Master Innovation & Development Plan

Technical Appendix

TITLE: Tall Timber Structural Systems

Cost and Performance of Core Walls of Cross Laminated Timber (CLT) as Compared to Steel, Concrete and Precast Concrete

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ABSTRACT

Prefabricated Mass Timber Towers offer a solution to the major urban challenge of sustainable and affordable development. A "Prototypical Model" varied at building heights of 10, 20 and 30 stories is used to compare four different structural solutions from a structural performance and cost perspective. By comparing Mass Timber to Cast-in-Place concrete, Precast concrete and Structural Steel cores, efficient Lateral Load Resisting Systems emerge, which are measured by the holistic cost of each system.

Most relevant sections: Vol 2 (Buildings and Housing)

TALL TIMBER STRUCTURAL SYSTEMS

Cost and Performance of Core Walls of Cross Laminated Timber (CLT) as Compared to Steel, Concrete and Precast Concrete

April 25, 2019

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Abstract / Executive Summary:

Prefabricated Mass Timber Towers offer a solution to the major urban challenge of sustainable and affordable development. Mass timber has many benefits such as a reduced construction schedule and cost, and improved environmental and social sustainability aspects. In order to achieve these benefits several challenges must be overcome such as efficient structural design of the lateral load resisting system, particularly for taller timber structures. A “Prototypical Model” varied at building heights of 10, 20 and 30-storey’s was used to compare four different structural solutions from a structural performance and cost perspective. By comparing Mass Timber or Cross Laminated Timber (CLT) to Cast-in-Place concrete, Precast concrete and Structural Steel cores, efficient Lateral Load Resisting Systems (LLRS) emerge, which are measured by the holistic cost of each system proposed. A final per square foot cost for each of the 12 options presented (4 systems and 3 heights), was calculated. Through a combination of characteristics including structural performance, cost, risk, and future opportunity, the structural steel braced frame core as the main LLRS in combination with a Tall Timber Gravity Load Resisting Structure (GLRS) was found to achieve the best overall performance.

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Table of Contents

Abstract / Executive Summary: ... *1*

Acknowledgements ... *2*

Chapter 1: Introduction ... *7*

1.1 Objectives & Research Methodology ... **8**

1.2 Thesis Outline ... **11**

Chapter 2: The History of Timber in Structural Systems ... *13*

2.1 Why Urban Tall Timber Development? ... **13**
Prefabricated Engineered Timber ... 15
The Forest Industry ... 15

2.2 General Structural Systems & Tall Timber Design ... **18**
Tall Wood Buildings in the 19th Century ... 18
Tall Building Structural System Innovations ... 18
Capacity Design of Concrete & Steel vs. Timber; Seismic Considerations ... 20
Modern Mid-Rise Hybrid Wood Buildings ... 21

2.3 Regulatory Framework ... **23**
Evolution of the NBCC – 2005: An Objective-Based Building Code ... 24
Tall Timber within Ontario's Regulatory Framework ... 27
The Future of Mass Timber in Code Documents ... 34

2.4 Tall Timber Case Studies ... **37**

2.4.1 Conceptual Designs of Tall Timber Towers ... **38**
2.4.1.1 FFTT (Finding the Forest Through the Trees) – MGA System: ... 39
2.4.1.2 Timber Tower Research Project – SOM System: ... 40
2.4.1.3 Oakwood Tower ... 42

2.4.2 European Tall Timber ... **43**
2.4.2.1 Treet ... 44
2.4.2.2 Mjøstårnet ... 45
2.4.2.3 Forté ... 46
2.4.2.4 HoHo ... 46
2.4.2.5 Masthamnen District ... 46

2.4.3 North American Tall Timber ... **47**
2.4.3.1 Brock Commons ... 47
2.4.3.2 T3 Minneapolis ... 48
2.4.3.3 WIDC ... 49
2.4.3.4 Origine ... 49
2.4.3.5 Framework ... 49
2.4.3.6 Sidewalk Labs at Quayside ... 50

2.5 Timber Analysis and Design Considerations ... **51**

Chapter 3: The "Prototypical" Structural System ... *53*

3.1 The "Prototypical Model" ... **54**

3.2 Gravity Load Resisting System ... **55**

3.3 Lateral Load Resisting System **57**

Chapter 4: Numerical Structural Performance Model ***58***

4.1 Qualitative Comparative Analysis **59**
4.1.1 Concrete Option 1 (Cast-in-Place Concrete) 59
4.1.2 Concrete Option 2 (Precast Concrete) 60
4.1.3 Cross Laminated Timber 61
4.1.4 Structural Steel 62

4.2 Overview & Assumptions **64**
4.2.1 Site Specific Parameters 64
4.2.3 Resistance Method: Lateral Structure & Material Option 65
4.2.4 ETABS Modelling Assumptions & Analysis 65
4.2.5 Model Limitations 68

4.3 Preliminary Structural Analysis Results **70**

4.5 Conclusion **77**
4.5.1 Total Building Drift 77
4.5.2 Wind Induced Accelerations 77
4.5.3 Other Design Considerations .... **Error! Bookmark not defined.**

Chapter 5: Cost Analysis ***79***

5.1 Efficient Structural Systems **79**
5.1.1 CLT Post Tensioned Wall and Outrigger Truss 79
5.1.2 Precast Concrete Walls 83
5.1.3 CIP Concrete Walls 85
5.1.4 Steel Braced-Frame Core 85

5.2 Cost Framework **87**

5.3 Material & Labour **88**

5.4 Schedule **90**
Schedule Comparison: The Cost of Time 90

5.5 Assemblies and Systems Integration **93**
5.5.1 Assemblies: Fire, Acoustic and Environmental Separations 93

5.6 Environmental Sustainability: Carbon Equivalents **96**

5.7 Other Design Factors **98**
5.7.1 Connections 98
5.7.2 Elevator Integration 98
5.7.3 Coordination Risk 99
5.7.4 Maintenance 99

Chapter 6: Conclusions & Next Steps ***104***
Timber 105
Steel 105
Precast Concrete 106
Cast in Place Concrete 106
Buildings Innovation 107

Recommendations **107**
Prefabrication 108

Future Work **109**
Bibliography ***113***
APPENDICES ***116***
Appendix A: Glossary of Timber Products ***117***
Appendix B: Alternative Solutions Code Statements ***119***
Appendix C: Redundancy for Timber Frame Construction For Fire Design ***120***
Appendix D: Equations for Calculating Acceleration Due to Wind ***121***
Appendix E: Steel Sections for 10, 20 & 30-Storey Core Walls ***123***
Appendix F: Loading Assumptions ***124***
Appendix G: Full Schedule for Gravity and Lateral Structural Systems ***125***
Appendix H: Background on Cost Model ***128***
Appendix I: Concrete Takeoff **128**
Appendix II: Cost of Fire Rating Timber **129**
Appendix III: Cost of Fire Rating Steel **130**
Appendix IV: Crane Cost **130**

List of Tables

Table 1: Lateral Load Resisting Systems 19
Table 2: Tall Timber Buildings Completed or Proposed (above 7 Storeys) 22
Table 3: Comparison of NBCC and the OBC Objective Statements 26
Table 4: Ontario Tall Wood Building Reference Building Classification 30
Table 5: Linked Code Statements to Fire Performance for Alternative Solution 33
Table 6: Linked Code Statements to Structural Performance for Alternative Solution 34
Table 7: "Protomodel" Typical Floor Characteristics 56
Table 8: Gravity Load Resisting Element Dimensions 64
Table 9: Material Property Calibration RFEM to ETABS 66
Table 10: Material Properties for Wall Modelling in ETABS 67
Table 11: Lateral Load Resisting System Weight and Volume 67
Table 12: Max Deflection of Towers with a 4.5m Fl. to Fl. Height 70
Table 13: Max Deflection of Towers with a 3.4m Fl. to Fl. Height 72
Table 14: Natural Frequencies of Timber Towers with Varying Lateral Materials with a 4.5m Fl. to Fl. Height 74
Table 15: Natural Frequencies of Timber Towers with Varying Lateral Materials with a 3.4m Fl. to Fl. Height 74
Table 16: The Weight and Volume of Lateral Load Structures as a Percentage of Overall Structure 75
Table 17: Geometry for Timber Towers @ 10, 20 & 30-Storey 87
Table 18: Material & Labour Cost for Various Structural Options @ 10, 20 & 30-Storey 88
Table 19: Main Value Drivers Related to Schedule 90
Table 20: Schedule Opportunity Cost for Various Structural Options @ 10, 20 & 30-Storey 91
Table 21: Fire Rating Cost for Various Structural Options @ 10, 20 & 30-Storey 95
Table 22: Acoustical Separation Cost for Various Structural Options @ 10, 20 & 30-Storey 96
Table 23: The Carbon Cost for Various Structural Options @ 10, 20 & 30-Storey 97
Table 24: Structural System Cost Comparison Matrix Summary 100
Table 25: Parametric Structural Model 109

List of Figures

Figure 1: Structural Design Flow Chart 10
Figure 2: "Racking" and "Bending" Deflection Shapes 20
Figure 3: Alternative Solutions Documentation Path 29
Figure 4: Isometric View of "Protomodel" Timber Superstructure 54
Figure 5: Plan View of a Typical Floor of the "Protomodel" 56
Figure 6: Visual Representation of Braced Frame Core & Core Walls 68
Figure 7: 10-Storey Post Tension Mass Timber Walls 80
Figure 8: 10-Storey Post Tension Mass Timber Walls W/ Outrigger Walls 81
Figure 9: 20 Storey Tower Post Tension Mass Timber Walls w/ Outrigger Truss 82
Figure 10: 10-Storey Precast Wall Section 83
Figure 11: 20 Storey Steel Braced Frame Core Structure Section 86
Figure 12: Structural Design Flow Chart 111

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Chapter 1: Introduction

In recent history the world has seen tremendous disruptive changes in the largest industries. Many in developed nations live in better conditions than royalty of less than 150 years ago with modern medicine, transportation, entertainment and all the other modern comforts we experience. Through tremendous innovation and at great cost to the environment the human population gained this high standard of living. Every industry should try to reconcile these two outcomes in order to create a sustainable future. The reconciliation starts and ends within cities, the largest 600 which produce more than half world GDP (Dobbs, et al., 2011), account for 67% of GDP growth (Bouchet, Liu, Parilla, & Kabbani, 2018) and house 1.5 Billion people. One vision for how this can be achieved in the real estate development industry is through prefabrication of timber hybrid towers in dense cities, through carbon sequestration, while providing a fast and cost effective building option which improves human health (Browning, Ryan, & Clancy, 2014).

From financial and insurance services to the manufacturing of goods and agricultural products, industries which had seen gradual productivity growth are now experiencing transformational changes due primarily to advances in technology. Contrast this with the construction industry which is slow to adopt innovations which disincentivizes upfront investment, suppressing great ideas before they have a chance to develop. Now, however, inevitable transformative disruption seems to be on the horizon for the construction industry due to the large productivity gap that has developed over the year. Companies from other industries are eyeing the industry's $11 trillion dollar pie (Global Construction Outlook to 2022 , 2018) to leapfrog traditional players. Is it possible to also work towards resilient and sustainable future, or can we merely achieve productivity growth at the next generations expense?

So why is does prefab timber construction fit the bill for a sustainable future? This construction methodology has the potential to save on building costs, deliver projects faster with healthier more beautiful and more sustainable buildings. Canada and parts of the U.S. have vast forest lands which are sustainably managed and on aggregate, growing in size year over year. Major North American markets have simultaneously been hit with labour shortages in the construction sector while manufacturing jobs continue to shrink, leading to friction within the jobs market. Instead of asking workers to leave their sheltered, productive and controlled factories to work in the unsheltered elements of today's urban construction environment, why not bring the site to the controlled environment. North American manufacturing has been in a decline over the last few decades with major operations outsourcing jobs to lower cost countries, the General Motors Oshawa facility being the most recent example. At the same time the construction sector has witnessed costs increasing at breakneck rates because labour supply cannot meet demand. This prefab timber technique offers a solution to slow productivity growth, poor safety and working conditions onsite, and higher quality products, while filling labour gaps effectively providing value for all.

1.1 Objectives & Research Methodology

Timber competes economically but at a slight premium with concrete and steel as a building material, however this is done today at the cost of great upfront work due to strict codes, lower standardization and generally a lower level of market understanding. The primary objective of this research is to directly compare the value of using different materials in the core walls as the main LLRS of tall timber gravity structures from a building cost perspective. Initially an in-depth literature review was performed on timber towers across Europe, North American and in small part, Australia. This study highlights important design considerations for timber towers, and in particular describes many of the different lateral load resisting systems which are most common in timber towers. A review of the Canadian building code then situates the current view on timber buildings. As recently as 2005 the National Building Code of Canada has shifted to an "Objective Based Code", meant to be a hybrid of Prescriptive and Performance Based Codes. The regulatory environment and recent history, especially in an Ontario context are discussed, including the most relevant factors and approval path for Tall Timber prefabricated construction systems under this relatively new code and evolving code view.

Structural Analysis of Different Systems

In order to compare the walls from a cost perspective, preliminary designs must be suggested and analyzed, to inform the material and site labour and constructability to ultimately obtain a cost figure in the correct range.

If a full design process was to be carried out, the following flowchart (Figure 1) shows the process that the structural engineer would undertake to find a safe and economical structure. For this simple study only one iteration was undertaken, in which an initial system was chosen with assumptions made for connections, and using FEM an analysis was performed for each of the 12 different structural systems. Shown in the flowchart's red box, we see that a much more in-depth process would be required to find a truly safe and economical solution (Drew, et al., 2015).

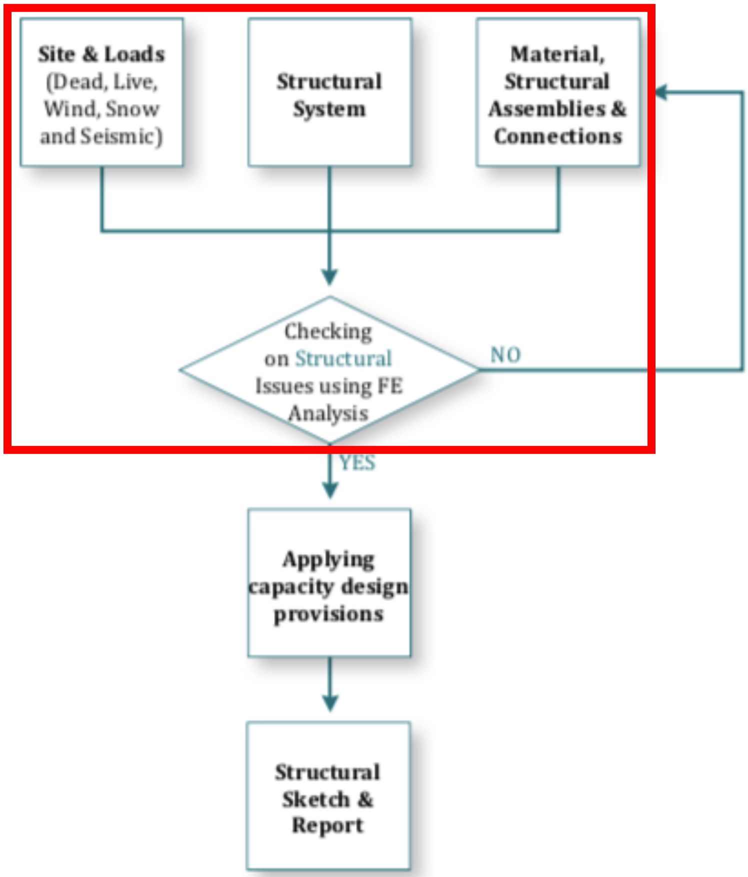

Figure 1: Structural Design Flow Chart

A simple typology was chosen which is symmetric, eliminating eccentric loading for simplicity. The twelve models of varying heights and lateral systems were compared to prescribed code design criteria.

Cost Comparison

The feasibility of each system is compared by: material and labour cost, schedule, as well as sub-assemblies such as elevators and fire & acoustically rated walls, and tax factors using carbon pricing scheme. There are several other factors which are challenging to quantify such as the difficulties coordinating different trade scopes, and how prefabrication will impact the construction industry in the future and so these are discussed from a qualitative perspective. Certain soft costs such as the cost of insurance and permitting would be significantly different for innovative systems as compared to more traditional systems but are not discussed and they will be investigated in future work.

Scope

The scope of this report covers topics of importance to prefabricated timber construction specifically related to the cost of lateral load resisting systems. The case studies demonstrate examples of both theoretically feasible and constructed structural systems. A major finding is that the mass timber industry is still in its relative infancy as compared with the concrete and steel building materials industries which each have had over a century to evolve in the modern sense. Understanding that this industry is evolving is a key factor that shouldn't be ignored when viewed from a cost and structural efficiency perspective, which is why research on this topic is important.

Feasibility Study Comparing Materials for Use in Tall Timber Lateral Systems

This study uses prototypical timber towers of 10, 20 and 30-storey heights with varied structural core systems, each with different building materials. CLT timber core walls as the main lateral resisting system are compared both from a structural performance and cost perspective with cast-in-concrete, precast concrete and steel braced frames is the lateral load resisting systems.

