FRR of 2 hours for the primary structural frame and floor and 1 hour for the roof. Type IV-B requires partial coverage of non-combustible material. Type IV-C requires 2 hours for the primary structural frame and floor and 1 hour for the roof. Type IV-C does not require any non-combustible protection. Type IV-HT does not require any non-combustible protection and should meet the minimum size requirements prescribed in IBC Table 2304.11. It should be noted that Types IV-A, IV-B, and IV-C also need to meet the requirements in IBC Table 2304.11.

3.3 Cost Estimation of Mass Timber Gravity System

The cost estimation in this study only includes cost of structural and fire-proofing materials and a rough estimations of the installation cost (factored into the unit material costs). The cost is calculated by summing the cost per square footage of the major system components: CLT, glulam, connections, and gypsum board. The cost per square footage of the system components is calculated from the unit cost of the material and an estimation of the installation cost. The unit cost for materials is hypothetical and based on the North American market at the time of this study. Because the market supply and demand are constantly fluctuating, the unit
The unit cost of the CLT and glulam depends on the manufacturer’s efficiencies. CLT is cut from a main panel press size, which varies by manufacturer. Some of the cut lengths will have a larger associated waste which results in a larger unit cost. Because of this, the unit cost of CLT is not a linear function but rather a function that is dependent on the ratio between the pressed length to the cut length. This relationship can be seen in Figure 2.1 (an example for press lengths of 5.6 m (18.5 ft), 6.58 m (21.6 ft), 7.53 m (24.7 ft), and 9.39 m (30.8 ft) is used). The unit cost of glulam in this study is dependent on the width of the member, and generally has a positive relationship. The assumed relationship of the unit cost as a function of width for glulam beams and glulam columns can be seen in Figure 2.2 and Figure 2.3, respectively.

Because currently there is no cost date for standardized mass timber connections available for the U.S. market, the cost for the connections is assumed to be a function of connection capacity. The beam to girder connections are divided into discrete classes that are dependent on the type of connection. Class 1 is bearing type connections, Class 2 is custom bucket or knife plate connections, and Class 3 is highly specialized connections. The column connections are divided into different classes based on capacity. Class 1 ranges from 22 to 89 kN (5 to 20 kips), Class 2 ranges from 22 to 178 kN (5 to 40 kips), and Class 3 ranges from 97 to 445 kN (20 to 100 kips).

The estimated unit cost of beam to column connections are summarized in Table 2.2. The estimated unit cost for column to column connections can be seen in Table 2.3. A detailed description of the adopted connection classes can be found in Chaggaris et. Al. (2020).

### 3.4 Automated Cost Estimating

There are five major modules for the automated design and cost estimation procedure used in this study. A schematic of the program can be seen in Figure 3.1. The five major modules include: Strength and Serviceability Limit States Design (Module 1), HT Size Limits Implementation (Module 2), IBC Building Type Implementation (Module 3), Limit States Re-check (Module 4), and Cost Estimation (Module 5). Module 1 designs each structural member for each CLT thickness (3-ply, 5-ply, and 7-ply) based on the strength and serviceability limits.
This module also designs for the FRR and the non-combustible protection requirements. A rendering of the mass timber gravity system that is used in this study can be seen in Figure 2.5. The height of the bay (h), the length of the bay (b), and width of the bay (d) is manually inputted. The beam spacing (c) is found by the program and depends on the maximum span of the CLT. This module produces three structural bay designs, one for each CLT thickness. Module 2 checks each structural member design to see if the minimum size requirements in IBC Table 2304.11 are met (for building Types IV-A, IV-B, IV-C, and IV-HT). If the member size is less than the member size in IBC Table 2304.11, than that member size is increased to meet the requirement. Module 3 verifies that the story limit and maximum height are not exceeded, as per the IBC restrictions. Module 4 updates the dead load from the self-weight of the member and checks each member with the same limit states that are used in Module 1. And lastly, Module 5 finds the cost of each mass timber gravity system. The material costs are calculated with the unit-price and quantity.

![Module 1: Strength and Serviceability Limit States Design](image1)

- Design CLT and framing members for strength and serviceability limits and FRR.
- Finds gypsum coverage for FRR.

![Module 2: HT Size Limits Implementation](image2)

- Verifies if member size meets HT requirement. If not, repopulates member size with HT requirement.

![Module 3: IBC Building Type Implementation](image3)

- Checks building height and number of stories.

![Module 4: Limit States Re-check](image4)

- Finds actual self weight of each member and checks all limits.

![Module 5: Cost Estimation](image5)

- Finds cost of each element, story, and building.

