Cost-Effectiveness of Mass Timber Beam–Column Gravity Systems

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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 those of steel, concrete, and light-framed wood buildings. With the new building categories (Types IV-A, B, and C) introduced in 2021, 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 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 mass timber categories. **DOI:** 10.1061/(ASCE)AE.1943-5568.0000494. *© 2021 American Society of Civil Engineers.*

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Introduction

Before the 2000s, modern engineered wood buildings in North America were predominantly constructed using light-framed wood systems that have stringent height and total area limits. The taller building categories in the current codes rely either on noncombustible structural materials or on noncombustible protection (i.e., gypsum board) to achieve required fire ratings. The 2–3-h 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 (HT) members have inherent fire resistance due to their size and naturally protective charring, there has not been suitable and planar massive wood elements (i.e., wall or floor) until the invention of cross-laminated timber (CLT) panel in the 1990s. Nailed laminated timber (NLT) and dowel laminated timber (DLT) had been adopted as alternative options of CLT for floor diaphragm elements to achieve cost-saving in some projects. CLT is an important addition to wood buildings because it enables the construction of building gravity systems 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 United States (e.g., states of Oregon and Washington and 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. (2021).

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 the high level of prefabrication (which allows for low on-site labor requirements and fast construction processes). 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 the 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 the material cost of a commonly adopted mass timber gravity system, namely, beam–column grid with CLT floor panels. The gravity system is the focus of this study because it consists of a significant

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Table 1. FRR, required noncombustible protection, story limit, and maximum height for each building type

Construction type	FRR (h)			Noncombustible protection	Story limit	Maximum height [m (ft)]
	Primary structural frame	Floor	Roof			
III-A	1	1	1	Not required	6	26 (85)
III-B	0	0	0	Not required	4	23 (75)
IV-A	3	2	1.5	Fully covered	18	82 (270)
IV-B	2	2	1	Partially covered	12	55 (180)
IV-C	2	2	1	Not required	9	26 (85)
IV-HT	HT[a]	HT[a]	HT[a]	Not required	6	26 (85)

[a] HT means that this member is required to meet the size prescribed in IBC Table 2304.11.

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.

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 nonstructural 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 7.6-cm (3-in.). 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 United States. Where fire rating is required at exposed wood conditions, fire design of the mass timber components is 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 the design of an exposed mass timber system under new IBC provisions. In fire design, serviceability requirements are not checked because 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 can also be used for mass timber construction. 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 noncombustible protection if required. The FRR and noncombustible protection requirements for each building type are summarized in Table 1. Fire rating in connections is 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 an FRR of 1 h for the framing members, floor, and roof, without explicitly requiring noncombustible 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 noncombustible material. This requirement can be achieved using three layers of Type X 1.6-cm (5/8-in.) gypsum board on the exposed mass timber members in addition to 1-h FRR of the mass timber members in the primary structural frame. Type IV-B requires partial coverage of the exposed mass timber elements by noncombustible 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, ICC 2018b). Type IV-C does not require any noncombustible protection, which means all FRRs 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) (ICC 2018a). Type IV-HT does not require any noncombustible 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. However, the final decision on which type to adopt is largely dictated by the first cost.

Cost Estimation for the 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 the installation cost of a mass timber gravity system. Thus, the scope of the discussion in the following only applies to