1.2 Thesis Outline

Chapter 2 situates this study within existing industry by looking at how the use of mass timber is evolving from both a market and code perspective and then considers cases which demonstrate taller timber projects completed around the world. Chapter 3 describes the "Prototypical" building ("Protomodel") which is a post and beam timber gravity structure with 4 unique lateral load resisting systems (LLRS). A structural analysis is performed in Chapter 4 on the four unique lateral systems in 10, 20 and 30-storey tower formats. Chapter 5 explores the practical use of each system by comparing the cost of each system based on the more important metrics including Material and Labour cost as well as cost related to schedule. Chapter 6 concludes this work by summarizing major implications from a structural and cost perspective and by introducing qualitative risk factors of each option followed by recommended approach's and next steps.

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Chapter 2: The History of Timber in Structural Systems

This chapter provides the background information necessary to understand how the use of timber in buildings systems has evolved from the early 20th century until today. The business case for using mass timber in structures is discussed along with environmental and social implications within cities. A diverse set of timber case studies are explored from various geographies and project types. The evolution of the building code is traced from the first Canadian edition in 1940 to the draft edition of the 2020 International Building Code (IBC 2020). Industry groups including building inspectors and fire marshals, developers, architects, engineers, construction professionals and suppliers, have very different but important perspectives, which are explored in this chapter.

2.1 Why Urban Tall Timber Development?

Across the globe the way people live is continuing to change dramatically. People have flocked to cities over the past several decades and now for the first time in history urban centres house over 50% of the human population. This densification continues in both the developing and developed world, in the millions of people per week and by 2050 two thirds of the human population will live in cities (United Nations, 2018). As demand for urban housing increases, cities struggle to house their growing population and affordability has become a major issue. Many factors have contributed to the rising cost of housing within major urban markets around the world. Canadian cities have been witnessing extreme economic pressures from both the supply and demand sides of the Real Estate equation. Lack of innovation within public and private organizations have contributed to the problem with antiquated approval processes and status quo building techniques. In the past few decades some industries such as agriculture and manufacturing have nearly doubled economic productivity. Unfortunately, during that same period the construction industry saw less than one percent productivity gain per year (Filipe Barbosa, 2017).

The Canadian construction sector has seen an uneven geographic distribution of jobs leading to labour shortages in cities for both skilled and unskilled workers, but this is hardly unique to Canada. The average age of the construction worker was 41.5 as of 2010, and this number is increasing leading to huge talent pipeline issues which will further exacerbate problems faced in the construction industry (Kusisto, 2018)

Worldwide about 40% of greenhouse gas (GHG) emissions come from the Real Estate and Construction industries, representing a huge environmental price to pay for urban development. Yet density is one tool which is helping curb worldwide carbon emission as it can be beneficial from both an environmental and economic standpoint, but only if administered properly. Through density, cities can reduce sprawl and therefore the overall footprint the human population has on finite global land. The land surrounding cities is often farmland and if sprawl is not minimized the quality and security of food can be degraded while exacerbating the greenhouse effect due to deforestation to replace farmland and related increased transportation needs. Public transportation is much more efficient in high density cities, both economically and environmentally.

To curb climactic carbon to acceptable levels and solve the urban housing crisis witnessed around the globe a fundamentally different approach to building construction is required. Prefabricated construction using Massive Timber (mass timber) can offer a solution to solve carbon related environmental issues by leapfrogging off innovations from technology and manufacturing industries to create highly efficient and automated construction techniques sustainably. Technical engineering and construction innovation are required to achieve the lofty goals of improved urban life by providing faster, higher quality and less expensive housing solutions that are sustainable both environmentally and socially.

Prefabricated Engineered Timber

Mass timber has become a viable material substitute to the two dominant existing structural materials, concrete and steel. There are numerous benefits to using timber to construct building. Wood buildings are **more sustainable**, since timber is a renewable resource and has a less energy-intensive process which leads to a lower carbon footprint as well as carbon sequestration from the elements themselves. Wood has a beautiful aesthetic and lends itself well to the recent shift in consumer preference towards **biophilic design** (Stephen R. Kellert, 2013), which has a measurably higher social and economic value. Leaving the structural timber exposed both improves occupant **well-being** and reduces building **material waste**, most notably in the form of gypsum wall board, both during construction and throughout the lifecycle of the structure. Timber has an **excellent specific strength**, which is the strength to weight ratio (Robert M. Foster, 2016), and more specifically high compressive and good tensile strength, when loaded parallel to the grain. Timber is modular by nature and utilising a holistic prefabricated approach can lead to more **efficient construction logistics**. The combined light weight nature and prefabricated delivery technique adds to the **transportation efficiency**, further positively impacting carbon footprint and cost. As the development industry adopts timber, new manufacturing entrants add supply to the market and construction expertise will improve driving down cost, which will make wood even more **cost competitive**.

The Forest Industry

According to Natural Resources Canada 37% of the worlds certified forests are located in Canada and as a result, higher demand for mass timber products would lead to economic growth within the Canadian forestry industry (Government of Canada, 2017). A key to understanding the sustainability of timber products lies in their supply chain. Within Canada there are almost 350 million hectares of forest. The vast majority of this forest land, over 90%, is controlled by the government. In the past 10 years, nearly 15 million hectares or 4.5% of this forest has been devastated by insects, primarily the mountain pine beetle. 3.3 million hectares were destroyed by forest fire, which is less than 1% of the forest and only about 0.5% or 766 thousand hectares were harvested for timber. The most recent (2016) published numbers on the sustainable level of harvest and the actual Canadian harvest are 232 million hectares and 155 million hectares, respectively. This means that Canada is currently only harvesting about two thirds of the timber that it could do sustainably.

In early 2019, companies within the Canadian forestry sector were dealing with increased log pricing mainly due to supply issues (The Beck Group, 2018). These issues stem primarily from the mountain pine beetle wreaking havoc in western Canadian forest lands. Though log supply to lumber mills saw an increase in the prior few years attributed to an attempt to salvage dead and dying trees, the annual allowable cut (ACC) numbers were stable at 50 million cubic meters. However, moving forward, it is estimated to be closer to 40 million cubic meters, a 20% decrease. Though Canadian crown lands supply is decreasing, supply from the southern United States is on the rise, with many new sawmills coming online or being upgraded in the coming years, which will increase lumber supply into 2025. It is important to note that lumber is a very fluid commodity, often travelling thousands of miles before reaching its end customer, which means that though Canadian markets may see a decrease in supply, overall North American supply is still increasing.

Assuming mass timber products reach a 5% market share in the building development industry, projected demand for mass timber products would double between 2020 to 2025, from 9MM m^3 to 18MM m^3. These numbers translate to about 1.3% and 2.5% of the overall market for log demand, still relatively small compared to the overall log market. There are currently 5 certified CLT manufacturing plants with an additional 5 uncertified plants manufacturing, however demand for these products is driving the launch of new fabrication facilities, which will more than double mass timber production capabilities in North America in the coming years. There are even more timber players exploring additional supply which have not yet been announced.

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2.2 General Structural Systems & Tall Timber Design

This section will discuss the history of timber buildings, the evolution of structural systems over the years including innovations beyond structure, which allowed towers to climb higher. It will lay out different tall building lateral resisting systems and provide a brief summary of the advantages of combining them. The fundamentally different capacity design approach for Timber systems is explained as compared to steel and concrete systems.

Tall Wood Buildings in the 19th Century

Prior to the 1940s, 129 timber buildings were constructed in Toronto, 43 of which were over 5 storeys and 19 between 7 or 8 storeys. During the early days of modern building codes, which were introduced in 1941, distinctions were made between combustible and non-combustible construction (Jones, 2014). This distinction limited heights for timber structures. Many of these same "Brick and Beam" buildings, which would not receive approval post the 1941 building codes, are still in use a hundred years later. Wood buildings are usually architecturally pleasing, with well-aged bricks and detailed facades, high ceilings, exposed timber posts and metal connections and beams (Koo, 2013). These "good bones" have allowed many of these buildings to survive and thrive to this day through adaptive reuse.

Tall Building Structural System Innovations

Widely considered to be the first modern tall building, the Chicago Home Insurance building was completed in 1884, 13 years after the great fire of 1871 in Chicago (Hawk, 2016). Innovative building features like new forms of steel, AC electricity, and sprinklers gave rise to ever taller towers in the following decades. As towers grew in height structural loads changed considerably.

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The gravity structure in these taller buildings is usually simple. Floors must resist the same gravity loading at every elevation and columns must be increased linearly to compensate for the increase in gravity loads with height. The Lateral Load System, on the other hand, must resist wind loading, which increases as a polynomial function due to the increasing wind velocity at higher heights. Many factors go into choosing lateral systems, such as the seismic zone, soil conditions, and architectural features, which have led to the development of different systems over the years. These systems generally fall into two main buckets: Frames and Walls and can be categorized. Table 1 lists these main two systems, and also lists the more detailed subsystems. Structural systems can be combined together in order to achieve better outcomes, and by combining a Frame-Wall system together very efficient systems can be achieved.

Table 1: Lateral Load Resisting Systems

Main System	**Frame**		**Wall**			**Outrigger**
Subsystem	Braced-Frame	Rigid-Frame	Shear Wall	Core	Framed-Tube	Outrigger-Truss
Braced-Frame						
Rigid-Frame						
Shear Wall						
Core						
Framed-Tube						
Outrigger-Truss						

The table shows potential combinations of different systems. The intended building-use, massing and architectural expression are the main factors to consider when deciding on a structural system, with the main goal being to design the most efficient and economical structural system. The lateral system is in place to reduce the side-to-side movement of structures, also known as the deflection, as well as the accelerations associated with the movement. To that end combining different systems usually has the best effects, particularly combining walls with frames can reduce the deflection greatly. This reduction in deflection is due to the different deflection profiles. Frames experience "Racking" deflections as shown in Figure 2.1, where the greatest inter-storey drift is at the base of the structure, while walls experience a "Bending Deflection" deformation, with the greatest inter-storey drift at the top of the structure. The combination of these two deformed shapes will compensate for each other's shape, reducing lateral deflection along the whole height.

In the context of tall timber buildings, which are generally lighter and less stiff, special consideration must be made when designing the lateral system. In high seismic zones, where forces are a function of building weight and ground acceleration, light weight and less stiff systems are advantageous. When considering wind forces, the opposite is true. Higher mass naturally resists the overturning moments.

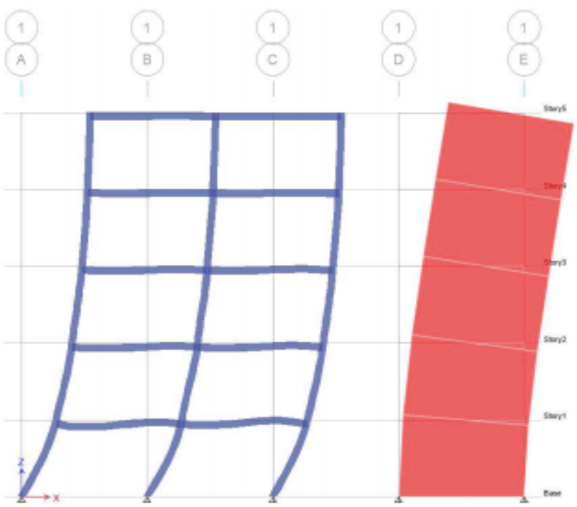

Figure 2: "Racking" and "Bending" Deflection Shapes

Capacity Design of Concrete & Steel vs. Timber; Seismic Considerations

When designing steel and concrete structural systems to resist seismic lateral loads, ductility must be holistically achieved by the structural system, so it can undergo large deformations without failing. The critical areas of the lateral load resisting system providing the ductile performance are called plastic hinges. To ensure the overall ductile behaviour of steel and concrete lateral load resisting systems, the locations of plastic hinges and their design should follow capacity design criteria.

Timber towers must take a fundamentally different approach to capacity design because unlike steel and concrete, whose beam and column elements can be designed to sustain large deformations, timber elements, on their own, are brittle. Deformations must be provided for by the connections between timber elements such as nails, screws and steel plates. In contrast, connections in concrete and steel buildings should be designed to resist failure to the highest amount. These design considerations are significant even in geographies which are not seismically active.

Modern Mid-Rise Hybrid Wood Buildings

As depicted in table 2 below, currently 48 Tall Timber Towers (7 stories or higher) have been either completed, under construction or proposed in the past 8 years (CTBUH, 2017). Most of these buildings are located in Europe, where the shift back to wood began the earliest partly by innovations like Cross Laminated Timber invented in the 1990s. North American and other international markets are beginning to embrace mass timber as well. Japan has perhaps had the longest and most consistent history of tall timber buildings.

Table 2 shows some important trends with respect to different mass timber products. CLT is, unsurprisingly, most widely used in floor systems. More interestingly the use of CLT in walls to support gravity and lateral loads is rare above 10-storeys. This indicates an economic limitation with current designs as it can structurally support buildings above this height. Taller buildings use either timber external braced frames or reinforced concrete core walls to support resist lateral loads.

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Table 2: Tall Timber Buildings Completed or Proposed (above 7 Storeys)

Building	City	Floors	Status	Gravity Load Resisting System	Lateral Load Resisting System
De Karel Doorman	Rotterdam	20	Complete	LVL beams, Spruce Plywood Floors, Steel Frames	Reinforced Concrete Core
Mjøstårnet	Brumunddal	18	Complete	Timber Framed Panel Construction (Floors 2-11), Composite Wood Floor with Concrete Topping (Floors 12-18)	Braced Glulam External Frames
Brock Commons	Vancouver	18	Complete	CLT Floors, Glulam Columns	Reinforced Concrete Core
The Treet	Bergen	14	Complete	Mass Timber Framed floors, Glulam Columns and Beams	Braced Glulam External Frames
Origine	Quebec	13	Complete	CLT Floors, Glulam Columns and Beams	CLT Core
Forte Tower	Melbourne	10	Complete	CLT Floors, CLT walls	CLT coupled walls and shafts
Lagerhuset	Eslov	10	Complete	Unknown - Adaptive Reuse	Unknown - Adaptive Reuse
Trafalgar Place	London	10	Complete	CLT Floors, CLT Walls	CLT Walls
Wenlock Cross / The Cube	London	10	Complete	CLT Floors, CLT Walls	Steel Frames
Dalston Works	London	9	Complete	CLT Floors, CLT Walls	CLT Walls, CLT Cores
Cenni di Cambiamento	Milan	9	Complete	CLT Floors, CLT Walls	CLT Walls, CLT Cores
Moholt 50/50	Trondheim	9	Complete	CLT Floors, CLT Walls	CLT Walls (interior + exterior)
Stadthaus	London	9	Complete	CLT Floors, CLT Walls	CLT Walls (interior + exterior)
Carbon 12 Building	Portland	8	Complete	CLT Floors, Glulam Columns and Beams	Steel Buckling Restrained Braced Frame Core
Arbora	Montreal	8	Complete	CLT Floors, CLT Walls, glulam columns and beams	CLT Walls & Core
Bridport House	London	8	Complete	CLT Floors, CLT Walls	CLT Walls
Holz8 (H8)	Bad Aibling	8	Complete	CLT Floors, CLT Walls	Reinforced Concrete Core
Life Cycle Tower (LCT) One	Dornbirn	8	Complete	Timber-concrete composite floors, glulam columns and beams	Reinforced Concrete Core
Limnologen	Växjö	8	Complete	CLT Floors, CLT Walls, glulam columns and beams	CLT Walls (interior + exterior
Pentagon II	Oslo	8	Complete	CLT Floors, CLT Walls	CLT Walls (interior + exterior
Puukuokka	Jyvaskyla	8	Complete	CLT Floors, CLT Walls	CLT Walls (interior + exterior
St. Diè-des-Vosges	St. Diè des Vosges	8	Complete	CLT Floors, CLT Walls, glulam columns and beams	CLT Walls (interior + exterior
Strand Parken	Stockholm	8	Complete	CLT Floors, CLT Walls	CLT Walls (interior + exterior
Studentenwohneim	Oslo	8	Complete	CLT Floors, CLT Walls	CLT Walls, CLT Cores
E3 Berlin	Berlin	7	Complete	Timber-concrete composite floors, glulam & steel columns and beams	Reinforced Concrete Core
Kingsgate House	London	7	Complete	CLT Floors, CLT Walls	CLT Walls
Maison de l'Inde	Paris	7	Complete	CLT Floors, CLT Walls, glulam columns and beams	Braced Glulam Braced Frames
Panorama Giustinelli	Trieste	7	Complete	Mass Plywood Beams/Slabs & columns	Reinforced Concrete Core

Building	City	Floors	Status	Gravity Load Resisting System	Lateral Load Resisting System
T3 Building	Minneapolis	7	Complete	NLT Floors, Glulam Posts and beams	Reinforced Concrete Core
Tamedia	Zurich	7	Complete	Glulam Columns and Beams, Connection All using Joinery	Reinforced Concrete Core
UEA (University East Anglia) Blackdale Student Residence	Norwich	7	Complete	CLT Floors, CLT Walls	CLT Walls (interior + exterior)
Wagramerstrasse	Vienna	7	Complete	Timber-concrete composite floors, CLT Walls	Reinforced Concrete Core
Wood Innovation Design Centre	Prince George	7	Complete	CLT Floors, CLT Walls, Glulam columns and beams	CLT Walls, LVL Wind Columns
Whitmore Road	London	7	Complete	CLT Floors / CLT Walls	CLT Walls
HoHo	Vienna	24	Construction	Timber floor with Concrete topping, Glulam columns and beams	Reinforced Concrete Core
HAUT	Amsterdam	21	Construction	Timber floor with Concrete topping, Glulam columns and beams	Reinforced Concrete Core
Terrace House	Vancouver	19	Construction	CLT Floors, CLT Walls, Glulam columns and beams	Reinforced Concrete Core & Steel Cores
Sanctuary	Yoker	7	Construction	CLT Floors, CLT Walls	CLT Walls (interior + exterior)
Baobab	Paris	35	Proposed	Glulam Columns and Beams	Reinforced Concrete Core
Silva	Bordeaux	18	Proposed	Glulam Columns and Beams	Reinforced Concrete Core, Braced Glulam External Frames
The Hyperion	Bordeaux	18	Proposed	Glulam Columns and Beams	Reinforced Concrete Core & Shear Walls
Canopia	Bordeaux	17	Proposed	CLT Floors, CLT Walls, Glulam columns and beams	Reinforced Concrete Core, Braced Glulam External Frames
Abebe Court Tower	Lagos	26	Proposed	Unknown @ time of Writing	Unknown @ time of Writing
55 Southbank Blvd.	Melbourne	16	Proposed	Unknown @ time of Writing	Unknown @ time of Writing
Kulturhus Skellefteå	Skelleftea	16	Proposed	Unknown @ time of Writing	Unknown @ time of Writing
25 King	Brisbane	10	Proposed	Unknown @ time of Writing	Unknown @ time of Writing
Ilôt Bois et Biosourcé	Strasbourg	9	Proposed	Unknown @ time of Writing	Unknown @ time of Writing
Ternes Villiers	Paris	9	Proposed	Unknown @ time of Writing	Unknown @ time of Writing
Barentshus	Kirkenes	20	Vision	Unknown @ time of Writing	Unknown @ time of Writing
Framework	Portland	12	On Hold*	CLT floors and glulam columns	Post-Tensioned Rocking CLT Core Walls

*Portland Project was placed on hold due to costs related to fire, tariffs and labour

2.3 Regulatory Framework

This section describes the significant regulatory hurdles that tall-wood buildings must overcome prior to being permitted. The steps taken from 1995 to 2005, to reform building codes, were mainly performed to have a major move from prescriptive design to performance-based design, a big first step fostering innovation within the construction industry. This step is very significant, particularly for timber design because of the height and area restrictions on timber buildings. The revamped building code provides an attainable path forward for buildings which lie outside current code compliance. Ontario has taken this further in recent years by publishing the "The Ontario Tall Wood Building Reference", which outlines important considerations within the province of Ontario.