**Figure 3.1** Schematic of the automated design and cost estimation program.

More details of the methodology for this study, including the cost assumptions and the procedures for the program, can be found in Chaggaris et al., 2020.

### 3.5 Sensitivity Study

To understand how the bay dimensions and different building configurations (height and building type) impact the overall cost of the design, the cost (USD/square footage) is found for multiple bay configurations for a specific building type and number of stories. A total of five different scenarios for each applicable building type were considered in this study. The analysis
was performance using the automated cost estimation tool described above, with a focus on overall building cost across the different options that are available. The analysis cases are shown in Table 3.2.

Each case uses the same stress grade for glulam, being 2.4F-1.8E. The CLT grade for each case is V2 based on APA-PRG 320. The design loads used for all cases include a roof live load of 1 kN/m² (20 psf), a floor live load of 2.4 kN/m² (50 psf), a superimposed dead load of 0.7 kN/m² (15 psf) for the roof and 2.3 kN/m² (47.5 psf) for the floor. The characteristics for each comparison include the number of stories, the building types analyzed, and the maximum floor-to-floor (FTF) height (in order to accommodate the overall building height restrictions). These characteristics are summarized in Table 3.1.

<table>
<thead>
<tr>
<th>Stories</th>
<th>Viable Building Types</th>
<th>Maximum FTF [m(ft)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>III-A, III-B, IV-A, IV-B, IV-C, IV-HT</td>
<td>3.5 (11.5)</td>
</tr>
<tr>
<td>6</td>
<td>III-A, IV-A, IV-B, IV-C, IV-HT</td>
<td>3.5 (11.5)</td>
</tr>
<tr>
<td>9</td>
<td>IV-A, IV-B, IV-C</td>
<td>2.7 (9)</td>
</tr>
<tr>
<td>12</td>
<td>IV-A, IV-B</td>
<td>3.5 (11.5)</td>
</tr>
<tr>
<td>18</td>
<td>IV-A</td>
<td>3.5 (11.5)</td>
</tr>
</tbody>
</table>

In the results below, each case outlined above will be designed with varying bay dimensions of every combination of b and d ranging from 20 feet to 30 feet. Very viable building type for a 4-story, 6-story, 9-story, 12-story, and 18-story are analyzed and their final costs compared. Since Type IV-A is the only building type that is allowed for up to 18 stories, a Type IV-A building of 4, 6, 12, and 18 stories is also compared.

3.5.1 Comparison of four-story building design

Each building type has different limits on story height and number of stories. Type III-B is restricted to four stories and is the smallest number of stories allowed out of the building types
in this study. This comparison can include all building types in this study. Figures 3.3 and 3.4 depict surface graphs and contour graphs of the cost of different bay sizes for building Types III-A, III-B, IV-A, IV-B, IV-C, and IV-HT. The bay sizes range from a bay length (b) and bay width (d) of 20 to 30 feet. Figure 3.2 depicts the surface and contour graph of Type IV-B to highlight general observations that apply to most cases in this study.

![Figure 3.2 Cost of bay configurations for 4-story Type IV-B building.](image)

There are some interesting observations that can be made from Figure 3.2. There is a significant increase in cost when b goes from 21 to 22 and from 24 to 25. This is due to the increase in cost for the CLT at those points because of the manufacturer’s panel cut lengths. This same trend can be seen in Figure 2.1. There are also a few trends that run diagonally which can be attributed to a various number of things, typically due to the beam design, and dependent on the building type. In Figure 3.2, the contour graph for Type IV-B shows three diagonal lines, one for shorter bays, one for longer bays, and one in the middle. The diagonal line in the middle (which runs from b = 20, d= 29 to b=28, d =21) is caused by an increase in the beam connection cost. At these points, the beam reaction surpasses 25 kips and so the connection cost increases significantly (the connection cost data can be seen in Table 2.2). Along this diagonal line, the bay area is the same, thus the tributary area of the beams are the same which results in a similar beam reaction. The diagonal near the top right corner of the contour graph in Figure 3.2 is caused by a decrease in cost for beams. This occurs at these points because at these bay dimensions the tributary area of the beams exceeds 400 square feet which allows for the live load to be reduced.
The diagonal at the bottom left corner occurs because the girder cost decreases. It seems that at these bay dimensions, the squarefootage of the bay is increasing faster than the volume of the girder.

Figure 3.3 Surface graph of cost of bay configurations for 4-story building types.
Figure 3.4 Contour graph of cost of bay configurations for 4-story buildings.