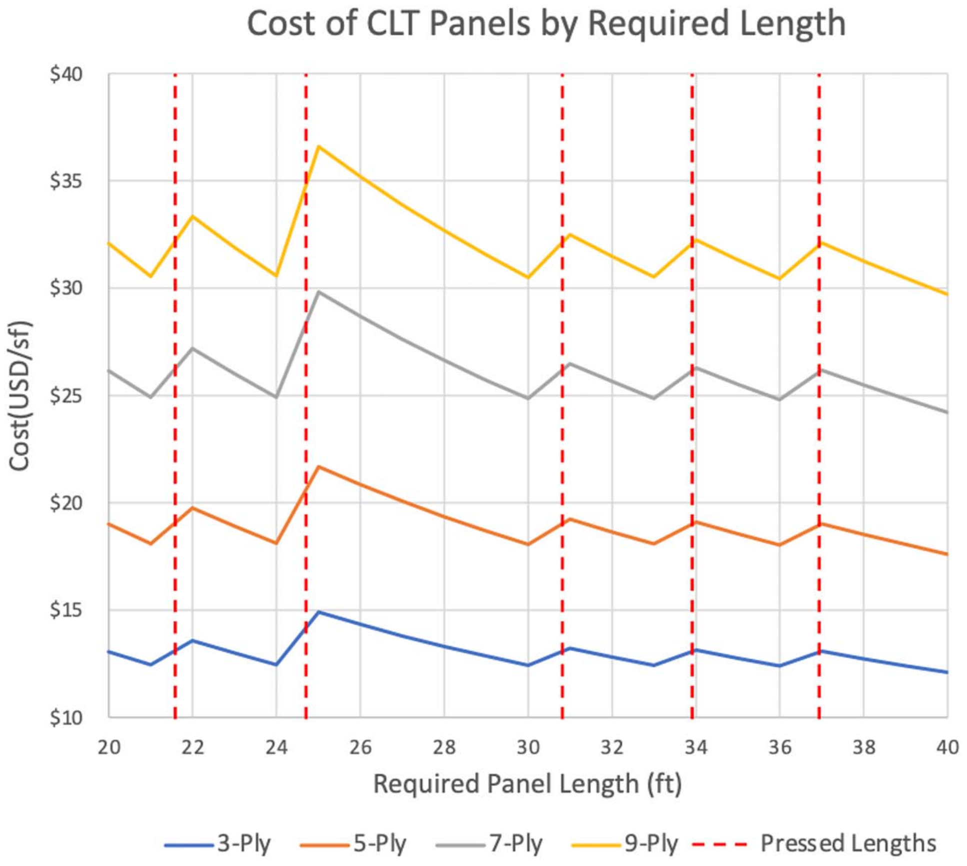


Fig. 1. Unit cost of CLT (1 ft = 0.3048 m and 1 $\mathrm{ft}^2 = 0.0929\ \mathrm{m}^2$).

the gravity system framing portion of a project. To calculate the gravity system cost, the cost for major system components is added together, namely, the material cost of the glulam, CLT panels, connections, fire-proofing material, and labor for installation (labor is included approximately in the unit costs of materials). No other cost component such as overhead costs or cost of architectural components is included. 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 a good reference value, the actual costs in this study should not be used directly in real construction projects.

The CLT unit cost is dependent on 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 the 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 Fig. 1. The example data in Fig. 1 represent the unit costs from one particular manufacturer at one point in time. The press lengths for this example are 5.6 m (18.5 ft), 6.58 m (21.6 ft), 7.53 m (24.7 ft), 9.39 m (30.8 ft), 10.33 m (33.9 ft), 11.24 m (36.9 ft), and 12.19 m (40 ft). The cost curve for other manufacturers with different production equipment and press sizes 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 Figs. 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 US market. In this study, we assume that 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.

Methodology for Automated Cost Estimation

The automated design and cost estimation procedure for mass timber gravity systems is summarized in Fig. 4. This process includes five 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 Recheck (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 the ASD procedure following NDS specifications and IBC serviceability requirements. The FRR requirements are also considered, and the noncombustible gypsum board coverage is added when needed. The program adopts a Type X 1.6-cm (5/8-in.). gypsum board as equivalent to an FRR of 40 min, 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, 5, 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 on a per-square-foot basis. The details for each module and key assumptions are explained in the following sections.

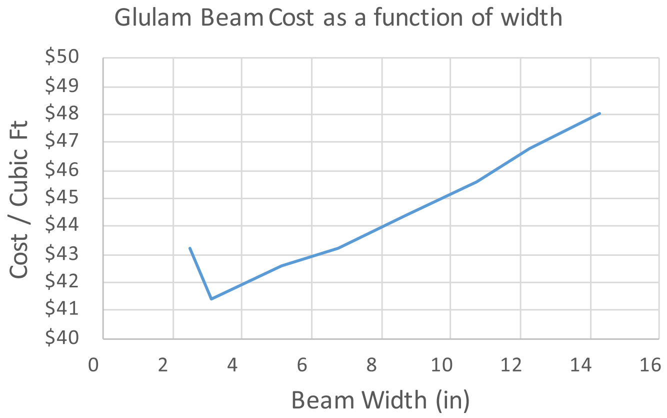


Fig. 2. Unit cost of glulam beams versus the beam width (1 in. = 25.4 mm).

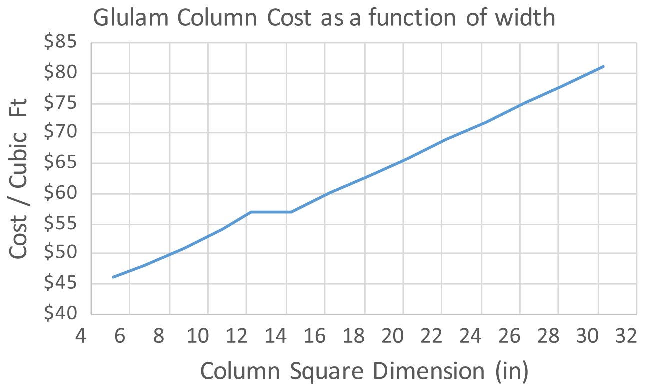


Fig. 3. Unit cost of glulam columns versus the column size (1 in. = 25.4 mm).