Evolution of the NBCC – 2005: An Objective-Based Building Code

Building codes around the world have seen development in the design of wood buildings that are based on wind, seismic, soil, climate and extreme events including weather, fire and explosions. Timber-Frame Construction was the main method employed in the centuries leading up to our current codes and can be linked to hundreds of the known major fire disasters including: The 1666 Great London Fire, the 1852 Great Montreal Fire, and the 1871 Great Chicago Fire. Building codes have begun to acknowledge the differences between mass timber and timber-frame construction, leading to acceleration in adoption of mass timber.

The Canadian Commission on Building and Fire Codes (CCBFC) is the Canadian body that oversees the National Construction Codes of Canada (NCCC), which include: The National Building Code of Canada (NBCC), the National Fire Code of Canada (NFCC), The National Plumbing Code of Canada (NPCC) and several other guidelines acting as best practices. In 1941, the first NBCC was published; it was modelled after prescriptive codes from the United States of America. These codes were rightfully restrictive on the use of wood in buildings as the technological limitations of the time could not reasonably guarantee occupant safety. In the early 1990s, conflicting goals from distinct code-user-groups presented challenges to the CCBFC. Designers and product manufacturers of that time were pushing for a less restrictive code, namely a Performance Based Code (PBC) to foster innovation. A second group comprised mainly of homebuilders, feared that this new PBC would eliminate their "recipe-based approach" covering one to three story residential framed structures in section 9 of the 1995 NBCC. The third group consisting of mainly of code officials were concerned that this new "Performance Based Code" would create an unsafe "anything goes" environment, where they would lose control of the ability to understand and approve safe designs and products (Bergeron, 2004). Three research groups, namely the CCBFC, the Canadian Codes Centre (CCC), and the National Research Council of Canada (NRCC), teamed up to lay out a solution that would satisfy all parties. Starting in 1995 the groups began a 10-year plan to revamp the codes. The result was the Canadian "Objective Based Code", which was meant to be a hybrid approach between a "Prescriptive Code" and a "Performance Based Code" (PBC). The new code was rearranged into 3 divisions:

- Division A – Compliance, Objectives and Functional Statements
- Division B – Acceptable Solutions
- Division C – Administrative Provisions (Includes the "Alternative Solutions" path)

The main difference between a PBC format and the Objective Based Code format is that while the PBC requires a "performance level" to be laid out and proven to be achieved through design, the Objective Based Code simplifies and reduces risk by pegging the performance levels to prescriptive code levels. Designs are acceptable if they follow prescriptive guidelines or achieve equivalent performance levels while utilizing innovative ideas, and/or materials.

A second initiative to revamp the Code Documents was to facilitate the coordination between the National and Provincial/Territorial codes, which is demonstrated partially in Table 3, summarizing the overlap of Objective Design clauses of the NBCC and the Ontario Building Code (OBC).

Table 3: Comparison of NBCC and the OBC Objective Statements

<table>
<tr><th><u>National Building Code of Canada</u></th><th><u>Ontario Building Code</u></th></tr>
<tr><td colspan="2">Safety — Fire Safety</td></tr>
<tr><td colspan="2">Safety — Structural Safety</td></tr>
<tr><td colspan="2">Safety — Safety in Use</td></tr>
<tr><td colspan="2">Safety — Resistance to Unwanted Entry</td></tr>
<tr><td>Safety — Safety at Construction and Demolition Sites</td><td>- - -</td></tr>
<tr><td colspan="2">Health — Indoor Conditions</td></tr>
<tr><td colspan="2">Health — Sanitation</td></tr>
<tr><td colspan="2">Health — Noise Protection</td></tr>
<tr><td colspan="2">Health — Vibration and Deflection Limitation</td></tr>
<tr><td colspan="2">Health — Hazardous Substances Containment</td></tr>
<tr><td>- - -</td><td>Health — Privacy</td></tr>
<tr><td>- - -</td><td>Health — View to the Outdoors</td></tr>
<tr><td colspan="2">Accessibility — Barrier-free Path of Travel</td></tr>
<tr><td colspan="2">Accessibility — Barrier-free Facilities</td></tr>
<tr><td colspan="2">Fire, Structural, Water and Sewage Protection of Buildings — Fire Protection of the Building</td></tr>
<tr><td colspan="2">Fire, Structural, Water and Sewage Protection of Buildings — Structural Sufficiency of the Building</td></tr>
<tr><td colspan="2">Fire, Structural, Water and Sewage Protection of Buildings — Protection of Adjacent Buildings from Fire</td></tr>
<tr><td colspan="2">Fire, Structural, Water and Sewage Protection of Buildings-Protection of Adjacent Buildings from Structural Damage</td></tr>
<tr><td colspan="2">Fire, Structural, Water and Sewage Protection of Buildings-Water and Sewage Protection of Buildings and Facilities</td></tr>
<tr><td>- - -</td><td>Resource Conservation-Water and Energy Conservation</td></tr>
<tr><td>- - -</td><td>Resource Conservation-Infrastructure Capacity</td></tr>
<tr><td>- - -</td><td>Environmental Integrity-Air Quality</td></tr>
<tr><td>- - -</td><td>Environmental Integrity-Water and Soil Quality</td></tr>
<tr><td>- - -</td><td>Conservation of Buildings</td></tr>
</table>

These building code changes are of critical importance to the design of tall timber structures because, as described earlier they will need to follow an alternative methods code approach. The new code has laid the alternative path for taller timber buildings to follow, and the work done to tie functional statements to objectives have made the code more transparent and accessible for those designers interested in taking an innovative approach to improve structural and building efficiency.

Tall Timber within Ontario's Regulatory Framework

The Ontario Code documents include the building, fire and plumbing codes, and explicitly the Electrical Safety Code, another factor which is differing from the NBCC. They were first enacted in 1974 and represent early efforts to create a uniform building standard across the province, replacing the existing codes administered by individual municipalities. However, municipalities play critical roles within building permit approvals, inspections and, in some cases such as in the City of Toronto, still have regulations differing from the provincial level requirements.

Changes expanding the scale of the use of timber as a structural building material began to be introduced in building codes across the country in the last few years prior to 2018. The NBCC 2010 provided a path to 6 storey combustible construction under certain stipulations. British Columbia, an early adopter, was the first province to allow timber construction up to 6 storeys in 2012. Ontario followed shortly after with the 2012 Ontario Building Code (OBC) allowing the prescriptive use of timber under certain conditions. The OBC lays out two paths to code compliance for timber construction, as given in Statement 1.2.1.1 in Division A, which now mirror the NBC 2015. This statement essentially states that code compliance can be based on

"Acceptable Solutions" or "Alternative Solutions". "Alternative Solutions" are defined as solutions that meet the same "level of performance" of the equivalent acceptable solutions.

Alternative Solutions in the Ontario Building Code 2012

As stated previously, "Alternative Solutions" in Division C, are benchmarked to the levels of performance of the "Acceptable Solutions" within Division B. Statement 2.2.1.1 in Division C outlines supporting documentation including (Dr. Moses, Alexander, & Dr. Craft, 2017):

1. Listing the applicable objectives, functional statements and acceptable solutions
2. Coordinating the Design for an Alternative Solution with a single point of contact
3. Establishing Level of Performance (based on documented testing)
4. Documenting Testing Approval Process ("Statement 2.1.1.2 Tests"):
5. Specifying Qualifications and Experience of design team
6. Summarizing Limiting or Restrictive Factors
7. Engineering Studies Performed
8. Building Performance Parameters

The simplified process for achieving compliance is given in figure 3. The final phase should consist of some of the following as supporting evidence:

a) Test results
b) Calculations
c) Computer modelling
d) Scenarios analysis
e) Design scenario documentations
f) Evidence of successful performance

Figure 3: Alternative Solutions Documentation Path

Key Objectives for Municipality Approval:

In addition to the above code criteria, municipalities are mainly looking at designs through the lens of the following parameters:

- Compliance with key building code requirements,
- Coordination of design,
- Peer review of key building design elements (third party review),
- Field review (general review) of key building elements during construction.

The above parameters highlight the high standards required to overcome the regulatory hurdles to achieve approval. Only companies with the resources, expertise and time should undertake such a path. Technologies such as BIM can help with document organization, simulations, design coordination and integration. 4D simulations can be carried out with clash detection for all components. There are clear advantages to use BIM, when considering undertaking such a path.

Alternative Solutions for Tall Timber Construction

As stated previously the 2012 OBC allows for prescriptive timber tower solutions. The following table was created as part of the "Ontario Tall Wood Building Reference" which summarizes how different timber buildings are organized from a code perspective.

Table 4: Ontario Tall Wood Building Reference Building Classification

Category	<= 3 Storeys	<= 3 Storeys*	<= 3 Storeys	<= 3 Storeys	<= 4 Storeys	<= 6 Storeys	7-12 Storeys	> 12 Storeys
OBC Designation	Acceptable Solution (Part 9 & 4)	Acceptable Solution (Parts 3 & 4)	Acceptable Solution (Parts 3 & 4)	Acceptable Solution (Parts 3 & 4)	Acceptable Solution (Parts 3 & 4)	Acceptable Solution (Parts 3 & 4)	Alternative Solution	Alternative Solution
Maximum Building Area (area per floor)	1, 2, or 3 storeys: 600m2	1 storey: 2700m2 2 storey: 1350m2 3 storey: 900m2	1 storey: 3600m2 2 storey: 1800m2 3 storey: 1200m2	1 storey: 5400m2 2 storey: 2700m2 3 storey: 1800m2	1 storey: 7200m2 2 storey: 3600m2 3 storey: 2500m2 4 storey: 1800m2	1 storey: 9000m2 2 storeys: 4500m2 3 storeys: 3000m2 4 storeys: 2250m2 5 storeys: 1800m2 6 storeys: 1500m2	---	
Maximum Physical Height		-		-		18 m from ground floor to top floor		
Sprinklers	None -	None	None	NFPA 13R	NFPA 13R	NFPA 13R for 1-4 storeys; NFPA 13 for 5 and 6 storeys		
Floor Assembly Construction		45-Minute Fire Rating	1-Hour Fire Rating	45-Minute Fire Rating	1-Hour Fire Rating	1-Hour Fire Rating		
Stairwell Construction		45-Minute Fire Rating	1-Hour Fire Rating	45-Minute Fire Rating	1-Hour Fire Rating	1.5 Hour Fire Rating for all exit enclosures (noncombustible construction)		
Elevator Shaft Construction		45-Minute Fire Rating	1-Hour Fire Rating	45-Minute Fire Rating	1-Hour Fire Rating	1-Hour Fire Rating		
Building Category	- Low-Rise	Low-Rise	Low-Rise	Low-Rise	Low-Rise	Low-Rise & Mid-Rise	Mid-Rise	High-Rise

This Ontario tall wood building reference was developed to reduce barriers to timber design and construction. Interestingly, *even* acceptable solutions for combustible (Timber) construction have a higher standard of safety performance within the OBC, specifically for 6 storey towers shown, by adding redundancy in the sprinkler systems and more strict height and area requirements.

Work performed by Foster et al. defines "tallness" as the balance between the slenderness and the relative building height (Foster, 2016). Timber buildings are usually defined as "tall" at lower heights than concrete or steel buildings, which is in line with the Ontario definition which places "tall" wood buildings at about 7 stories. The term "tall" seems to be a moving target as it not only refers to a building's aspect ratio (height to floor area), but also the inherent differences with building systems in resisting damage from extreme forces, fire, smoke, moisture, rheologic (creep) and acoustic, including vibrations. These specific building loadings are of particular importance for timber structures due to the combustible, lightweight and nature of the material. The first three steps along the path to determining an adequate Alternative Solution are to determine the applicable code provisional statements, the objectives and functional statements and to identify the level of performance for each. The tables below, from the "Ontario Tall Wood Reference" summarize these specifically as they relate to the fire, smoke and structural topics for Tall Timber Buildings.

Fire Resisting Design

The actual code reference which limits the use of timber in tall buildings is shown in Table 5. The intent statement which is linked to this table is: "*To limit the probability that combustible construction materials within a storey of a building will be involved in a fire, which could lead to the growth of the fire, which could lead to the spread of fire within the storey during the time required to achieve occupant safety and for emergency responders to perform their duties*". As previously discussed, the 2005 NBCC has successfully linked all objectives and functional statements to the intent or the reasoning behind the rules. Table 5 would be part of an

Alternative Solutions document, which describes which items break the prescriptive rules from the code documents, and the original intentions for those code rules. Alternative solutions would then describe a different method by which the same level of performance is achieve through the new proposed solution.

Tall Timber buildings have unique characteristics based on their occupancy, type of structural systems, massing and m any other factors which make the alternative solutions route an onerous undertaking. An interesting goal or objective for prefabricated buildings pursuing this path should be to not only standardize assemblies for manufacturing and construction ease, but also for the purposes of expedited approvals on future projects. This "Kit of Parts" solution clearly has many advantages. Very common contradictions to acceptable solutions related to fire safety appearing in tall timber are listed below with descriptions:

- Article 3.1.5.1., "Fire-Retardant Treated Wood"

If timber products are not treated with Fire-Retardant, they are deemed "combustible"

- Subsection 3.1.11., "Fire Blocks in Concealed Spaces"

In order to reduce the spreading of fire, concealed spaces and fire blocks should be of "non-combustible" material

- Subsection 3.1.13., "Interior Finish"

Buildings which wish to expose the structural timber are non-conformant to the allowable flame spread and dimensional requirements required by code.

- Article 3.2.3.6., "Combustible Projections"

Mass timber balconies are considered combustible projections and have building to building flame spread conditions which may require special treatment.

- Article 3.2.3.7., "Construction of Exposing Building Face"

Consideration must be given to the combustibility when including timber in the wall assembly or as the exposed façade

Table 5: Linked Code Statements to Fire Performance for Alternative Solution

OBC Code References	Objective	Function	Link	Unacceptable Risks
Sentences: 3.2.2.42.(2) (Residential) And 3.2.2.49.(2) (Office)	OS1.2	F02: To limit the severity and effects of fire or explosions	so that	a person in or adjacent to the building is not exposed to an unacceptable risk of injury due to fire or explosion impacting areas beyond its point of origin
	OP1.2	F02: To limit the severity and effects of fire or explosions	so that	the building is not exposed to an unacceptable risk of damage due to fire or explosion impacting areas beyond its point of origin

Lateral Load Resisting System

Recent changes have been made within section 4 of the Code, which is the structural section. Rules have been added for both seismic and wind lateral loading. Since Toronto is a low seismic area, wind will usually govern the design of tall buildings. Notably the rules outlined for wind were updated by inserting more specific references to Wind Tunnel Testing, which should be in accordance with the procedure outlines in the American Society of Structural Engineers / Structural Engineering Institute (ASCE)/(SEI)-49.