In every building type, there is the same trend that is caused by the CLT cost increasing because of the efficiencies of the manufacturer, which can be clearly seen in Figures 3.3 and 3.4. When comparing the surface graphs and contour graphs in Figure 3.3 and 3.4, respectively, it can
also be seen that Types III-A, III-B and IV-A have similar patterns while Types IV-B, IV-C, and IV-HT have similar patterns. This is because Types III-A, III-B, and IV-A use 3-ply CLT while Types IV-B, IV-C, and IV-HT use 5-ply CLT in the bays studied. Since the design of the beams, girders, and columns depend on the CLT type used, the building types with the same CLT have similar cost trends that depend on design. For Type III-A, III-B, and IV-A, there is an increase when \( b = 27 \). This is due to the beam cost increases because at this panel length for the 3-ply CLT, another beam is required. This does not occur for the building types that use a 5-ply CLT since the 5-ply CLT has different member properties and so the maximum panel length is different. There is also a diagonal line for the types that use 3-ply that is most evident in Type IV-A. At this point, the beam cost decreases due to the program’s fire design for Types III-A and IV-A. For Type III-B, the beam cost increases because the beam width has to increase at these bay dimensions. As for Types IV-C and IV-HT, the same trends described above for Type IV-B apply. When it comes to total cost, building Type III-B is the cheapest type for all bay dimensions for a four story building. This is the case because there is no fire design needed for Type III-B, so there is not an added cost from gypsum board or extra wood for a char layer.

### 3.5.2 Comparison of six-story buildings

The next shortest story restriction is six stories and applies to Types III-A and IV-HT. This comparison is of all building types except Type III-B. Figures 3.5 and 3.6 depict the surface and contour graphs of the cost for multiple bay sizes. The bay sizes include a bay length (\( b \)) and bay width (\( d \)) of 20 to 30 feet. Figure 3.7 shows the surface and contour graphs of the cheapest building type for that bay configuration. Figure 3.8 depicts which building type is cheapest for a given bay dimension.
Figure 3.5 Surface graphs of cost of bay configurations for 6-story buildings.
Figure 3.6 Contour graphs of cost of bay configurations for 6-story buildings.
The cheapest building type is mainly Type III-A for 6 stories, as seen in Figure 3.8. For some bay sizes, the cheapest building type is Type IV-HT. This occurs largely when \( d \) is between 20 and 22. The main design differences, and therby cost differences, for Types III-A and IV-HT is the thickness of the CLT and the non-combustible protection. Type III-A uses 3-ply CLT and has the added cost of gypsum board due to the requirement to be fully covered and having a large FRR, while Type IV-HT uses 5 ply CLT and has no gypsum cost or FRR. The peak unit cost of
CLT is when \( b \) equals 24–26 (as seen in Figure 3.1), and at that time, Type III-A is the cheapest as this type’s design uses the cheaper 3-ply CLT. When \( d \) is between 22–20, Type IV-HT is cheaper. This is because at these bay sizes, the added gypsum cost for Type III-A surpasses the cost difference between the 3-ply CLT and the 5-ply CLT. It should be noted that at the bay sizes where the cheaper cost changes from Type IV-HT to III-A, and vice versa, the cost differences of the two types are very minimal and come down to rounding. At the bay sizes further away from the line between Type IV-HT and III-A, the cost difference becomes larger.

Each building type experiences the same trends seen in the four-story comparison. There is an increase in cost when \( b \) goes from 21 to 22 and from 24 to 25 due to the increase in the unit cost of CLT. There are also cost changes running diagonally due to various reasons that are described for the four-story comparison and apply to the six-story comparison.

### 3.5.3 Comparison of nine-story buildings

The next shortest story restriction is nine stories and applies to Types IV-C. This comparison is of Type IV-A, IV-B, and IV-C. Figures 3.9 and 3.10 depict the surface and contour graphs of the cost for multiple bay sizes. The bay sizes include a bay length (\( b \)) and bay width (\( d \)) of 20 to 30 feet.

The cheapest building type for a nine-story building is Type IV-C. This because Type IV-C does not require any noncombustible protection and so there is no gypsum board cost, while Type IV-A requires to be fully covered and Type IV-B partially covered with non-combustible material.