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 shown in Fig. 5. The input parameters include the 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), CLT properties from the manufacturer (or design values from ANSI/APA-PRG 320), 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.

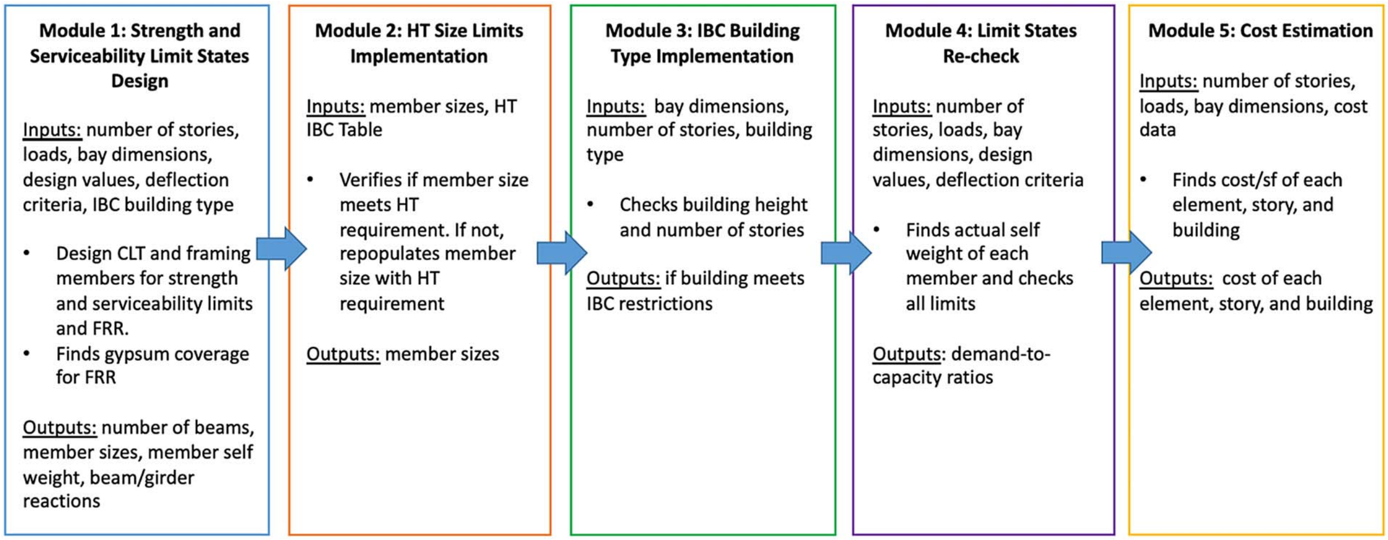


Fig. 4. Schematic of the program used in this study.

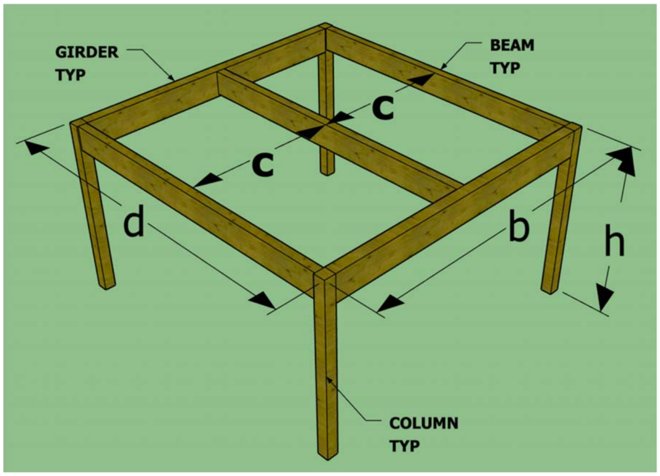


Fig. 5. Mass timber gravity system and associated grid dimensions.

Module 1: Strength and Serviceability Limit States Design

This module will conduct the 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- 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 the live load, deflection from the 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 the 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 postfire floor access.

Module 1 also calculates the weight from the required gypsum board to design each member. The program designs for Type X 1.6-cm (5/8-in.) gypsum board that has an FRR of 40 min. Type III-A does not require any noncombustible protection, but the floor and roof are designed with one 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 three layers of gypsum board for the primary framing members and two layers for the floor and roof. 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 is designed with two 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 two layers of gypsum board. The beams, girders, and columns are fully exposed. For Types IV-C and IV-HT, there is no noncombustible coverage required or used in the calculations.