Table 6: Linked Code Statements to Structural Performance for Alternative Solution

#	General Code Topic	Link to Functional Statements	Link to Objectives
1	Basic Conditions	F02: To limit the severity and effects of fire or explosions	
2	Engineering Design, Structure & Fasteners	F20 – To support and withstand expected loads and forces F21 – To limit or accommodate dimensional change F22 – To limit movement under expected loads and forces F23 – To maintain equipment in place during structural movement F80 – To resist deterioration resulting from expected service conditions F82 – To minimize the risk of inadequate performance due to improper maintenance or lack of maintenance	OS2 – Structural safety OS2.1 – Loadbearing capacity OS2.2 – Foundation capacity OS2.3 – Damage/deterioration of structural members OS2.4 – Vibration and deflection OS2.5 – Structure stability OS2.6 – Excavation OH4 – Vibration and deflection limitation OP2 – Structural sufficiency of the building OP2.1 – Loadbearing capacity OP2.2 – Foundation capacity OP2.3 – Damage/deterioration of structural members OP2.4 – Vibration and deflection OP2.5 – Structure stability OP2.6 – Foundation movement OP4 – Protection of adjacent buildings from structural damage OP4.1 – Foundation settlement OP4.2 – Building collapse OP4.3 - Impact OP4.4 - Excavation

The Future of Mass Timber in Code Documents

NRCan have stated their intentions to continue research contributing to safer and taller timber structures. In 2017 the NBCC proposed changes to the future 2020 code to allow a prescriptive solution allowing for up to 12 stories for a building type which will be referred to as EMTC (Encapsulated Mass Timber Construction). This means that timber will be the main structural material up to 12 storeys, however, it will be required to be fully encased in gypsum wall board so that there is a 2hr rated separation in case of fire. In March 2019, the provincial government of

British Columbia decided to adopt the 12 storey rules ahead of the rest of the nation, which may cut years off the formal provincial code text.

The International Code Council intends to revamp the International Building Code (IBC) by adopting the 14 new provisions, listed below, within the code (AWC, 2019).

1. Section 602.4 – Type of Construction **(G108-18)**
    a. Type IV-A (18 Storeys), which is fully protected structural timber,
    b. Type IV-B (12 Storeys), which allows some structural timber to be exposed and
    c. Type IV-C (9 Storeys) which allows for fully exposed structural timber
2. Section 703.8 – Performance Method **(FS5-18)**
3. Section 722.7 – Fire Resistance Rating **(FS81-18)**
4. Section 703.9 – Sealants @ Edges **(FS6-18)**
5. Chapter 7 – Section 718.2.1 – Fire and Smoke Protection **(FS73-18)**
6. Section 403.3.2 – High Rise Sprinkler Water Supply **(G28-18)**
7. Section 701.6 – Owners Responsibility **(F88-18)**
8. Section 3308.4 of the IFC – Fire Safety During Construction **(F266-18)**
9. Table 504.3 – Three Code Changes dealing with
    a. Height **(G75-18)**
    b. Number of Storeys **(G80-18)**
    c. Allowable Area **(G84-18)**
10. Chapter 31 Section 3102 – Special Construction **(G146-18)**
11. IBC Appendix D – **(G152-18)**
12. Section 508.4 and 509.4 – Fire Barriers **(G89-18)**

There are 3 new proposed construction types: Type IV-A (18 Storeys), which is fully protected structural timber, Type IV-B (12 Storeys), which allows some structural timber to be exposed and Type IV-C (9 Storeys) which allows for fully exposed structural timber. These construction types come with many additional requirements for example redundancy of sprinklers, additional fire resistance ratings on structural elements, etc. for a full list of changes, American Wood Council (AWC) created a summary document located on their website.

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2.4 Tall Timber Case Studies

There is a premium to be paid for increasing building heights, regardless of the structural material (Khan, 1969). This premium stems from the cost of the structural system. As the tower grows in height, it becomes governed by lateral forces, wind and seismic. Furthermore, as towers grow in height the p-delta effect significantly increases the demand on the vertical elements. As with any tower the significance of the following factors increase as the building becomes taller (Foster, 2016):

- Lateral Forces due to Wind and Seismic actions
- Actual lateral sway – Structural
- Perceived lateral sway – Human Comfort
- Differential vertical movements due to thermal effects and axial shortening

The inherent lightweight nature of timber and the low relative stiffness of the overall system create challenges to resist lateral forces. But even with these structural challenges and about 5% premium to account for material cost of mass timber, there are amazing benefits, outweighing the challenges. In 2012, a white paper by Michael Green titled "The Case for Tall Wood Buildings" was published providing a rationale for timber buildings in Canada (THE CASE FOR Tall Wood BUILDINGS, 2012). He has also published a book called "Tall Wood Buildings" which describes criteria to consider when designing timber structures, and also documents case studies performed on timber buildings around the world. Through the continued effort of designers like Michael Green, the world is beginning to understand and realize the benefits of building with timber.

The following summary discusses notable timber buildings from around the world. The summary will focus on structural systems employed and then list out the main learning points from these case studies as they relate to LLRS design. Following the summary, a discussion is provided about ongoing research to improve structural systems used in tall wood buildings.

2.4.1 Conceptual Designs of Tall Timber Towers

Several groups have proactively designed conceptual Timber Towers in order to push the industry forward towards acceptance of mass timber as a competitive material to build with. MGA Architecture, in concert with Equilibrium Structural Engineers, have been working in this space for many years and have created open source designs. Their work forms the basis for the "Prototypical" shell acting as the gravity load resisting system. As discussed previously, the Lateral Load Resisting System, consisting of core walls, is the topic of exploration for this study. Below is a description of the system.

2.4.1.1 FFTT (Finding the Forest Through the Trees) – MGA System:

Completed in 2012 the following excerpt from the Michael Green white paper (THE CASE FOR Tall Wood BUILDINGS, 2012) describes the structural system, which is a conceptual design:

"FFTT IS A UNIQUE TILT-UP SYSTEM THAT EFFECTIVELY BALLOON-FRAMES MASS TIMBER PANELS IN A COST EFFECTIVE AND SIMPLE MANNER TO BUILD TALL WOOD BUILDINGS. THE SYSTEM USES A STRONG COLUMN – WEAK BEAM STRUCTURAL APPROACH THAT IS DESCRIBED IN DETAIL LATER IN THE REPORT. FFTT WAS FIRST DEVELOPED BY MICHAEL GREEN AND ERIC KARSH IN 2008 AND HAS EVOLVED TO THE CURRENT APPROACH DESCRIBED HERE. MASS TIMBER PANELS ARE USED FOR FLOORS, WALLS AND THE BUILDING CORE WITH ENGINEERED WOOD COLUMNS (UP TO 12 STOREYS) AND STEEL BEAMS AND LEDGER BEAMS (12 STOREYS AND UP) INTEGRATED INTO THE MASS TIMBER PANELS SUPPORTING FLOORS. THE INTRODUCTION OF STEEL ALLOWS FOR THE 'WEAK BEAM' SOLUTION AND GREAT FLEXIBILITY FOR THE SYSTEM TO ACHIEVE HEIGHTS WITH A PREDOMINANTLY ALL-WOOD SOLUTION".

This building has a composite lateral load system. Plastic hinges were designed to happen in the steel beams to provide adequate ductility as the building was particularly geared for high seismic zones. The majority of the steel structural material exists within the walls and floors, which is the reason for referring to the building as a "predominantly all-wood solution". To achieve building heights between 12 and 30 storeys, four different configurations were outlined by Micheal Green in collaboration with Eric Karsh of Equilibrium Engineering.

- Option 1: 12 Storey building with core only
- Option 2: 20 Storey building with core and interior shear walls
- Option 3: 20 Storey building with core and perimeter moment frames
- Option 4: 30 Storey building with core and perimeter moment frames and interior walls

The different options exist to both show the limitations of certain types of systems, but also to show the importance that architectural and programmatic intent takes. The final use is extremely important and should be central to the design. Offices are usually designed to have an open concept which allows for more flexible use, whereas the residential typology will often compartmentalize units which will naturally lead to regular partition walls. Flexibility over time is a hugely important factor as buildings might change use several times over their typically 100-year life.

2.4.1.2 Timber Tower Research Project – SOM System:

The SOM Engineering Timber Tower Research Project was initiated to design a Mass Timber structural system for a real residential tower in Chicago, considering different heights (10, 20, 30 and 42-storeys). This hypothetical and conceptual timber design was compared to the benchmark tower designed by SOM decades before, which was a 42-storey tower of concrete construction. The study highlights many of the benefits and issues with using Timber in high rise buildings and speaks to the benefits of using timber composite elements and assemblies. The use of different materials, where their overall strength and benefits are maximized will create more optimal design outcomes.

The following is an excerpt explaining the Lateral Load Resisting System (SOM, LLP, 2013):

"The lateral load resisting system consists of solid mass timber CLT or similar shear walls. The shear walls are primarily located around the vertical transportation and service core at the center of the building forming a large tube which resists wind in both directions as well as overall building torsion. Supplementary shear walls extend from the central core to the perimeter of the building at the east and west ends of the core. These walls are critical to resist net building uplift due to wind forces on the broad

face of the building. The shear walls that extend from the central core reduce in length along the height of the building as the overturning demands from wind decrease. The shear walls are coupled by reinforced concrete link beams to make the entire building act like one large vertically cantilevered beam similar to a traditional tall building system. The link beams must resist large shears and bending moments to couple the walls and are reinforced accordingly. The design approach for this system followed similar strategies that would be applied to a tall concrete building utilizing coupled shear walls.

Acoustic and architectural finishes applied to the floor panels result in 3 inches of additional ceiling sandwich thickness for the Prototypical Building compared to the Benchmark Building. This requires the floor to floor dimension to increase from 8'-9" to 9'-0" in order to maintain the same floor to ceiling height. The additional floor to floor height increases the total height of the Prototypical Building by 10'-6" which results in additional wind loads on the building".

The interesting elements of the SOM Engineers design lay in their innovative use of different structural materials maximizing their inherent strength. Timber is the primarily gravity structure and is used in the floors of the tower, where most of the building material is to maximize the CO_2 sequestration benefits. Concrete is used in the exterior spandrel beams, which add ballast weight to the structure, important to counteract the overturning moment. These link beams also minimize beam depth adding natural light and maximizing spans between columns, and improving flexibility. These longer spans also add load to the timber columns, and as a result there are fewer and larger exposed timber columns improving efficiency as larger square columns reduce the amount of sacrificial timber to be used in fire protection. A concrete topping is added to the timber slabs, which improves ICC sound transmission protection, while increasing ballast weight further counteracting the overturning moment.

2.4.1.3 Oakwood Tower

As the development world grapples with the idea of using mass timber as the main structural material in relatively modest 20 to 40 storey towers, the architecture firm PLP along with leaders in timber design have outlined a technically feasible 300m tower located in the heart of London, England. This tower and research project push out the boundaries of what was thought possible for an all wood tower.

The light weight nature of timber buildings poses unique design challenges and opportunities. A typical concrete building will have a bulk density of 300kg/m3, steel buildings with poured concrete deck typically have a mass of 160kg/m3, while all timber structures can have a bulk density in the range of 110-125kg/m3. Timber has high axial strength parallel to the grain, however strength and stiffness perpendicular to the grain are an order of magnitude less, this orthotropic property is unique as compared with concrete and steel, which are isotropic. Timber must be carefully detailed to ensure proper load transfer through connections, which must also be designed to create a stiff interface. These properties make an external braced frame with wide open interior spans, the ideal system as it ensures all gravity loading is fed to the exterior lateral and gravity support system. An excerpt from a paper by Foster and Ramage summarizes a major consideration for any tall building utilizing a frame structure independent of material (Robert M. Foster, 2016): *"As buildings get taller, the overturning moment at the base increases by a power of two, and the bending deflection at the top of the building increases by a power of four. Shear deflections can increase total displacements at the top of the building by*

EVEN GREATER AMOUNTS. THIS MEANS THAT SUPERTALL BUILDING DESIGN IS OFTEN GOVERNED BY THE DESIGN OF THE LATERAL LOAD RESISTING SYSTEM. IT IS GENERALLY DESIRABLE FOR A BUILDING TO BE CAPABLE OF RESISTING OVERTURNING UNDER THE STRONGEST LATERAL LOADS DUE TO ITS SELF-WEIGHT ALONE, AND FOR IT TO BE CAPABLE OF RESISTING NORMAL SERVICE LOADS WITHOUT UNDERGOING LOAD REVERSAL. SINCE SUPERTALL BUILDINGS ARE USUALLY RATHER SLENDER – TYPICALLY HAVING SLENDERNESS RATIOS GREATER THAN SEVEN – THEY ARE GEOMETRICALLY DISADVANTAGED IN RESISTING OVERTURNING. IN ORDER TO MITIGATE THIS FUNDAMENTAL GEOMETRICAL DISADVANTAGE, IT IS IMPORTANT TO DIRECT THE VERTICAL LOADS IN THE BUILDING INTO THE LATERAL LOAD RESISTING SYSTEM AND TO POSITION THE LATERAL LOAD RESISTING SYSTEM AS CLOSE TO THE PERIMETER OF THE BUILDING AS POSSIBLE"

Initially two different structural systems were explored, namely a "Crossed Mega I-Beam" and a "Buttressed Mega Truss". Ultimately the Buttressed Mega Truss system was chosen because it better met the architectural aspirations. As the central tower rises up to the ultimate 300m height, buttress towers at the four perimeter corners drop away which act to confuse the wind while providing a large footprint at the base of the structure. This "Large-Scale Bracing" is used in the form of "Diagonal-Braces" which span within the façade of the building. Brace spans the width of each individual face and 10-storeys in height.

2.4.2 European Tall Timber

Europe has utilized mass timber in construction in modern history much more than the rest of the world and have been innovating over the past 50 years, which can be attributed primarily to the more favorable view from a code perspective as well as higher environmental design standards. The Softwood Lumber Board and Forestry Innovation Investment sponsored the production of

"100 UK CLT (Cross Laminated Timber) Projects", an assemblage of over 100 cases of CLT projects completed in the UK. Scandinavian countries have long utilized mass timber which is where the CLT product was invented over 30 years ago. Timber towers across Europe use different structural systems, however, the use of External Braced Frames is by far the most common type of LLRS, for the tallest towers completed.

2.4.2.1 Treet

Treet is a tower constructed in Bergen, Norway, the name means "The Tree" in Norwegian. The structural system utilizes an external braced frame with members spanning half of each face and several storeys. An excerpt from a paper (K. A. Malo, 2016) below describes the structural system in detail:

THE IDEA OF THE STRUCTURAL DESIGN CONCEPT MAY BE EXPLAINED BY AN ANALOGY TO A CABINET RACK FILLED WITH DRAWERS (ABRAHAMSEN AND MALO 2014). HERE, THE CABINET RACK IS FORMED BY LARGE GLULAM TRUSSES, AND THE DRAWERS CONSIST OF PREFABRICATED RESIDENTIAL MODULES. THE GLULAM TRUSS WORK HAS CLOSE RESEMBLANCE TO THE DESIGN CONCEPTS USED IN MODERN TIMBER BRIDGE STRUCTURES." AND "THE GLULAM TRUSSES ALONG THE FAÇADES GIVE THE BUILDING ITS NECESSARY STIFFNESS. THE CLT ELEMENTS ARE LIGHTLY SUPPORTED BY THE LOAD BEARING STRUCTURE, BUT THE CLT STRUCTURE HAVE INSIGNIFICANT CONTRIBUTION TO THE GLOBAL STIFFNESS OF THE OVERALL BUILDING. THE CLT WALLS ARE HENCE ALMOST INDEPENDENT OF THE MAIN LOAD BEARING SYSTEM, AND DO NOT SHOW HIGH STRESSES FOR HORIZONTAL LOADING". AND "PREFABRICATED BUILDING MODULES COMPRISE THE MAIN VOLUME OF THE BUILDING. THE MODULES ARE STACKED UP TO FOUR STOREYS, AND ARE FOUND ON LEVELS 1–4, 5, 6–9, 10 AND 11–14".

The building self-weight does not counter overturning and therefore tension piles were used in the foundation, which hold the building in tension through concrete anchors which connect to columns and beam-columns, which were also designed with these tensile forces in mind.

2.4.2.2 Mjøstårnet

Soon to take the lead as the world's tallest timber building, this 18-storey timber building is under construction and will be opened in March 2019 with a net building area of 11,300m2. This is a mixed-use building. Below is an excerpt describing the structural system (Abrahamsen, 2017): "THE MAIN LOAD BEARING CONSISTS OF LARGE SCALE GLULAM TRUSSES ALONG THE FAÇADES AS WELL AS INTERNAL COLUMNS AND BEAM. THE TRUSSES HANDLE THE GLOBAL FORCES IN HORIZONTAL AND VERTICAL DIRECTION AND GIVE THE BUILDING ITS NECESSARY STIFFNESS. CLT WALLS ARE USED FOR SECONDARY LOAD BEARING OF THREE ELEVATORS AND TWO STAIRCASES. THE CLT DOES NOT CONTRIBUTE TO THE BUILDING'S HORIZONTAL STABILITY. MJØSTÅRNET HAS MANY SIMILARITIES WITH THE 14-STOREY TIMBER BUILDING TREET IN BERGEN, WHICH WAS COMPLETED IN DECEMBER 2015. THE TWO MOST SIGNIFICANT DIFFERENCES ARE THAT MJØSTÅRNET WILL BE ABOUT 30 M TALLER, AND THAT THE BUILDING MODULES USED IN TREET ARE EXCHANGED WITH PREFABRICATED FLOOR AND WALL ELEMENTS. BUILDING MODULES RESTRICT THE FLEXIBILITY OF THE AREAS, AND THIS WAS NOT COMPATIBLE WITH THE MIXED FUNCTIONS REQUIRED FOR MJØSTÅRNET. THE LARGE PREFABRICATED FAÇADE ELEMENTS ARE ATTACHED TO THE OUTSIDE OF THE TIMBER STRUCTURES AND MAKE UP THE ENVELOPE OF THE BUILDING. THESE SANDWICH TYPE ELEMENTS COME WITH INSULATION AND EXTERNAL PANELS ALREADY FIXED. WALL ELEMENTS DO NOT CONTRIBUTE TO THE GLOBAL STIFFNESS OF THE BUILDING. IN TOTAL THERE ARE ABOUT 2600 M3 OF TIMBER STRUCTURES IN MJØSTÅRNET".