Again, similar trends that occurred for the four-story and six-story building comparison exist for the nine-story building comparison. The cost increases due to CLT cost and other design reasons occur. These trends seem to be more distinct for building Type IV-B and IV-C. These cost trends are less drastic for Type IV-A because the cost of gypsum board for this type is significant and does not change as drastically as the CLT and connection cost.
Figure 3.9 Surface graphs of cost of bay configurations for 9-story buildings.
3.5.4 Comparison of 12-story buildings

Building Type IV-A is allowed have up to 18 stories and Type IV-B is allowed to have up to 12 stories. This comparison is of 12-story buildings for Types IV-A and IV-B. Figures 3.11 and 3.12 depict the surface and contour graphs of the cost for multiple bay sizes. The bay sizes include a bay length (b) and bay width (d) of 20 to 30 feet. Figure 3.13 shows the surface and contour graphs for the cheapest buliding type for that bay configuration. Figure 3.14 depicts which building type is cheapest for a given bay dimension.
Figure 3.11 Surface graphs of cost of bay configurations for 12-story buildings.

Figure 3.12 Contour graphs of cost of bay configurations for 12-story buildings.

Figure 3.13 Surface and contour graph of the cheapest cost of bay configurations for 12-story building.
The main design differences between Types IV-A and IV-B are the type of CLT and amount of gypsum board. Type IV-A uses 3-ply CLT and Type IV-B uses 5-ply CLT. Type IV-A also uses more gypsum board than Type IV-B as Type IV-A requires for full coverage and more FRR than Type IV-B, which requires partial coverage. At a $b$ equal to 24.5 until 27, Type IV-A is cheaper than IV-B, for the most part. This is due to the cost increase of the unit cost of CLT. At almost all other bay dimensions, the cost of gypsum board for Type IV-A supersedes the costlier CLT that Type IV-B is designed with. The diagonal section where Type IV-A is cheaper than Type IV-B coincides with the increase in cost due to beam connection cost for Type IV-B, making Type IV-A cheaper.

3.5.5 Comparison of Type IV-A cost effectiveness at different height

Because Type IV-A buildings are allowed to be built up to 18 stories, this comparison is focused on the cost effectiveness of the system at different heights. A series of designs for Type IV-A building were generated for 4-story, 6-story, 9-story, 12-story, and 18-story height. Figures 3.15 and 3.16 are of surface and contour graphs for each number of stories. The data for the 4-story, 6-story, 9-story, and 12-story are the same as the comparisons earlier but the color scale is different now that the color scale is the same for each building in this comparison. The bay sizes

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**Figure 3.14** Building type of the cheapest cost of bay configurations for a 12-story building. (3 = Type IV-A, 4 = Type IV-B).
include a bay length (b) and bay width (d) of 20 to 30 feet. The cost breakdown for a 25x25 foot bay for each building can be seen in Figure 3.17.

Figure 3.15 Surface graphs of cost of bay configurations for Type IV-A buildings.
Figure 3.16 Contour graphs of cost of bay configurations for Type IV-A buildings.
Figure 3.17 Cost breakdown for a 25x25 foot bay for a 4-story, 6-story, 12-story, and 18-story building.

As the stories increase, every major component system increases except for the CLT cost. The largest increase is seen with the column and column connections cost. This makes sense, as the columns must become much larger as the stories increase. The beams and girder cost increases because as the number of stories increase, more floor designs are added which requires larger beams and girders than the roof. And so the roof design becomes less impactful for the overall building cost. The gypsum board cost increases because there is more surface area to cover from the increase in column size.

However, it may be more economical to have a building with more storeis when the cost of the land and other building components are factored in. Assuming that the structural system is 30% of the total construction cost, and given a 160 ft x 80 ft floor plan and a 25 x 25 foot bay
system, the land price needs to be approximatley 465.43 USD/ft² for the Type IV-A 18-story to be the same cost as the Type III-B 4-story building. The calculations for the needed land price are shown below.

\[
\text{gravity system cost}_{4\text{-story}} = 27.23 \text{ USD/ft}^2 \quad \text{(from Figure 3.17)}
\]
\[
\text{gravity system cost}_{18\text{-story}} = 54.38 \text{ USD/ft}^2 \quad \text{(from Figure 3.17)}
\]

\begin{align*}
(3) \quad \text{other building cost} &= \frac{2}{3} (\text{gravity system cost}) \\
\text{other building cost}_{4\text{-story}} &= \frac{7}{3} \left( 27.23 \text{ USD/ft}^2 \right) = 63.54 \text{ USD/ft}^2 \\
\text{other building cost}_{18\text{-story}} &= \frac{7}{3} \left( 54.38 \text{ USD/ft}^2 \right) = 126.89 \text{ USD/ft}^2
\end{align*}

\begin{align*}
(2) \quad \text{building cost} &= \text{gravity system cost} + \text{other building cost} \\
\text{building cost}_{4\text{-story}} &= 27.23 \text{ USD/ft}^2 + 63.54 \text{ USD/ft}^2 = 90.77 \text{ USD/ft}^2 \\
\text{building cost}_{18\text{-story}} &= 54.38 \text{ USD/ft}^2 + 126.89 \text{ USD/ft}^2 = 181.27 \text{ USD/ft}^2
\end{align*}