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 HT member sizes specified in IBC Table 2304.11, then that member size will be increased to the minimum size required.

Module 3: IBC Building Type Implementation

Module 3 confirms that the building height and number of stories do 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.

Module 4: Limit States Recheck

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.

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 mentioned previously, all material costs are calculated based on unit price and quantity. The formula to calculate the cost of each material is shown in Eq. (1). 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 one layer of Type X 1.6-cm (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 the installation cost for each structural member can be added to the program when better cost data becomes available.

$$\sum_{\text{All MT products}} \left(\text{MT product unit cost}\,\frac{\text{USD}}{\text{ft}^3}\right) \times (\text{MT product volume ft}^3) \times \left(\frac{1}{\text{bay area ft}^2}\right) = \text{cost}\,\frac{\text{USD}}{\text{ft}^2} \quad (1)$$

Table 2. Estimated unit cost of beam–column connections

	Beam–column connection class		
Reaction (lbs)	1	2	3
0	$15.00	$75.00	$270.00
5,000	$30.00	—	—
10,000	—	$117.00	$325.00
15,000	$35.00	—	$405.00
18,000	—	$139.00	—
20,000	$85.00	$141.00	$485.00
25,000	$120.00	$163.00	—
30,000	—	—	$565.00
40,000	—	—	$645.00
>40,000	$500.00	$500.00	$1,000.00

Note: 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.

Table 3. Unit cost of column connections

	Column–column connection class		
Col square dim (in.)	1	2	3
8	$50	$100	$150
10	$75	$150	$250
12	$100	$200	$350
14	$125	$250	$450
16	$150	$300	$550
18	$175	$350	$650
20	$200	$400	$750
22	$225	$450	$850
24	$250	$500	$950
26	$275	$550	$1,050
28	$300	$600	$1,150
30	$325	$650	$1,250

Note: The cost data included in this table for connections are rough estimates and for this comparative study only. These are not reflective of the cost for any specific design.

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 US 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 that 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 Figs. 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.

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

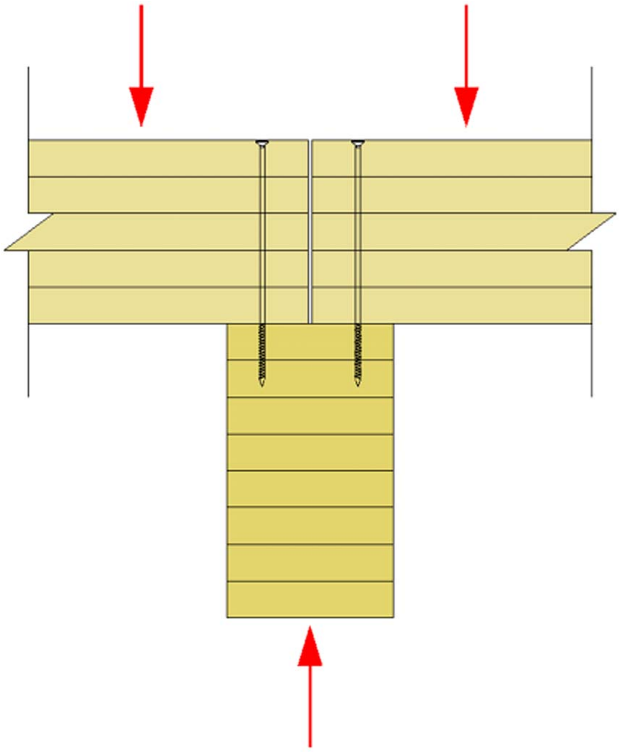


Fig. 6. Example of a bearing type connection in Class 1.