Interestingly this tower utilizes an external braced frame, and though the core is made of CLT, which has structural strength, it does not contribute to the lateral load resisting system.

2.4.2.3 Forté

This 10-Storey apartment building is located in Victoria, Australia. It was, however, built with mainly CLT elements shipped by sea freight from Austria. Lendlease, a massive multinational vertically integrated developer, has helped pave prefabricated mass timber to begin gaining traction in the Australian market.

The 1st floor, which required long spans to accommodate retail space, was built using concrete. The Self-Supported CLT structure is used to support the tower from both gravity and lateral loads. This form of CLT construction lends itself efficiently to a residential typology where the structural walls are used to partition units as well.

2.4.2.4 HoHo

This 84m, 24-floor tower will be a mixed use development located in Vienna, Austria currently under construction and slated to be complete in 2019 (The Skyscraper Center, 2017). This composite building is comprised of about 76% timber with a CIP concrete core which acts as the lateral support for the structure (Timber Technology and Design, 2017).

2.4.2.5 Masthamnen District

Located in Stockholm, Sweden, this new neighbourhood will utilize primarily CLT to construct 31 slender towers of heights varying between 25 and 30 storeys. Though plans are very preliminary, this master-planned community is yet another demonstration of the proliferation of the use of mass timber as a structural material (Block, 2018).

2.4.3 North American Tall Timber

The use of mass timber in the North American market have been accelerating, especially in the last several years, having followed the lead of Europe. These ideas have been incubating the longest on the west coast in geographic pockets like Vancouver, British Columbia, which is a microcosm for what the industry could become across the continent. The spread has already begun and 2018 has marked what seems like a significant shift in the red-hot Toronto housing market with several mid to high-rise mass timber towers beginning construction and being announced. The Canadian government is supporting the development of this industry by dedicating tens of millions of dollars towards the research and development of new systems and proof-of-concept towers. Brock Commons and Origine, described below, are two examples of buildings which were part of some of these Canadian government competitions.

2.4.3.1 Brock Commons

Currently the tallest wood structure in the world, this building in Vancouver, British Columbia, employs a composite structural system in which the gravity loads are resisted by the timber elements and the lateral loads are resisted by the CIP concrete core walls. This comparatively simple lateral system has many advantages such as non-combustible egress paths, an abundance of supply and contracting expertise, and a relatively well-known structural system which allows for incremental innovation. This system has drawbacks such as requiring site labour upfront which extends the construction phase and additional coordination burden between two structural contractors. A description of the structural system is paraphrased below (Canadian Wood Council (CWC), 2017): "TWO CONCRETE CORES, DESIGNED AS DUCTILE CONCRETE SHEAR WALLS IN THE SHORTER, NORTH/SOUTH DIRECTION, AND PARTIALLY COUPLED DUCTILE CONCRETE SHEAR WALLS IN THE LONGER, EAST/WEST DIRECTION, PROVIDE THE PRIMARY LATERAL SUPPORT FOR

EARTHQUAKE AND WIND LOADING IN THE BUILDING. THE FLOOR DIAPHRAGMS ARE A CRITICAL PART OF THE LATERAL SUPPORT SYSTEM. THE CLT PANELS AND CONNECTIONS FOR THE STRUCTURE HAD TO BE DESIGNED TO REMAIN ELASTIC FOR ENERGY DISSIPATION WHEN THE CORES YIELD IN FLEXURE. CONTINUOUS DOUGLAS FIR PLYWOOD SPLINES, NAILED INTO CLT DADOES WITH RING SHANK NAILS, TRANSFER IN-PLANE DIAPHRAGM SHEAR FORCES BETWEEN PANELS. PARTIALLY THREADED SCREWS TRANSFER VERTICAL SHEAR ACROSS PANEL JOINTS AND ENSURE A FLUSH PANEL-TO-PANEL FIT. STEEL STRAPS, FASTENED TO THE CLT FLOOR PLATES WITH PARTIALLY THREADED SCREWS AND BOLTED TO CAST-IN EMBED PLATES, DRAG DIAPHRAGM FORCES INTO THE CORES. AS WITH THE CLT FLOOR PLATE DIAPHRAGMS, THE REINFORCED CONCRETE FOUNDATION AND PODIUM WAS DESIGNED AS A "CAPACITY PROTECTED" ELEMENT TO RESIST OVERTURNING MOMENTS EQUAL TO THE PROBABLE FLEXURAL CAPACITY OF THE CORES.8 SPECIFIC FACTORS ALSO ADDRESSED IN THE DESIGN OF THE BROCK COMMONS HYBRID MASS TIMBER STRUCTURE WERE AXIAL COLUMN SHORTENING, DYNAMIC AND WIND-INDUCED VIBRATIONS AND PROGRESSIVE COLLAPSE"

2.4.3.2 T3 Minneapolis

Completed in 2016 this 7-storey (6 stories of mass timber) tower was built within the prescribed code requirements for Mass Timber. The building was constructed by using post and beam GLT columns supporting NLT slab panels (Guevara, 2017). The primary LLRS utilized a concrete core. Multinational developer Hines developed the "T3" concept, which stands for "Timber Technology and Transit, was tested first in Minneapolis but there are plans to continue iterating designs to improve economy and build several towers around North America. The next generation, T3 Atlanta, will utilize a steel "External Braced Frame" as the lateral load resisting system. There are rumors of a T3 Toronto, but the structural system has not yet been released.

2.4.3.3 WIDC

The Wood Innovation and Design Centre at the University of Northern British Columbia in Prince George was completed in 2016. It is a 6 Storey structure, with a total height of 29.5m. The main LLRS employed CLT Elevator Core walls coupled with additional CLT Shear walls. "*THE LATERAL-LOAD RESISTANCE IS PRIMARILY PROVIDED BY THE ELEVATOR AND STAIR CORE WALLS, WHICH CONSIST OF CLT PANELS. THE SHEAR WALLS ARE ANCHORED TO THE FOUNDATIONS USING A COMBINATION OF SHEAR BRACKETS AND HOLD-DOWN ANCHORS*". (Naturally Wood, 2015)

2.4.3.4 Origine

Constructed in Quebec City, Quebec, this 13-storey tower has a total height of 41m. Using post and beam GLT with CLT floors and walls. CLT elevator and stair cores make up the Lateral Load Resisting System. CLT was balloon framed mainly three stories, increasing stiffness and reducing construction time. The system used special shear keys to reduce construction time as well, whereby 1 shear key replaced 400 nails. Origine performed both full-scale fire and structural testing on the shear walls as part of their alternative means to prove the life safety is preserved even when utilizing combustible and to optimized structural design (CWC, 2016).

2.4.3.5 Framework

Framework, to be built in Portland, Oregon is a 12 storey, 39.6 m tower of post and beam construction utilizing Glulam for both (McDonnell, 2017). Columns are double height which reduces connections and increases building stiffness and lowers the total number of picks. CLT is used in the floor panels, which are up to 40 feet long. A LLRS system developed in New Zealand uses post tension cables with CLT core walls to dissipate energy and allow for a ductile rather than brittle failure. This system, called Rocking Wall, will be used in the seismically active zones.

"THE LATERAL FORCE-RESISTING SYSTEM CONSISTS OF ROCKING/RE-CENTERING CROSS-LAMINATED TIMBER (CLT) WALLS WITH GLULAM COLUMNS BOUNDING EACH WALL END, AS SHOWN IN FIGURE 1C. THE CLT WALLS ARE EXTERNALLY POST-TENSIONED WITH THREADED RODS AT THE WALL CENTERLINE AND ARE CONNECTED TO THE BOUNDING GLULAM COLUMNS THROUGH U-SHAPED FLEXURAL PLATE (UFP) CONNECTORS (BAIRD ET AL. 2014). THE UFP CONNECTORS SERVE AS THE PRIMARY SOURCE OF ENERGY DISSIPATION FOR THE BUILDING WHILE THE POST-TENSIONED THREADED RODS PROVIDE THE RESTORING FORCE. GLULAM COLUMNS AND BEAMS ALONG WITH CLT FLOOR PANELS FORM THE GRAVITY FORCE-RESISTING SYSTEM. THE FLOOR PANELS AND BEAMS DELIVER GRAVITY LOADS DIRECTLY TO THE COLUMNS, PERMITTING THE CLT WALLS TO MOVE VERTICALLY DURING ROCKING WITHOUT DAMAGING OR LIFTING THE FLOOR SYSTEM. TOGETHER, THE LATERAL AND GRAVITY FORCE-RESISTING SYSTEMS WERE DEVELOPED AND DETAILED USING THE PRINCIPLES OF RESILIENT/LOW-DAMAGE DESIGN, AS DISCUSSED IN MORE DETAIL IN THIS PAPER"

2.4.3.6 Sidewalk Labs at Quayside

In 2016 a Request for Proposal (RFP) was released by the Tripartite governmental agency- Waterfront Toronto seeking a company to help develop an efficient, sustainable and technologically advanced community on a 12-acre parcel of land on the Toronto waterfront. Sidewalk labs, a company owned by parent Alphabet (formerly Google), responded to and was awarded the right to co-create a vision for this development. Starting in October 2017, the company began soliciting feedback from City of Toronto residents and partners to develop, among other things, the largest Mass Timber community in the world. The project would have over 3.3 million square feet spread over 5 parcels of land. On these parcels between 8 to 12 Timber towers between 10 and 30-storeys would be built. Some towers will use a fully self-supported CLT structure, and would reach approximately 10 to 12-storeys, which would be primarily residential in use. The CLT would support the structure from both gravity and lateral loads. Another typology would be post and beam Glulam timber structures which would house "Loft" typologies, with floor to floor heights between 4 and 4.5m and large open floor plates. The structure would ease adaptability and flexibility over the life of the project. This thesis uses the post and beam gravity system and varies the shear wall materials in order to test the feasibility of using prefabricated approaches and of different materials over a more status quo system of CIP concrete core walls.

2.5 Timber Analysis and Design Considerations

Derived from a book titled "Application of Analysis Tools from NEWBuildS Research Network in Design of a High-Rise Wood Building", a procedure is outlined to develop lateral load resisting systems in high rise timber buildings (Drew, et al., 2015).

Research has been performed comparing mass timber core walls to the CIP concrete core walls for the UBC Brock Commons Tall Wood House in two different papers. One research paper titled "Feasibility Study of Mass-Timber Cores for the UBC Tall Wood Building" suggested the use of LVL (Laminated Veneer Lumber) cores with 2 supplementary C-shaped walls across the hall from the existing shaft walls (Thomas Connolly, 2018). This was suggested to reduce Torsion on the tower and optimize mechanical properties. The second paper, a thesis entitled "Feasibility Study of Using Cross-Laminated Timber Core for The UBS Tall Wood Building", suggested the use of CLT cores with additional CLT L-walls at the four corners of the structure in order to reduce torsion which was the first modal response when modeled without the L-walls (Moudgil, August 2017).

A paper titled “Wind-Induced Motions of “TREET” - A 14-Storey Timber Residential Building in Norway” explores the serviceability criteria for an all timber tower (Magne Aanstad Bjertnæs, 2017). The relatively tall light building does not fully counter overturning loads, which not only has an effect on the structural system, but places importance on the understanding of motion, vibrations and sounds that the building might cause to inhabitants.

A study comparing different shapes, sizes and locations of shear and core walls in an all concrete building was reviewed in order to better understand the effect these factors have on overall LLRS. The results can be used to better understand and optimize shears walls in buildings of any material and are especially important if they can be implemented early on during the architectural design phase.

The industry is rapidly innovating new approaches to manufacturing and installation, new connection details and member styles, different acoustic and fire rated assemblies. There is a plethora of research work continually being performed in mass timber. This rapid pace of change makes it clear that there is much efficiency still to be achieved. Though Building Codes differ across jurisdictions, major markets within Canada have prescriptive guidelines allowing for only 6 storeys of Mass Timber Construction. Alternative solutions are required to satisfy the construction of buildings above this height, and the previous case studies have begun to highlight many of these challenges and solutions. Continued documented research is still required to push the boundaries to allow for more economical, sustainable and safe buildings.

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Chapter 3: The "Prototypical" Structural System

Sidewalk Labs, an urban innovation and development company, which recently won a request for proposal (RFP) bid issued by Waterfront Toronto[1], has expressed the ambition to build a tall timber community. The mission from of Sidewalk Labs from a building perspective is to promote **Affordability, Flexibility and Sustainability** without sacrificing on world class **Design** and aesthetics. In general, work presented in this chapter was provided by Sidewalk Labs and specifically, all building shapes, floor plates, and gravity element sizing was performed on a preliminary basis by their consulting companies. Mass timber, an inherently environmental-sustainable material, is modular by nature and is easier to work from both a factory and site perspective. To take full advantage of the speed of construction provided by prefabrication, site work should be minimized. It is also important to integrate the site and factory early to achieve manufacturing efficiency at a factory scale. This integration can be achieved through a "Kit-of-Parts" approach, which will reduce the variability of building assemblies and ensure coordination of all elements during construction. When this process is housed in a "Protomodel", early regulatory buy-in can be achieved, potentially streamlining the approval process on future buildings. Background information presented in this chapter was by Sidewalk Labs and their consulting team.

[1] Waterfront Toronto is the public advocate and steward of waterfront revitalization. Created by the Governments of Canada and Ontario and the City of Toronto, Waterfront Toronto is mandated to deliver a revitalized waterfront.

3.1 The "Prototypical Model"

The "Protomodel" concept has been developed to both house the kit-of-parts building components and to visually describe the program and building typologies down to the systems and assemblies (Sidewalk Labs, 2018). The Protomodel is a living model, which will overtime be iterated upon, from both a design/analysis perspective and from the physical construction of buildings. The efficiency of the system will improve with every iteration leading to continuous improvement, a methodology borrowed from automotive and manufacturing and rarely found in construction.

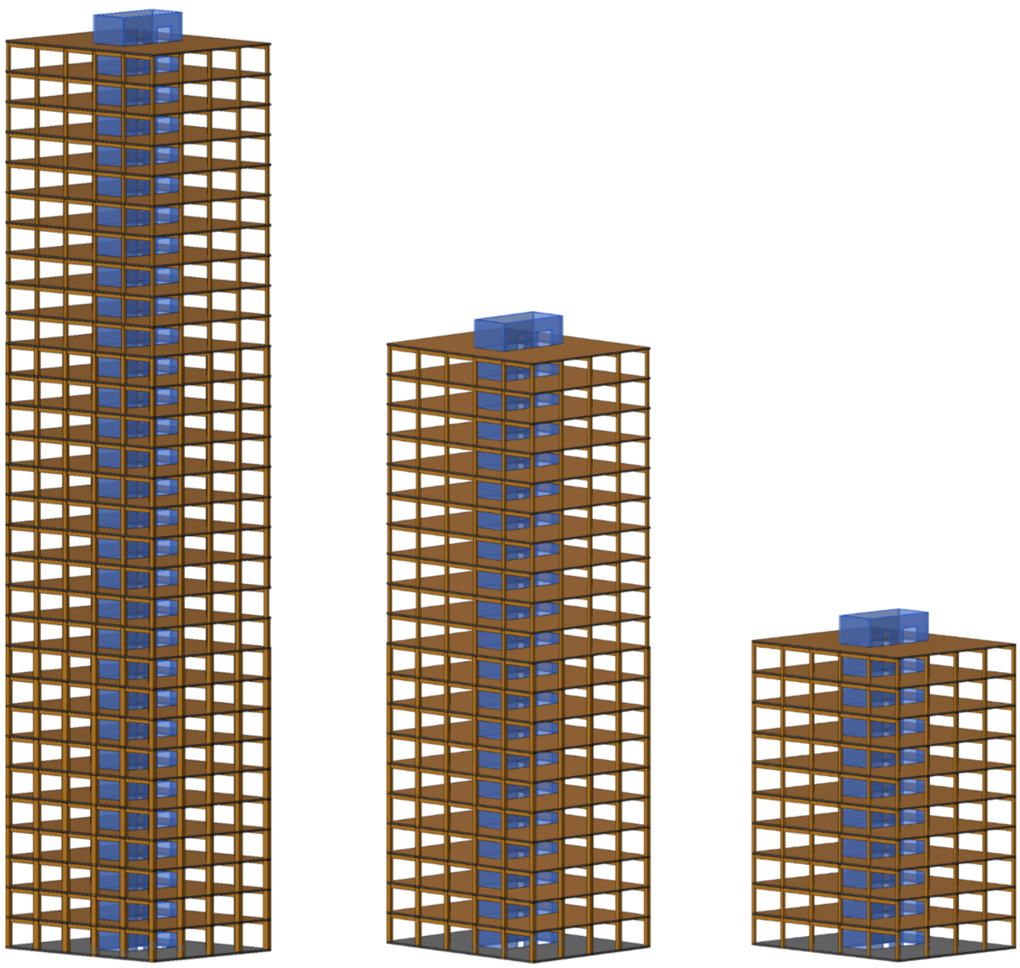

Figure 4: Isometric View of "Protomodel" Timber Superstructure

The visual representation is an idealized tower with bays of set widths and lengths and of rectilinear form. Though the library of parts was designed while reducing variability in components and associated manufacturing costs, it also provided the needed flexibility in building massing to create more visually appealing structures. A generous floor to floor height of 4.5m was chosen, which allows change of use overtime. This was to promote greater flexibility and extend the usable life of the structure well into the future, as measure by old post and beam structures remaining in service well after their initial useful lives (many were built over a hundred years ago). The gross floor area for the floors is 8000 sq ft, close to the outlined parameter for a point tower as laid out by the Toronto "Tall Building Design Guidelines" (City of Toronto, 2013). With proportionally smaller cores, the overall building dimensions make sense for the intended comparative purposes. The building typology was chosen to be symmetric, which would reduce torsional eccentricity and simplify the analysis.