\begin{align*}
(3) \quad \text{building cost}_{4\text{-story}} + \frac{\text{land price}}{\text{total square footage of building}_{4\text{-story}}} &= \text{building cost}_{18\text{-story}} + \\
\frac{\text{land price}}{\text{total square footage of building}_{18\text{-story}}}
\end{align*}

\[
\begin{align*}
90.77 \frac{\text{USD}}{\text{ft}^2} + \frac{\text{land price}}{4 \text{ stories} \times (160 \text{ feet} \times 80 \text{ feet})} &= 181.27 \frac{\text{USD}}{\text{ft}^2} + \frac{\text{land price}}{18 \text{ stories} \times (160 \text{ feet} \times 80 \text{ feet})} \\
\text{land price} &= 465.43 \frac{\text{USD}}{\text{ft}^2}
\end{align*}

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3.6 Conclusions

The program in this study that includes automated design and cost estimation provides a practical method to examine the cost of a gravity mass timber system for different IBC building types and grid configurations. Many general conclusions of how design choices affect cost can be made from this study:

- The cost of CLT and gypsum board for non-combustible protection tend to have the greatest effect on cost for the building types considered in this study.
- The cost of CLT is greatly affected by the pressed lengths used by the manufacturer. This trend is specific to the manufacturer.
- For a four-story building, the most economical building type is Type III-B due to no FRR or non-combustible protection is required for this building type.
- For a six-story building, Type III-A is the cheapest option for most of bay sizes used in this study. For bay sizes with a smaller bay width, Type IV-HT may be cheaper than Type III-A. These building types either require less FRR than the other building types or no FRR.
- For a 12-story building, Type IV-B is a cheaper option than Type IV-A for most of the bays sizes investigated in this study. The unit cost of CLT plays a large part on which building type is cheaper and so the cost of these building types greatly depend on the manufacturer.
- For building Type IV-A, the cost of the gravity system increases as the number of stories increases due to the amplification of column size and the gypsum board needed. It should be noted that this trend may not be true once other costs are factored in, such as the cost of the land.

3.7 Data Availability Statement

All data, models, and code that support the findings of the study are available from the corresponding author upon reasonable request.
REFERENCES


Automated design provides a powerful tool to seek optimal configurations of member size, grid spacing, and fire protection approach for a mass timber gravity system regarding costs. While the results from this study are limited to a very simple bay configuration with estimated cost data, some general conclusions can be drawn here:

- The most influential component for a mass timber gravity system cost is either the CLT or the non-combustible protection, depending on the IBC building type. Increasing the CLT thickness greatly increases the unit-cost of the floor system and thereby increases the overall cost of the system. For every building type, the bay that is designed with the CLT with the smaller thickness is cheaper than the bay that is designed with the CLT with the larger thickness, for all scenarios in this study.

- The unit-cost of CLT is dependent on the manufactures press panel size. As the required panel length is closer to the press panel length, the unit-cost decreases due to reduction in waste. This dynamic in pricing can sometimes affect costs of different grid dimension options, and even change the most optimal IBC building type for particular situations. The press panel lengths varies by manufacturer so it is crucial to communicate with the manufacturer of the CLT panels to find the press panel lengths so one can understand the unit-cost of the CLT.

- Only considering mass timber gravity system cost, the cheapest building type is typically dependent on the number of stories and is usually the building type that allows for that story height in the IBC. This is expected to change when other costs of the project are considered, such as non-structural finishing, lateral system, and land price.

- For gravity system price only and with the unit price assumptions made in this study, the most economical building type options for different story heights are:
  - Four-story building: exclusively Type III-B because this building type does not require any FRR or non-combustible protection.
Six-story building: Type III-A for most bay configurations in this study, because it requires the least amount of FRR. Sometimes the cheaper option is Type IV-HT, depending on the bay size.

Nine-story: exclusively Type IV-C because it requires the least amount of FRR and non-combustible protection.

 Twelve-story: Type IV-B is mainly cheaper than Type IV-A due to the added cost of gypsum board. When CLT is very costly, than Type IV-A is cheaper.

Future work should consider the cost of other building components and the land price to better compare mass timber systems to other materials. The cost data of connections (including the connection materials and installation) should also be improved when more data becomes available. Other common mass timber systems, such as the system without intermediate beams or the “honeycomb” style, should also be studied to give a more wholesome understanding of the cost effectiveness of mass timber construction as a new building style.