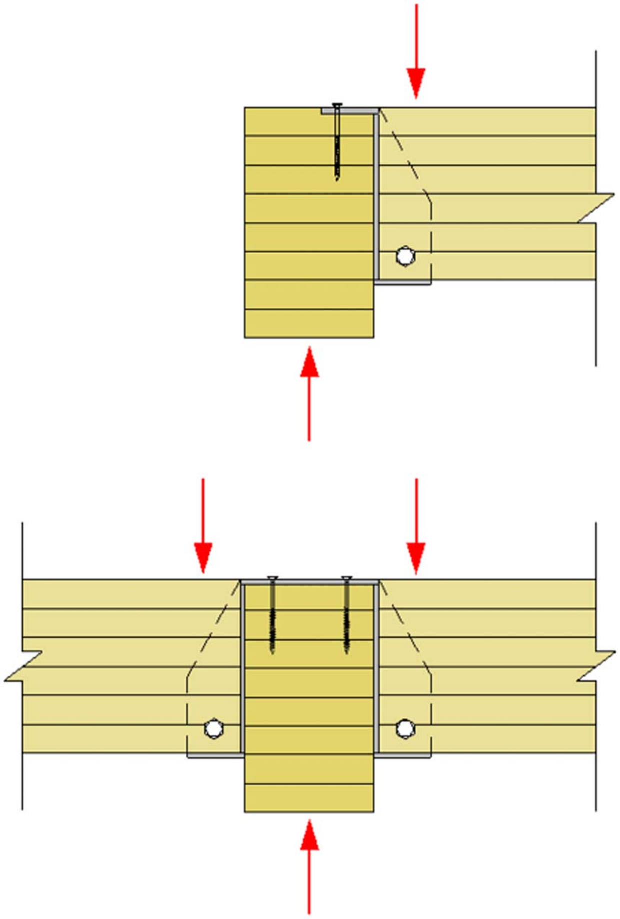


Fig. 7. Example of knife plate connection in Class 2.

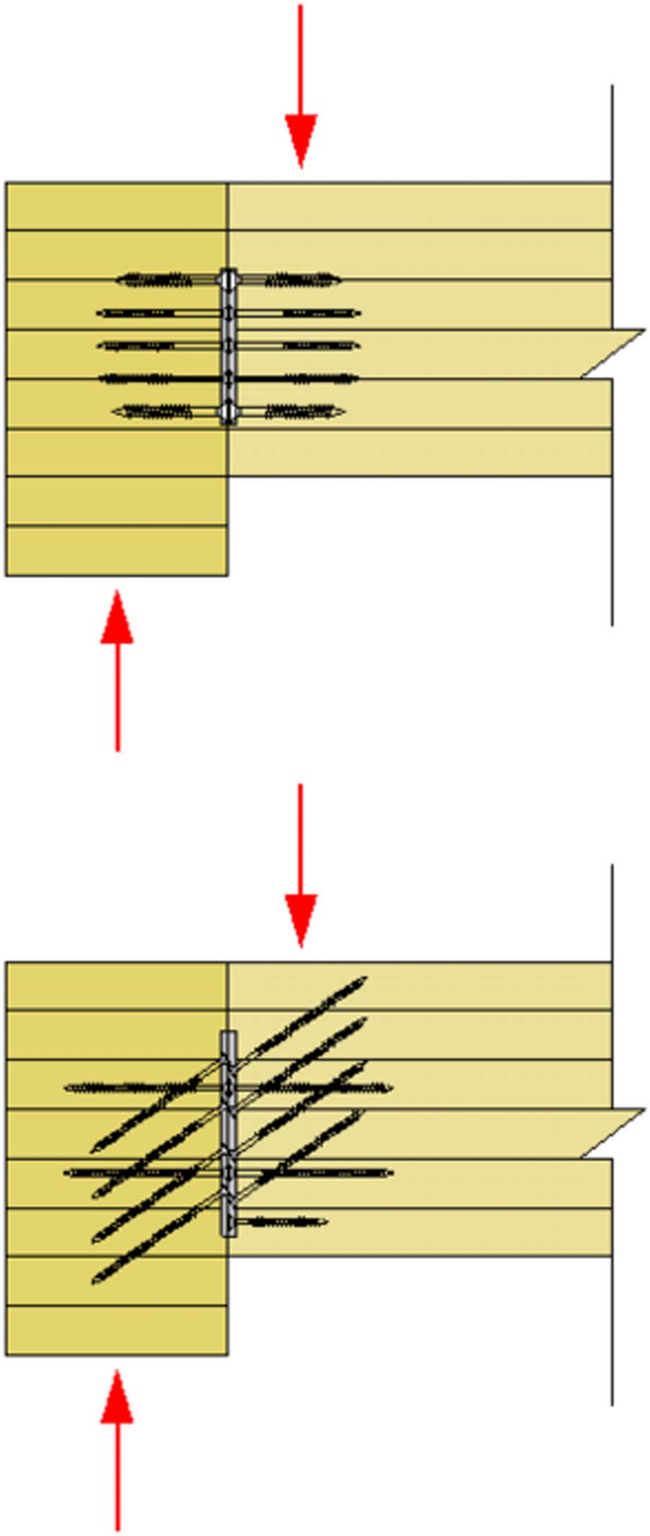


Fig. 8. Example of a concealed and high-capacity connection in Class 3.

connections 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 (5–20 kip). Class 2 is medium-strength, ranging from 22 to 178 kN (5–40 kip), and Class 3 is high-strength, ranging from 97 to 445 kN (20–100 kip). 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.