3.2 Gravity Load Resisting System

The Gravity Load Resisting System (GLRS) consists of Glulam (Glue Laminated Timber) frame elements and CLT (Cross Laminated Timber) floor elements. The Frame consists of columns, with beams running in one direction supporting CLT panels. The one-way CLT floor elements are intended to be encapsulated eliminating the need for a char layer (fire protection) leading to five layers of timber with a total thickness of 175mm. These floor elements transfer their self-weight, the Superimposed Dead and Live Loads to the beams, which for simplicity are chosen to have the same dimensions (b=315mm and d= 570mm). The loads are then transferred to the columns. Columns vary in dimensions depending on the building height. They are (1) 365x532mm for the 10-storey building, (2) 265x760mm for the 20-story building, and (3)

315x988mm for the 30-story building. The core walls transfer the gravity loads acting on the supported tributary area. The below table summarizes the above information.

Table 7: "Protomodel" Typical Floor Characteristics

Gravity	Quantity	Units
Storey Height	4.5	M
Grid Spacing	6.1	M
Length of Tower	30.5	M
Width of Tower	24.4	M
Area of one Level	137.25	m2
Columns	24	# / Fl.
Beams	22	# / Fl.

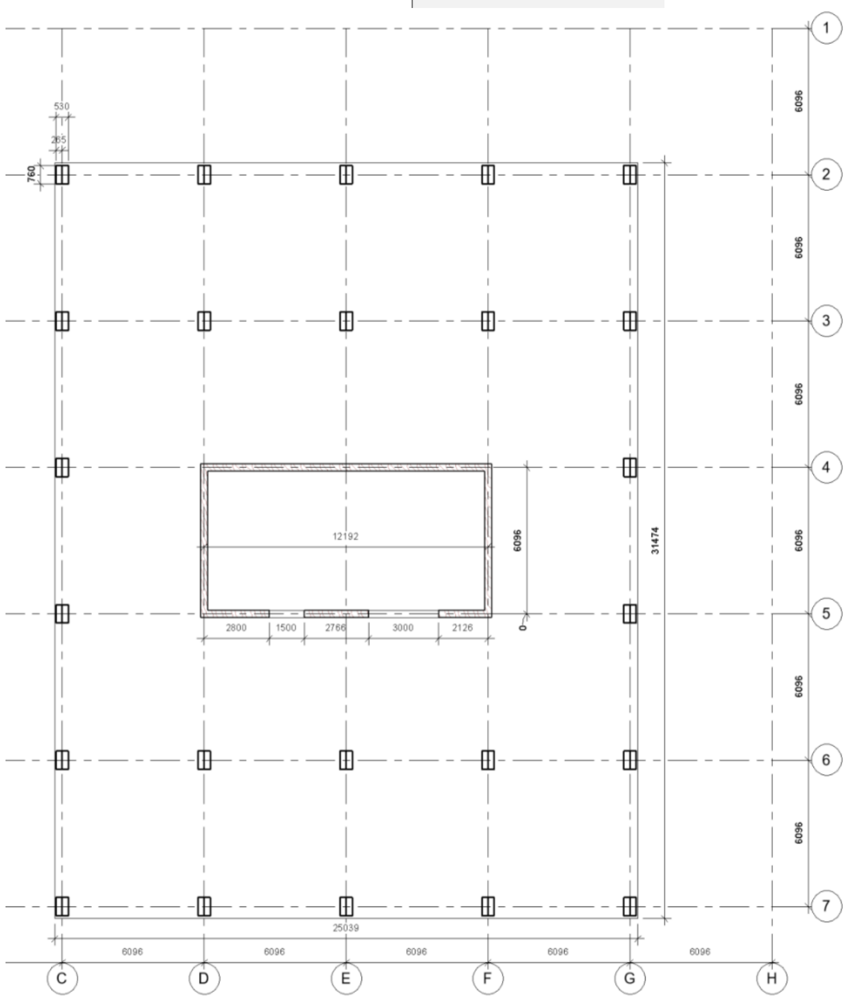

Figure 5: Plan View of a Typical Floor of the "Protomodel"

Buildings with large mass require larger and typically deeper foundations, depending on the bearing capacity of the soil. As the mass of building decreases, as experienced in comparatively light timber structures, foundation requirements are typically lower from a bearing standpoint, which usually reduces the overall cost. This cost reduction continues until the building becomes too high and light to resist overturning moments resulting from the lateral forces. Building heights were chosen to be ten, twenty and thirty storeys to fit into the context of existing conceptual research. for this 5x6 bay tower.

3.3 Lateral Load Resisting System

In general, there are several types of lateral loads, which can act on structures. The most common ones are wind, seismic, soil and hydro-static loads. Wind and seismic loads vary depending on the geographic region due to varying climactic conditions, and seismicity. This study is performed for the geographic region of Toronto, and more specifically the Quayside location on the Eastern waterfront. Previous structural designs in the GTA have shown that due to the low seismic activity in this region, seismic forces can be largely omitted as wind forces are much greater and will ultimately govern the lateral design.

The self-weight of timber elements is considerably lower than both concrete and steel and overturning moments can have a greater effect on the overall system. Columns can experience tensile forces. These forces are then transferred into the foundations requiring installation of tension piles or rock anchors. Though the actual analysis and design for tension in members and the foundation is out of the scope of this report, it no doubt increases complexity and cost.

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Chapter 4: Numerical Structural Performance Model

Tall timber structures have many advantages measured by the sustainability, economic opportunity and efficiency. However, a major technical challenge to consider is the lighter weight and lower stiffness on the lateral load resisting system. There are challenges and opportunities, both socially and technically, with using different types of lateral resisting systems, which are explored generally in the first section of this chapter. Section two will detail the structural assumptions made to analyze the prototypical model. Section three will present findings based on simple structural analyses performed in ETABS which compare four lateral structural systems using different materials in the core walls of the protomodel. Conclusions are drawn from this chapter which act as the jumping off point for the cost estimating work in Chapter 5.

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4.1 Qualitative Comparative Analysis

Many factors play into the decision of choosing structural solutions to the development of towers. Local market knowledge and material availability are important factors which speak to the history of development within the area. Loading conditions vary based on localized climate, wind, seismic, geotechnical and disaster events, and building codes are often tailored based on these factors. Different materials and structural systems have had varying amounts of time and adoption, which influences the level of innovation and therefore maturity of structural options developed. The political landscape is made up of many important stakeholder groups which have influence on factors including union strength, regional industries, regulatory innovation, social and environmental sustainability, developmental speed and red tape. These political factors can often have a major influence on the availability, cost, speed, risk or even whether different materials or systems are approved altogether.

Toronto has several hundred years of history, and as such, the construction and development markets have had time to develop these aforementioned nuances. Below is a summary of how these qualitative factors affect the decision-making process with respect to the choice of building materials within the Toronto Market.

4.1.1 Concrete Option 1 (Cast-in-Place Concrete)

Toronto is known as a "Concrete Town"; most of the mid to high rise buildings in this region are built using concrete, making the labour knowledge base as well as the supply chain for the material itself very well developed. Due to such widespread use it has reliable and competitive pricing and the approval process is streamlined saving time on the front end. Concrete also has many technical benefits, including structural stiffness, sound, mold and fire resistance.

The concrete industry is, however, a major contributor to greenhouse gas emissions, significantly reducing the sustainability of this material. Aggregate and cement mining operations are required for concrete production and can often scar the land and damage ecosystems. The concrete construction process can also have negative impacts to the surrounding neighbourhood including truck congestion and localized air and sound pollution. The construction process is often much longer as compared to prefabricated options, with core wall construction installed at roughly 1 floor/week for typical Toronto point towers, which are typically 8072 square feet. Contrast this with the mass-timber superstructure at about 15,000 square feet installed per day. In a hybrid timber-concrete tower the concrete trade and timber trade both use an abundance of site space and hook time leading to potential conflicts and difficult coordination and sequencing of construction work. The use of self-climbing formwork could reduce hook time demanded by the concrete trade, however, the use of this process is usually only effective with buildings near 20 floors and above. Composite solutions do exist, which use permanent gravity load bearing formwork, providing the schedule compatibility with the physical material advantages of concrete, however these systems are relatively more expensive and have not been widely tested. The material compatibility between two different trade contractors can pose coordination risk including tolerance issues and issues with varying material properties.

4.1.2 Concrete Option 2 (Precast Concrete)

In the following sections discussing the ETABS modelling, the concrete option 2 was modelled as cast-in-place concrete as the connection details were not modelled. This section will provide a discussion on the choice of precast as an option compared to other wall systems. Chapter 5 provides further information on this system.

Precast increases the modularity of concrete, which improves the sequencing of work compared to CIP Concrete. Precast still has all of the material benefits of CIP concrete such as fire rating, superior acoustics, rigidity and is a large mass which acts as an energy sink to regulate temperature. Precast is still made of concrete and steel, two energy and CO2 intensive building products, lowering the overall sustainability with respect to climate goals and recyclability. The design of precast is centered around the connections, special care should be taken in designing connections as loading tends to get concentrated at these locations. As lateral forces increase with building height complex and time-consuming on-site connection detailing become necessary, driving up cost.

Relatively few use cases exist for the use of precast which has a mid to high rise lateral support structure, compared to steel and CIP concrete, and with this uncertainty comes higher costs associate with this risk and potentially unforeseen cost construction or future costs. Precast usually has a higher quality than CIP Concrete with respect to finish as well as tighter strength and dimensional tolerances. Precast concrete was developed more recently as a building material option: this material therefore continues to see relatively fast innovation, which could have promising implications for its use in taller buildings.

4.1.3 Cross Laminated Timber

The regulatory environment is very comfortable with tall CIP concrete buildings, however, in recent years there has been a push to open the possibilities for Tall Timber structures. Documents such as the "Ontario Tall Wood Building Reference" and the new IBC 2020 rules on tall timber are a few examples for regulations responding to market demand for timber. Governing bodies are not only responding, but actively incentivizing this work through research programs that bring together institutional, regulatory and private sectors groups to innovate. However, to achieve fire, and structural performance, an alternative solution path is still required for the approval of building permits in Toronto. These solutions might include adding redundant fire protections, oversizing timber members, and building rated assemblies or some combination of these and others.

CLT has been developed in the last 30 years and has, relatively fewer use cases as the main lateral supporting structure as compared to steel and concrete, and this uncertainty could impact schedule and cost. External braced frame systems utilizing large glulam member have been used in timber structures as tall as eighteen storeys, however to date CLT has been used in supporting structures in the ten to twelve storey range. There are experimental systems that could help push this taller; prestressing cables can be used to stiffen and anchor the CLT Panels and outrigger truss systems could be used in conjunction with core walls to push further the capacity of an all timber structure to taller ranges. Using CLT as the core material keeps the superstructure within one skilled trade reducing coordination and compatibility risks. Importantly, sequencing becomes seamless with the superstructure. The use of Timber as the lateral support system would also save the equivalent of 20 metric tons of CO_2.

An additional 5 major mass timber factories are planned in North America to compete with the existing 5 certified plants (including the Mass Plywood Panel plant), and new entrants are driving down the cost curve and accelerating supplier optionality. With increased use, technology improvements further accelerate adoption and cost competitiveness.

4.1.4 Structural Steel

Steel core structures are generally configured by using braced frames or full plate walls, depending on the size of the external forces. The system could be easily combined with other structural assemblies such as exterior braced frames or outrigger/truss bridges, so the versatility of this material allows for huge optionality in structural solutions.

The structural steel installation process is similar to that of mass timber creating the opportunity for accelerated sequencing. Steel itself is non-combustible, however, the material will fail unexpectedly in fire situations if not insulated from heat, which is a major hazard to firefighters and building occupants. Diagonally braced steel frames require wall assemblies to achieve acoustic and fire rating requirements. Though steel has many benefits it is an energy and CO2 intensive material to produce, potentially leading to negative sustainability outcomes. Steel is one of the most recyclable materials and if recycled steel is used in construction these negative sustainability outcomes can be reduced from a waste and embodied energy perspective.

A major cost in the steel scope are within the connections which increase with complexity, at twenty and thirty storeys, with a very light timber superstructure, these connections are critical. Timber structures will typically always use steel connections for taller structures, as such the material compatibility issues are reduced. Though lessened compared with concrete, there are still two different trade contractors, which increases the uncertainty and coordination complexity compared to an all timber solution. One install trade could theoretically take on the installation of steel and timber, simplifying the administration and reducing risk, however, politics with respect to different labour groups would play into the feasibility of this.

A structural steel solution is potentially the most versatile solution with respect to prefabricating other building system in a factory setting. Prefabricated elevator solutions already exist possibly combining scopes and allowing for further schedule acceleration.

4.2 Overview & Assumptions

The identification of the Quayside site location located in Toronto, Ontario, narrows many of the criteria. Toronto is in a low seismic region, thus the wind loads are expected to govern the design of this system as long as a Site Class D soil condition can be achieved. Seismic forces may begin to govern if the soil conditions are too weak, due to liquefaction of layers below. Though it is known that this area has poor soils since much of this region consists of fill material previously used to build out the waterfront over the past century, the assumption of adequate soil conditions is made. To assess the structural performance of the various options several preliminary decisions must be made regarding 1) Site & Loading Conditions, 2) the Structural System and 3) Materials, Assemblies and Connections.

4.2.1 Site Specific Parameters

Initially the floor to floor heights were chosen to be 4.5m, an extremely generous quantity, as outlined in Chapter 3. All loading parameters were taken from the NBCC values and modified accordingly based on site specific design factors. Dead loads were calculated based on the timber structural elements and are 8343.28, kN, 19162.08 kN and 32652.55 kN for the 10, 20 and 30-storey towers, respectively. As discussed previously, the columns step 3 times as the tower increases with the following parameters:

Table 8: Gravity Load Resisting Element Dimensions

Element Criteria	Dimensions		Volume	
10-Storey Columns	0.365 x 0.532	M	0.87	m3
20-Storey Columns	0.265 x 0.760	M	1.81	m3
30-Storey Columns	0.315 x 0.988	m (x2)	2.80	m3
Beam	0.315 x 0.570	M (x2)	1.00	m3
CLT Slab Element	2.650 x .175	m3	117.21	m3

The partition loading comprised of a floor assembly for acoustics and fire, the ceiling and services for a total of 1.7 kPa. The façade load used was a 3.0kN/m line load. The floor live load used was 4.8kPa, from table 4.1.5.3 of the NBCC, considered the worst-case scenario and could accommodate either light industrial, office or residential uses. The roof loading considered was 1.12kPa based on historical climactic information in Toronto and the flat roof shape. Wind loading was taken from table C2 in the NBCC Appendix, and a hourly wind pressure for a 1 in 50 year design period was used, which in the Toronto region is a 0.44kPa load. The Importance factor taken from Table 4.1.6.2 for Ultimate Limit State was 1, and 0.9 for Serviceability Limit State. As discussed seismic loading is not considered.

4.2.3 Resistance Method: Lateral Structure & Material Option

The floor to floor height was modelled first with very high floor to floor heights of 4.5m. Following this a second analysis was performed at a 3.4m height to understand the overall sensitivity of the LLRS. The core size did not vary and was modelled with a footprint of 12.2m long and 6.2m wide, which could fit a 3-elevator core with two stairs (rough estimate for simplicity).

4.2.4 ETABS Modelling Assumptions & Analysis

The gravity system as well as loading scenarios remained constant for each model to isolate the lateral load resisting systems. In the worst-case soil conditions would be a highly limiting factor in choice of the lateral load resisting system. For this initial study and since it is a "Protomodel" the foundation was not modelled, and all elements were pin connected at the base level. Diaphragms are assumed to be fully rigid.

The Finite Element Models were all built within the ETABS Structural Engineering Software. Wind loading was generated based on the NBCC 2015 procedure. Connection details were not specified for steel or timber, they were rather assumed to be continuous stiff connections for the preliminary analysis. For the modelling component of this work two concrete options were used, the first was to be considered for the CIP concrete condition with a wall thickness of 300mm with 30MPa strength characteristics and named “Concrete 1”, and the second based on a wall thickness of 250mm with 40MPa strength characteristics and named “Concrete 2”. In this case the “Concrete 2” is used to simulate the precast option. For simplified modelling in ETABS was considered acceptable, but a more detailed design would be eventually required to properly detail the reinforcing steel and connections.