Estimated Costs for a Typical Column Grid

The automated design and cost-estimation procedure described previously is implemented using MATLAB (R2020b). The algorithm was applied to a typical column grid of 9 × 9 m (30 × 30 ft) to evaluate the cost-effectiveness of different CLT panel thickness options and IBC construction types. The selected column grid was applied to a typical six-story office building with a 60 × 90 m (200 × 300 ft) floor plan.

The design loads for the example building include a roof live load of 1 kN/m^2 (20 psf), a floor live load of 2.4 kN/m^2 (50 psf), a superimposed dead load of 0.7 kN/m^2 (15 psf) for the roof, and 2.3 kN/m^2 (47.5 psf) for the floor. The CLT panel is Grade V2 based on the properties outlined in Table 5A in ANSI/APA-PRG 320 (APA 2018). For example, the bending capacity is 18 × 10^6 N·mm/m (2,030 lbf-ft/ft), the effective stiffness is 884 × 10^9 N·mm^2/m (95 × 10^6 lbf-in^2/ft), and the shear capacity is 34 kN/m (1,430 lbf/ft) for the 3-ply CLT in the strong direction. The glulam is a 24F-1.8E grade based on the NDS (ANSI/AWC 2018). The bending stress is 16.5 N/mm^2 (2,400 psi), the compression parallel to grain stress is 11 N/mm^2 (1,600 psi), the shear stress is 1.8 N/mm^2 (265 psi), and the modulus of elasticity is 12,411 N/mm^2 (1,800,000 psi) for the glulam members. The top of the girders and the top of the beams are assumed to be below the ceiling. The total building height is 22 m (72 ft) with six 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, this is how some of the early mass timber building projects in the United States 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. 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).

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-, 5-, and 7-ply CLT. Each of these gravity systems has different costs as they have different member sizes, different CLT thicknesses, different gypsum board coverages, and different numbers of beams.

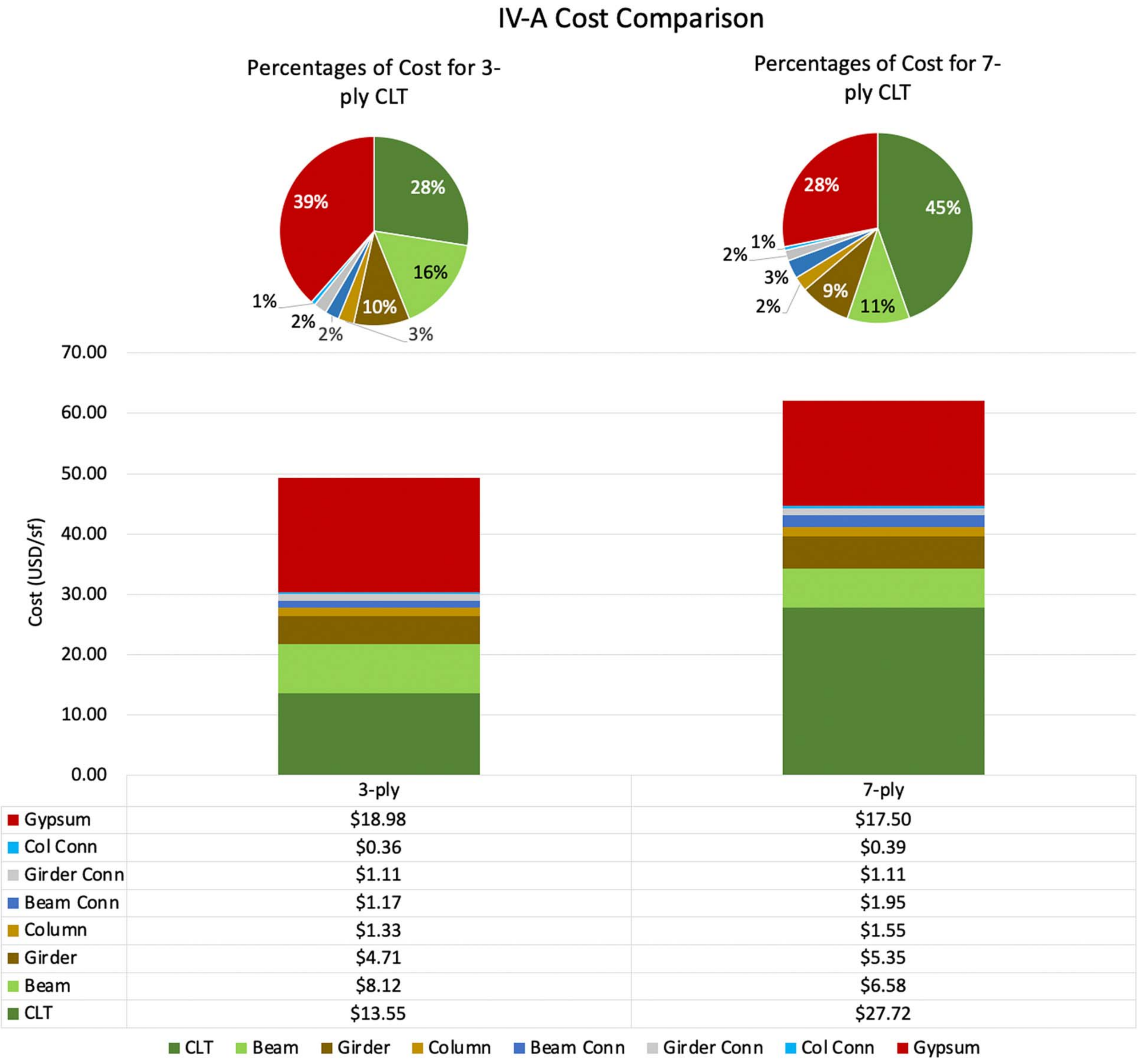
Based on IBC requirements, gravity framing members in Type IV-A need to be fully covered by three layers of Type X 1.6-cm (5/8-in.) gypsum board to achieve 120 min of FRR. The floor CLT requires two layers of gypsum board, resulting in 80 min of the FRR. A sacrificial charring layer of wood members is 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 4.