The CLT properties do not exist within the ETABS Database so they were modeled using shell elements with special properties. To ensure accurate results, a CLT wall was modelled in a Finite Element Modelling (FEM) Software twice, by using wall properties standard CLT material specification sheet, and by modifying wall section properties. A Modulus of Elasticity of 9500 MPa and a Poissons ratio of 0 yielding a Shear Modulus of 4,750 were used, these chosen base conditions are similar to CLT material properties, yet simplified so that a trial and error matching method could be carried out. The 7m long wall was subjected to a 50kN point load at the top of the wall. Modification factors of 0.56 for f22 and 0.065 for f11 directions were varied until the deflection for the two models were equal. This CLT wall section was then modeled in ETABS using the same properties. The resulting deflection of the wall was 2% lower than the accurate model which was deemed to be acceptable.

Table 9: Material Property Calibration RFEM to ETABS

Software	*RFEM Software*	*RFEM Software*	*ETABS*
Material Properties	N/A	E=9500MPa v=0 G=4750	E=9500MPa v=0 G=4750
Modification Factors	N/A	*f22=0.56* *f12=0.065*	*f22=0.56* *f12=0.065*
Deflection	58.6	58.0	57.4

The table below compares the strength properties of the various materials used.

Table 10: Material Properties for Wall Modelling in ETABS

Lateral Structure Materials	CLT		CIP Concrete Option 1	CIP Concrete Option 2	Steel
Density kg/m3		515.0	2400.0	2400.0	7849.0
Force-Density kN/m3		5.1	23.5	23.5	77.0
Modulus of Elasticity (MPa)		9,500[(1)]	27,386	29,725	200,000
Poison's Ratio		0[(1)]	0.2	0.2	0.3
Shear Modulus (MPa)		4,750[(1)]	11,410	12,386	76,903
Modification Factors	f22	0.560			
	f11	0.065			

(1) Modification factors were used from a comparison in a Timber Design Software

The overall volume and weight of each system was calculated below:

Table 11: Lateral Load Resisting System Weight and Volume

Lateral Structure Weight Takeoff	10-Storey (kN)	20-Storey (kN)	30-Storey (kN)
CLT	2646	5,292	7,938
Concrete 1	11,611	23,223	34,834
Concrete 2	9,676	19,352	29,028
Steel	592	1,184	1,776
Volume Takeoff	*(m3)*	*(m3)*	*(m3)*
CLT	519	1038	1556
Concrete 1	494	988	1482
Concrete 2	412	824	1235
Steel	7.7	15.4	23.1

The below images pictorially represent the different structural systems evaluated within the ETABS FEM software. The steel braced frame is depicted on the left and the three wall options are represented on the right.

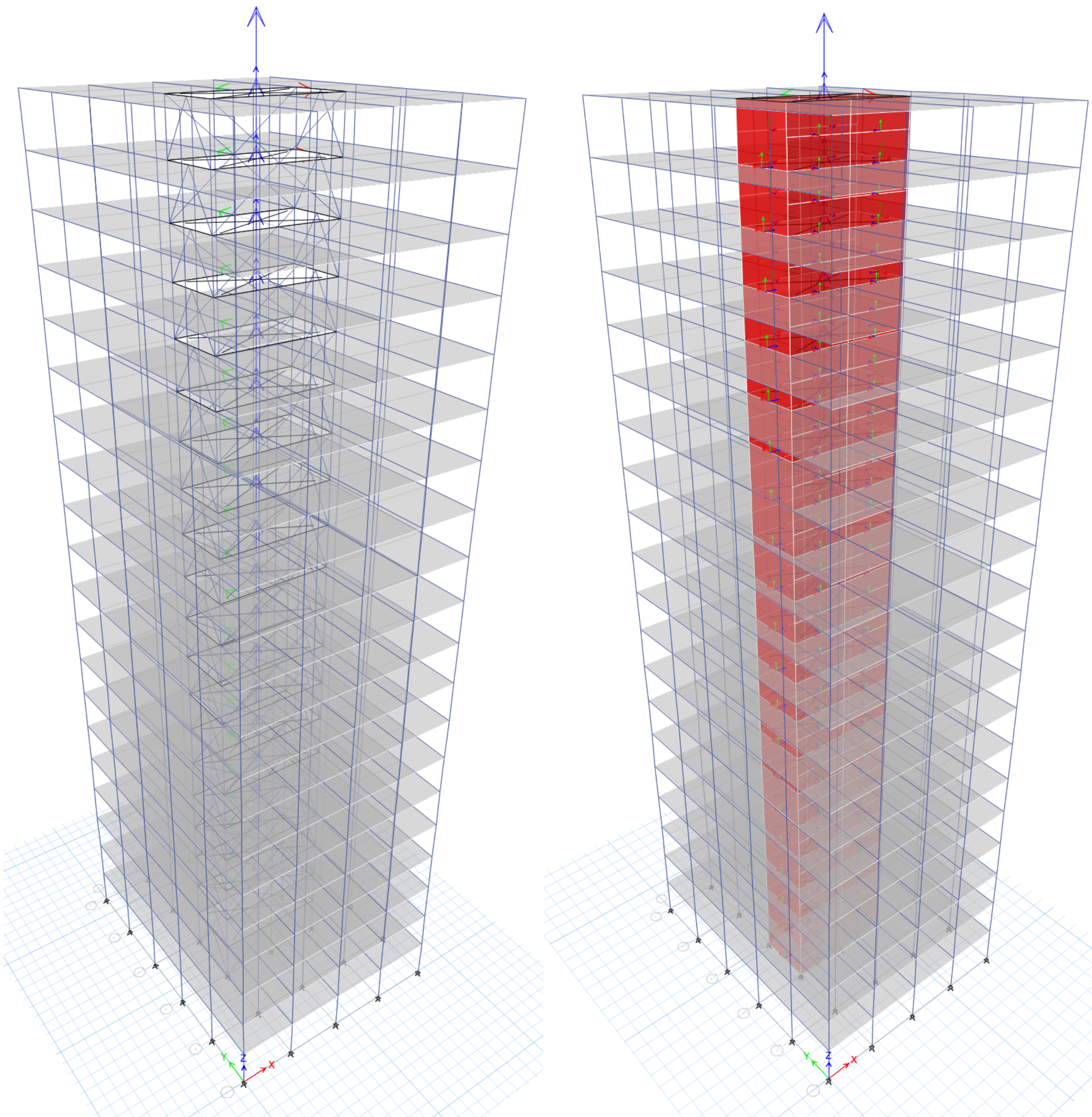

Figure 6: Visual Representation of Braced Frame Core & Core Walls

4.2.5 Model Limitations

Concrete slabs rigid are most commonly what designers consider rigid diaphragms. Though CLT diaphragms with 3-inch concrete topping are generally modelled as rigid diaphragms they are some higher degree of flexibility as compared to full concrete. The intent for timber structures designed by Sidewalk Labs is to eliminate all "wet trades" in order to speed up the construction process and reduce moisture concerns. The CLT slabs without this topping are no doubt less rigid than concrete and so they may fall into the semi-rigid category. The connections were also assumed rigid, which is unrealistic especially for timber buildings. The use of post tensioning cables is one solution which could stiffen the system and connection enough to validate the rigid connection assumption. Further refinement on these models is required, however, they are deemed acceptable to begin making decisions towards overall structural direction.

4.3 Preliminary Structural Analysis Results

Building Drift at 4.5m Storey Height

The total building drift and inter-storey drift for all lateral load systems was measure below:

Table 12: Max Deflection of Towers with a 4.5m Fl. to Fl. Height

Height	Lateral Material	Lateral Deflection (Wind X-Dir)	Lateral Deflection (Wind Y-Dir)	NBCC Code Check (Worst Case)	Max Inters-Drift (Wind X-Dir) (Unitless)	Max Inters-Drift (Wind Y-Dir) (Unitless)
10				**90**		
	CLT	52	59	**O.K.**	0.19 %	0.19 %
	CONCRETE 1	3	9	**O.K.**	0.01 %	0.02 %
	CONCRETE 2	4.3	9.2	**O.K.**	0.01 %	0.02 %
	STEEL	64	72	**O.K.**	0.21 %	0.19 %
20				**180**		
	CLT	1,130	1,534	8.5**x**	2.25 %	2.62 %
	CONCRETE 1	46	118	**O.K.**	0.08 %	0.16 %
	CONCRETE 2	65	141	**O.K.**	0.09 %	0.20 %
	STEEL	392	615	3.4**x**	0.50 %	0.85 %
30				**270**		
	CLT	3,670	5,230	19.4**x**	5.02 %	6.29 %
	CONCRETE 1	288	620	2.3**x**	0.27 %	5.90 %
	CONCRETE 2	315	675	2.5**x**	0.29 %	6.40 %
	STEEL	930	1,640	6.1**x**	0.90 %	1.60 %

Note 1: All Displacements in mm

The total allowable top deflection for the 10-Storey (45m), 20 Storey (90m) and 30 Storey (135m) towers are 90mm, 180mm and 270mm respectively. These numbers are set by building code limitations but in place in order to limit unsafe movement associate lateral loading. If buildings deflect excessively, columns along the building receive extra loading from the P-Delta effect, which is equal to the force of gravity on the building times the deflection. This displacement is limited in order to ensure buckling of columns does not occur. By comparing the worst-case deflections compared to code acceptable limits it becomes clear that the designs need to be revised. The CLT walls are over 8 and 19 times the acceptable code limitations for the 20 and 30 storey building respectively. Since this analysis used the current manufacturing limit of 9-ply 315mm panels, multiple panels will need to be coupled, which will impact the flexibility of the open floor plans. Another option to would be to introduce an outrigger truss at several floors combined with CLT walls. Finally, an external braced frame option for the 30 storey all timber tower could likely meet lateral code requirements.

Though the concrete option 2 (precast) appears to be quite feasible at this 30-storey height it should be noted that the largest concrete option 2 (precast) structure in the world is 35 storeys, at 150m as of 2014, and the largest in Ontario is 20 Storeys. The concrete option 2 (precast) core wall options could be redesigned to achieve the 20-storey height with no code issues but additional walls and special attention to connections would be required to achieve a compliant 30 storey tower.

The steel braced frame and CIP concrete options are the most feasible in the current configuration for the 30-storey height. It is likely that with redesigns in sizing the braced frames and concrete shear walls could achieve the code compliant drift levels up to the 30 storey tower in both directions.

Building Drift at 3.4m Storey Height

In order to benchmark timber buildings against similar market conditions a sensitivity to building height was performed using an updated 3.4m floor to floor height, compared to the 4.5m height used in the above table. The 10-storey options were not included as they already satisfied code drift parameters.

Table 13: Max Deflection of Towers with a 3.4m Fl. to Fl. Height

Height	Lateral Material	Lateral Deflection (Wind X-Dir)	Lateral Deflection (Wind Y-Dir)	NBCC Code Check (Worst Case)
20				**136**
	CLT	509.80	682.96	5.0x
	CONCRETE 1	19.068	38.84	**O.K.**
	CONCRETE 2	20.911	45.73	**O.K.**
	STEEL	114.881	197.21	1.5x
30				**204**
	CLT	1583.062	2251	11.0x
	CONCRETE 1	92.988	202	**O.K.**
	CONCRETE 2	101.504	222	1.1x
	STEEL	378.613	580	2.84x

Note 1: All Displacements in mm

Due to the change in building height, the maximum code drift has changed to 136mm and 204mm of lateral deflection at the top of the 20 and 30 storey timber towers, respectively. This was proportionally reduced along the lateral load supporting members, however the wind loading was disproportionately reduced, since at taller heights the wind loading is higher.

An obvious conclusion from the above figure is the importance of height compared on the lateral load resisting system. The architectural decision to increase the floor to floor height can improve flexibility, however there is an opportunity cost associated with the lateral system, among other things like façade and heating/cooling costs, which should be considered. By reducing the floor to floor heights all options are in the realm of feasibility for the 20 storey tower, although significant changes are still required for the timber option. When considering the 30 storey option, an all CLT timber core appears to be infeasible, however, the steel option could be optimized using different sections throughout the height in order to achieve code compliant deflection targets.

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Dynamic Sensitivity

Taller timber buildings are sensitive to lateral accelerations due to their light weight, compared to similar concrete and steel structures. This makes them particularly susceptible to dynamic wind loads. These dynamic loads translate to motion which should be limited to avoid human discomfort from the swaying action of buildings. Therefore, even after redesigning these lateral load resisting systems to meet lateral drift requirements, the towers lateral systems should be tested for dynamic sensitivity.

Wind loads for buildings should be calculated by using either the Static, Dynamic or Wind Tunnel Procedure, depending on the dynamic sensitivity. Forces must be calculated using the Dynamic Procedure if any of the following conditions apply:

1) The Lowest Natural Frequency is less than 1Hz and greater than 0.25Hz
2) The Height is greater than 60m
3) The Height is greater than 4x Effective Width

A building will be classified as "Very Dynamically Sensitive", requiring specialized wind tunnel testing, if the answer is yes to either of the following conditions:

1) The Lowest Natural Frequency is less than 0.25Hz
2) The Height is greater than 6x the Effective Width

The following table summarizes the natural frequency of the different systems with a 4.5m floor to floor height:

Table 14: Natural Frequencies of Timber Towers with Varying Lateral Materials with a 4.5m Fl. to Fl. Height

NATURAL FREQUENCY 4.5M FL. TO FL.	***10-STOREY*** *(Hz)*	**20-STOREY** *(Hz)*	**30-STOREY** *(Hz)*
Concrete 1	*0.3028*	*0.0197*	*0.0116*
Concrete 2	*0.2957*	*0.0195*	*0.0089*
Steel Braced Frame	*0.1108*	*0.0137*	*0.0105*
CLT Wall	*0.1176*	*0.0135*	*0.0044*

These buildings, especially at the taller heights, are "Very Dynamically Sensitive". The obvious takeaway is that additional mass will actually help to reduce building accelerations. These buildings were considered without a concrete topping on the floor slabs, however there is an opportunity to add mass and improve vibrational and acoustical characteristics which improving the overall building lateral conditions.

The following table shows how the frequencies of these buildings change when the height is reduced to 3.4m floor to floor:

Table 15: Natural Frequencies of Timber Towers with Varying Lateral Materials with a 3.4m Fl. to Fl. Height

NATURAL FREQUENCY 3.4m fl. to fl.	**20 STOREY** *(Hz)*	*PERCENT INCREASE (from 4.5m)*	**30 STOREY** *(Hz)*	*PERCENT INCREASE (from 4.5m)*
Concrete 1	*0.0290*	*26.2%*	*0.0128*	*28.3%*
Concrete 2	*0.0289*	*46.9%*	*0.0131*	*10.5%*
Steel Braced Frame	*0.0173*	*48.6%*	*0.0149*	*47.5%*
CLT Wall	*0.0171*	*25.7%*	*0.0056*	*42.6%*

This second table above shows that the relative effects of reducing the floor to floor heights are large from a building frequency perspective. However, the building overall is so light that impact on frequency from the reduced building height does not move the needle from a dynamic sensitivity. Though wind tunnel testing has become the norm in Toronto, it is *required* by code if a building is found to be dynamically sensitive. All options considered would require wind tunnel testing whether a 3.4m or 4.5m floor to floor height is used.

Building acceleration is a function of the stiffness, weight, turbulence, overall dimensions and the external forces applied. The final three factors remain constant in this exploration, but the stiffness and weight do change among the different systems. Concrete option 1 is the most stiff system among all of the options, followed by the concrete option 2, steel and then timber. The connections in these more modular systems cause a reduction in stiffness, the timber system especially reduces this stiffness since these components must also provide the overall ductility in the system.

The below table shows the weight of the lateral system as compared to the overall building weight, highlighting a secondary reason why concrete and concrete option 2 (precast) perform better from an acceleration perspective, as they are significantly heavier.

Table 16: The Weight and Volume of Lateral Load Structures as a Percentage of Overall Structure

Core Walls as % of Total Weight	*10Storey*	*20 Storey*	*30 Storey*
CLT	24.08%	21.64%	19.56%
Concrete 1	58.19%	54.79%	51.62%
Concrete 2	*53.70%*	50.25%	47.06%
Steel	6.63%	5.82%	5.16%
Core Walls as % of Total Volume	*10 Storey*	*20 Storey*	*30 Storey*
CLT	19.65%	18.85%	18.08%
Concrete 1	18.89%	18.11%	17.37%
Concrete 2	16.25%	15.56%	14.90%
Steel	0.36%	0.34%	0.33%

Votex shedding oscillates the building from side to side to negative pressure differentials occurring on the far side of the building as wind passes the sides. Careful consideration should be placed on these factors and appropriate measure taken to reduce accelerations. By placing shapes at the edges of the structures the wind can be confused and therefore these negative pressure zones reduced or eliminated.

4.5 Conclusion

The most important factors governing the design of the lateral load resisting system are the height, weights and materials used in in towers. Structural efficiency must be balanced with the architectural program needs, in this case flexibility for use change and a more pleasant aesthetic. Though these idealized ETABS models require further refinement, the designs inform the feasibility of different systems.

4.5.1 Total Building Drift

The floor to floor heights have the single effect on the viability of all options. Though upfront cost is often dwarfed by the operational costs of the building over the life, there is still balance that should be considered. By reducing floor to floor height lateral loads are significantly reduced, reducing the cost of the systems and creating a lot more flexibility in structural options.