It can be seen from Table 4 that the number of beams needed in a typical column grid decreases 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 an increase in column size. The

Table 4. Member sizes for each CLT option for Type IV-A

Level	CLT ply	Column width,[a] mm (in.) (from fifth story to first story)	No. of beams	Beam width (mm) × depth (mm) (in. × in.)	Girder width (mm) × depth (mm) (in. × in.)	Average wood volume, m^3 (ft^3)	Final cost, USD/m^2 (USD/ft^2)
Roof	3	273 (10.75)	3	222 × 521 (8.75 × 20.5)	273 × 686 (10.75 × 27)	16.8 (593.4)	547 (49)
Floor		[311 (12.25), 362 (14.25), 413 (16.25), 464 (18.25), 514 (20.25)]	4	222 × 610 (8.75 × 24)	311 × 965 (12.25 × 38)		
Roof	5	273 (10.75)	2	222 × 597 (8.75 × 23.5)	273 × 724 (10.75 × 28.5)	22.8 (802.8)	616 (55)
Floor		[311 (12.25), 362 (14.25), 413 (16.25), 464 (18.25), 514 (20.25)]	3	273 × 660 (10.75 × 26)	311 × 965 (12.25 × 38)		
Roof	7	273 (10.75)	2	222 × 610 (8.75 × 24)	273 × 724 (10.75 × 28.5)	33.5 (1182.9)	697 (62)
Floor		[362 (14.25), 362 (14.25), 464 (18.25), (20.25), 514 (20.25)]	2	273 × 787 (10.75 × 31)	362 × 927 (14.25 × 36.5)		

[a]All columns in this study have a square cross section.



	3-ply	7-ply
🟥 Gypsum	$18.98	$17.50
🟦 Col Conn	$0.36	$0.39
⬜ Girder Conn	$1.11	$1.11
🟦 Beam Conn	$1.17	$1.95
🟨 Column	$1.33	$1.55
🟫 Girder	$4.71	$5.35
🟩 Beam	$8.12	$6.58
🟩 CLT	$13.55	$27.72

Fig. 9. Cost of each structural component for the 3- and 7-ply CLT options for Type IV-A.

	IIIA	IVA	IVB	IVC	IVHT
Gypsum	3.90	18.98	7.80	0.00	0.00
Col Conn	0.35	0.36	0.40	0.39	0.36
Girder Conn	1.11	1.11	1.11	1.11	1.11
Beam Conn	1.16	1.17	2.88	1.01	1.01
Column	1.24	1.33	1.55	1.48	1.33
Girder	4.55	4.71	5.95	5.72	4.55
Beam	8.09	8.12	10.34	9.92	7.92
CLT	13.55	13.55	18.99	18.99	18.99
Girder Depth	36.50	38.00	41.00	39.50	36.50

Fig. 10. Cost per square foot of each component for building Types III-A, IV-A, IV-B, IV-C, and IV-HT.

breakdown of cost composition attributed to each member type is depicted in Fig. 9 for 3-ply (most economical) and 7-ply (most costly) CLT options.

The main cost difference between the two CLT ply options in Fig. 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 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 modified allowable stress based on NDS).

Comparison among Different IBC Types

As 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 options from different IBC building types were compared. This will help provide a preliminary insight into the cost-effectiveness of these options for the six-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 overall cost of a unit bay for each building type is shown in Fig. 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 or the amount of gypsum board used becomes larger.

Table 5. Member sizes for each building category

Level	Building type	CLT ply	Column width,[a] mm (in.) (from fifth story to first story)	No. of beams	Beam width (mm) × depth (mm) (in. × in.)	Girder width (mm) × depth (mm) (in. × in.)	Average wood volume, m^3 (ft^3)	Final cost, USD/m^2 (USD/ft^2)
Roof Floor	III-A	3	273 (10.75) [311 (12.25), 362 (14.25), 413 (16.25), 464 (18.25), 464 (18.25)]	3 4	222 × 508 (8.75 × 20) 222x (8.75 × 24)	273 × 686 (10.75 × 27) 311 × 927 (12.25 × 36.5)	16.5 (584.0)	366 (34)
Roof Floor	IV-A	3	273 (10.75) [311 (12.25), 362 (14.25), 413 (16.25), 464 (18.25), 514 (20.25)]	3 4	222 × 521 (8.75 × 20.5) 222 × 610 (8.75 × 24)	273 × 686 (10.75 × 27) 311 × 965 (12.25 × 38)	16.8 (593.4)	547 (49)
Roof Floor	IV-B	5	311 (12.25) [362 (14.25), 413 (16.25), 464 (18.25), 464 (18.25), 514 (20.25)]	2 3	273 × 597 (10.75 × 23.5) 311 × 724 (12.25 × 28.5)	273 × 724 (10.75 × 28.5) 362 × 1041 (14.25 × 41)	24.4 (860.0)	543 (49)
Floor Roof	IV-C	5	311 (12.25) [362 (14.25), 413 (16.25), 413 (16.25), 464 (18.25), 514 (20.25)]	2 3	222 × 673 (8.75 × 26.5) 311 × 699 (12.25 × 27.5)	273 × 686 (10.75 × 27) 362 × 1003 (14.25 × 39.5)	24.0 (847.1)	428 (39)
Floor Roof	IV-HT	5	273 (10.75) [311 (12.25), 362 (14.25), 413 (16.25), 464 (18.25), 514 (20.25)]	2 3	222 × 584 (8.75 × 23) 273 × 648 (10.75 × 25.5)	273 × 686 (10.75 × 27) 311 × 927 (12.25 × 36.5)	22.3 (786.8)	391 (35)

[a] All columns in this study have a square cross section.

The final member dimension designs for each building category are listed in Table 5. Like the trend observed in building Type IV-A with different CLT options, the number of beams decreases as the CLT goes from 3 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 a 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-h FRR, while Type IV-HT only needs to follow prescriptive minimum size requirements.

Overall, it can be seen from the comparison that for the specific example studied here, Type III-A is the most economic option based on material cost. If fully exposed wood is important to the developer, then Type IV-HT should be used. This example only demonstrated the process and potential analysis outcome of the proposed cost estimation methodology using a single building height (six-story) and specific material choices (e.g., specific cost values for mass timber products used in the study). Thus, it is possible that other building types will become more economic for different height and grid configurations, or even when a different supplier is used. The results here only reflect the cost of the specific example. IBC mass timber building types were designed to each have their own applicable conditions (i.e., heights and wood exposure options). The cost is only one of the many factors to be considered in a design project. The cost composition and results from this example are reasonable and comparable to realistic projects based on the authors' experience, thus confirming the accuracy of the design cost estimation algorithm proposed.

Conclusions

An automated design and cost estimation procedure is proposed and implemented in this study for a mass timber gravity system consisting of a 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 is analyzed, several general conclusions can be drawn from this study:

- The automated algorithm can provide a reasonable and accurate estimation for material cost for the mass timber gravity system if accurate unit cost data are given. The cost data used in this study are 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 the building cost. When noncombustible fire protection is required, the added gypsum board and installation cost will also contribute greatly to the 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. Although the cost data used in this study are based on realistic projects conducted by the authors at the time of writing the paper, the variation of these costs will happen over time due to manufacturer change and overall MT market/economy. It is important to note that the systematic approach proposed to calculate cost by using a unit bay will be valid regardless of unit price changes, as long as the user of this approach adopts accurate material cost data as their inputs. The cost values shown in the example should not be used directly in cost estimation in real projects; they should only be used to inform relative choices between one grid layout and another. The proposed approach focusing on a representative bay does not consider the factor of economy of scale for the project. This is a real consideration in construction that is complicated and interconnected with specific site, market, and logistic conditions and thus not included in the scope of the current study. Such consideration should be incorporated in addition to unit costs calculated using the proposed approach. With the proposed cost estimation tool developed, a future study can be undertaken to study the sensitivity of costs to other important design parameters such as grid geometry and building height.

Data Availability Statement

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

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