4.5.2 Wind Induced Accelerations

Building accelerations play a major role in tall timber towers, and at the 20 and 30 storey heights for these buildings, accelerations will likely govern the structural design. In order to properly design systems against this acceleration specialized wind testing is required. Tuned Mass Dampers are one option to reduce the accelerations experienced at the upper floors of the light timber structures. As timber towers are so much lighter, these TMD systems will be particularly effective, compared to similarly dimensioned concrete solutions. Another option could be to add mass to each floor. The additional mass, perhaps in the form of concrete, has many benefits, but it can also reduce the usable floor to floor height, since a thickness is added to each floor slab. Pouring concrete onsite would slow down the construction process, and if speed is a primary goal, this method may not be desirable.

In summary, from a pure structural analysis perspective, concrete is the simpler and most market ready solution for use in timber towers above the 10 to 15-storey range. Steel has been used in high rise construction from the outset and, once refined, could achieve adequate structural support for these towers at all of the heights provided.

Recently completed in Norway, an 18 storey all timber tower called Mjøstårnet was constructed using an external braced frame system. Innovative thinking is required in order achieve all timber solutions above the 20 storey range.

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Chapter 5: Cost Analysis

The use of prefabrication and mass timber for mid to high rise applications has been accelerating extremely quickly in recent years. This interest is centered around the factory efficient processes and project schedule acceleration. In order for tall timber projects to achieve their full potential, the lateral resisting system must keep pace with the gravity system from a construction scheduling perspective. As an illustrative example, the entire timber superstructure for the 18 storey Brock Commons building in Vancouver took just ten weeks, while the cast in place core walls construction took fourteen weeks (Moudgil, August 2017). This chapter focuses on comparing different core wall structural systems from a cost perspective, keeping in mind time and other important factors.

5.1 Efficient Structural Systems

The previous chapter outlined idealized lateral systems in order to analyze which options were feasible. The design assumptions were stretched in these idealized models, for example connections provided in the steel timber and precast options were assumed rigid. In an effort to test the feasibility from both a technical and cost perspective, expert subcontractors were contacted to aid with design input. The designs are outlined within this section and cost details are explored further in the following sections.

5.1.1 CLT Post Tensioned Wall and Outrigger Truss

To push the lateral capacity boundaries of structural core walls work was performed in collaboration with an innovative North American engineering firm as well a specialized timber manufacturer. The suggested designs were produced for 10-storey and 20-storey all timber tower options for the protomodel buildings, including:

1. 10-Storey
   a. Post Tensioned 315mm 9-Ply CLT Core
   b. Post Tensioned 305mm Mass Plywood Panel (MPP) Core Walls

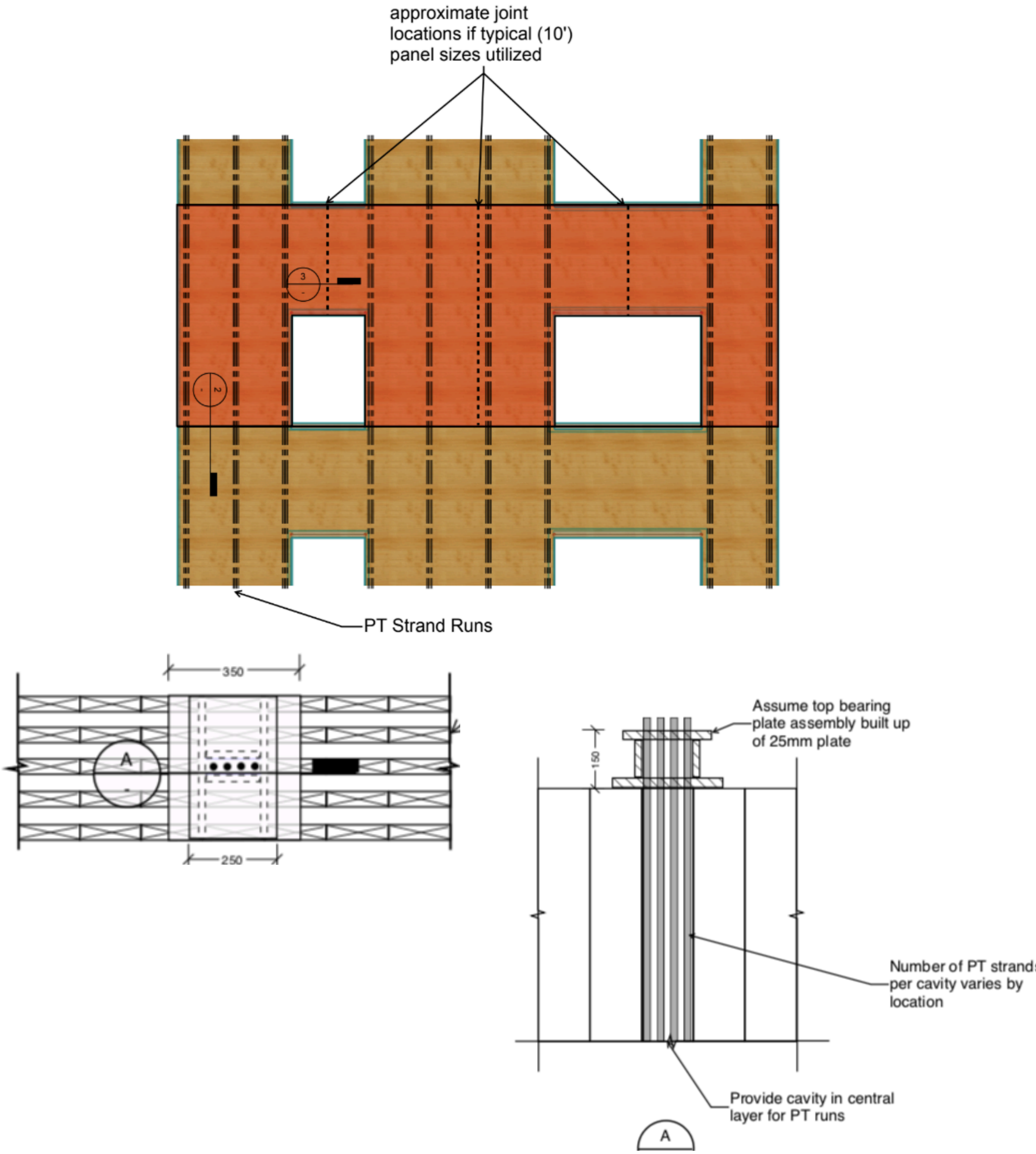

Figure 7: 10-Storey Post Tension Mass Timber Walls

c. 305mm Mass Plywood Panel Core Walls w/ Outrigger Truss

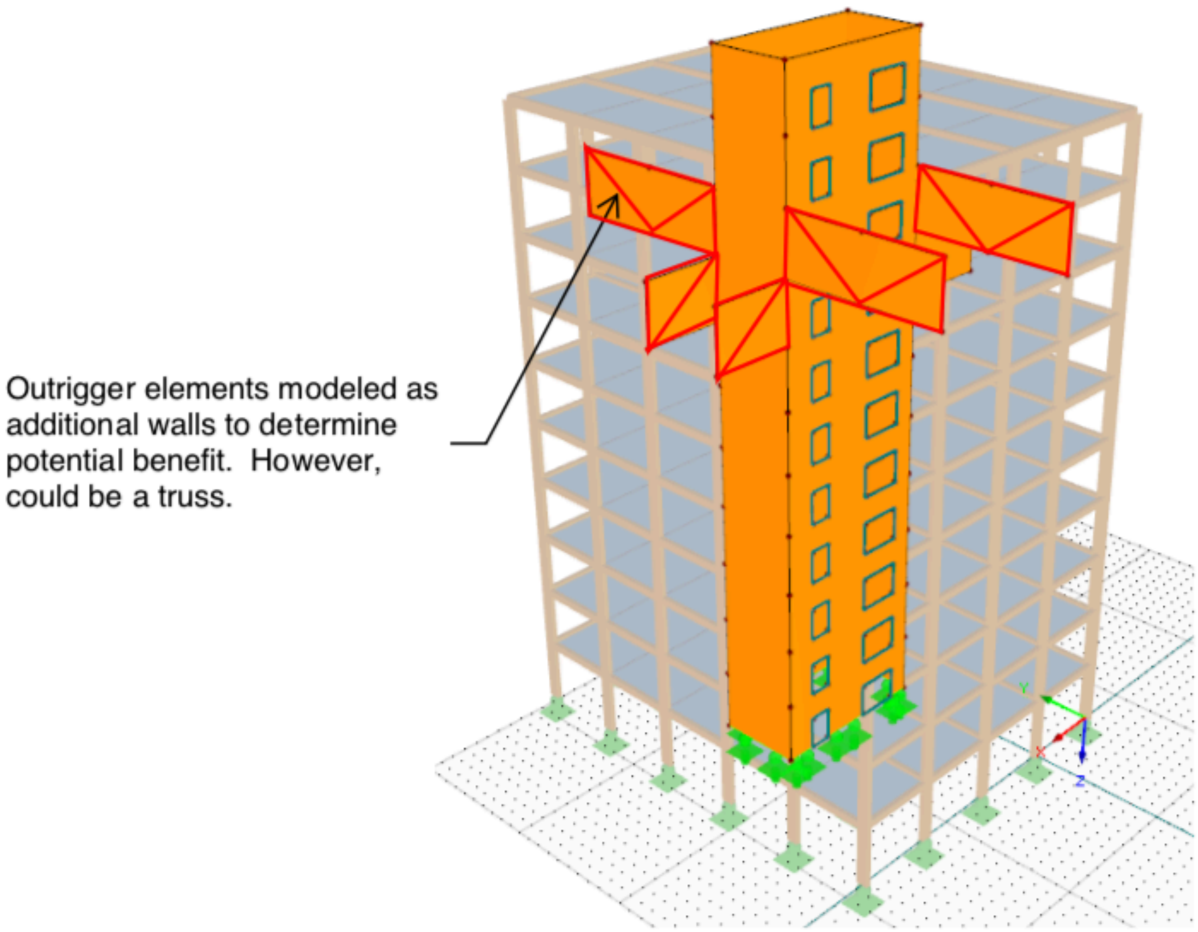

Figure 8: 10-Storey Post Tension Mass Timber Walls W/ Outrigger Walls

This system combines additional bracing to share lateral loading with the external columns.

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2. 20 Storey

   a. 305mm Post Tensioned Mass Plywood Panel Core Walls w/ Outrigger Truss

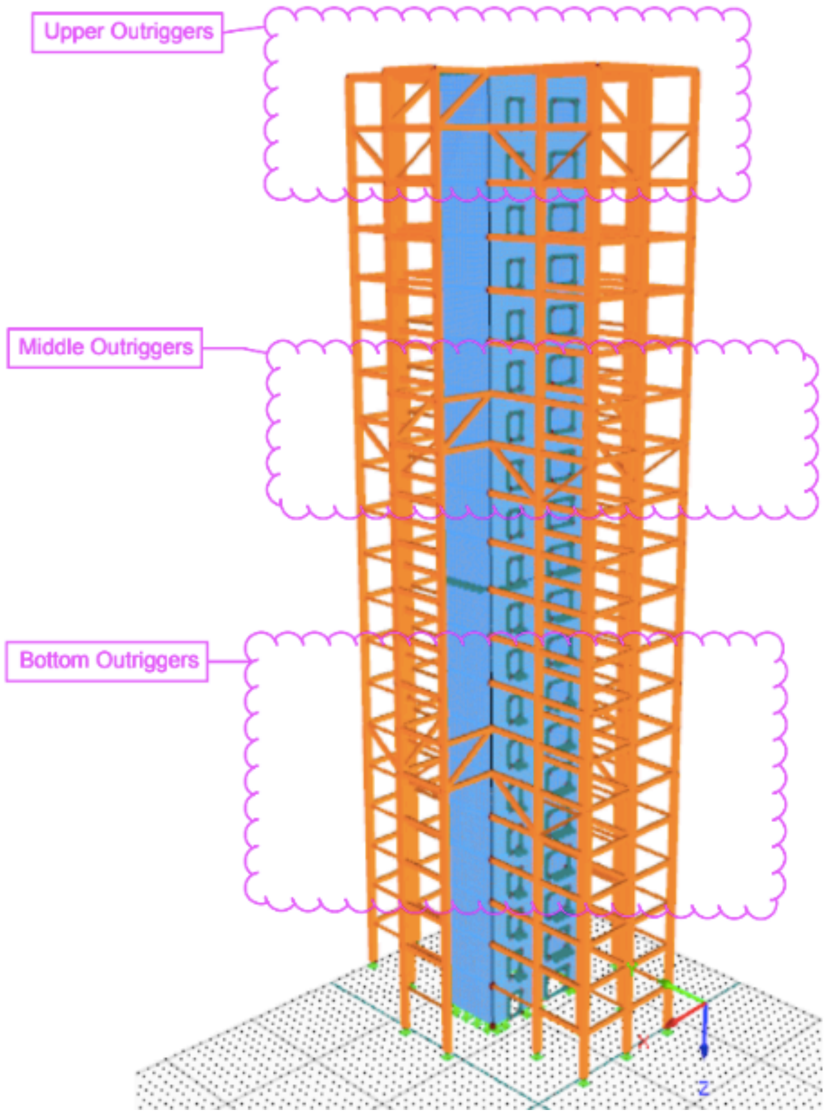

Figure 9: 20 Storey Tower Post Tension Mass Timber Walls w/ Outrigger Truss

5.1.2 Precast Concrete Walls

Work was performed with a Canadian Precast manufacturer in order to develop the structural and cost information required for an estimate. By providing the initial framework and engineered wind forces on a 10-storey concrete core the Precaster was able to provide wall details, pictured below:

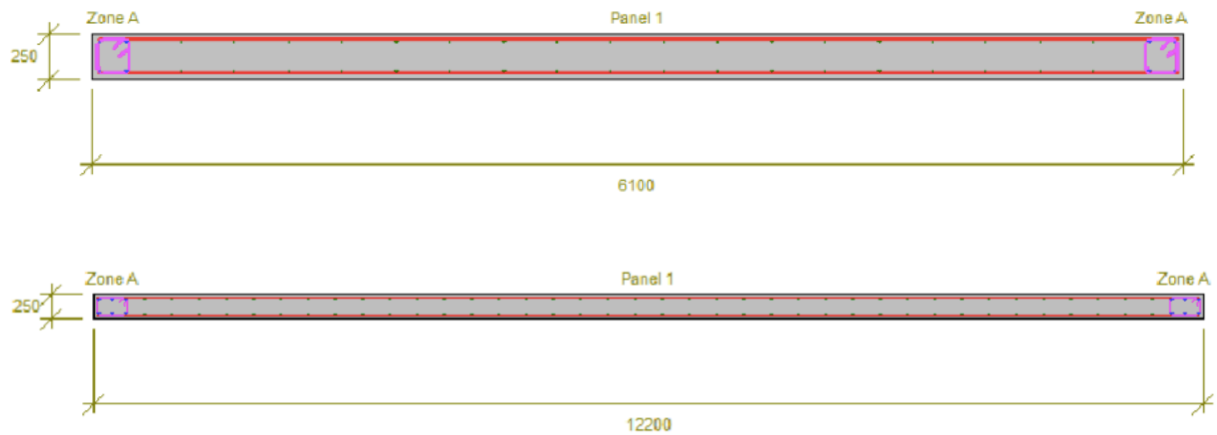

Figure 10: 10-Storey Precast Wall Section

The above details for the 10-storey option were specified at 40MPa concrete with rebar detailing listed below:

DETAILING

COMPRESSION ZONE	*6.1m Panel*	*12.2m Panel*
VERTICAL BARS	4-15M	6-20M
TIES	10M @ 200mm	10M @ 200mm
SPLICE	Tangential	Tangential
AS =	800mm^2	1800mm^2
Y:	2@150	2@150
Z:	2@161	2@158
PANEL ZONE		
VERTICAL BARS	36-10M @ 300 V.E.F	76-10M @ 300 V.E.F
HORIZONTAL BARS	10M @ 300 H.E.F	10M @ 300 H.E.F

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The 20-storey option was achievable with a precast wall solution, albeit it is more involved from an engineering standpoint. At the 20-storey height the building is dynamically sensitive and the connection details become extensive. A cracked 20-storey CIP concrete core wall section was used in a dynamic analysis of the protomodel. The connections were idealized as rigid and fully developed using typical CIP concrete as the model. In the current building configuration, it was unlikely that a 30-storey wall solution would achieve the required core results. A cost was provided, however it was not used in the cost analysis because it was not supported by engineering work.

5.1.3 CIP Concrete Walls

CIP Concrete core walls has been well proven as an effective solution for lateral support, especially in the Toronto market with the low seismic demands and the familiarity to this material. A local engineering firm performed a structural analysis on a similar building typology using concrete core for lateral support on a post and beam timber tower. Their findings were similar to the preliminary assessment with the same base conditions; after doubling the thickness of the concrete walls to 600mm the analysis was approaching acceptable drift limitations. Based on these findings it was concluded that pursuing pricing for a concrete option with a wall thickness of 300mm was reasonable for the 10 and 20-storey options and using a thickness of 600mm was reasonable for the 30-storey timber tower option. Detailed pricing and construction timelines were generated by a contractor local to the Toronto market.

5.1.4 Steel Braced-Frame Core

One of the largest structural steel fabricators in North America provided detailed information and engineering services to better understand the feasibility of a timber tower with a steel lateral structure. The engineering team performed structural design of steel x-braced frame cores for the 10, 20 and 30-storey towers. Detailed information can be found in Appendix E for these braced frame member details and data. The below image is a section cut from the long direction showing the configuration of steel.

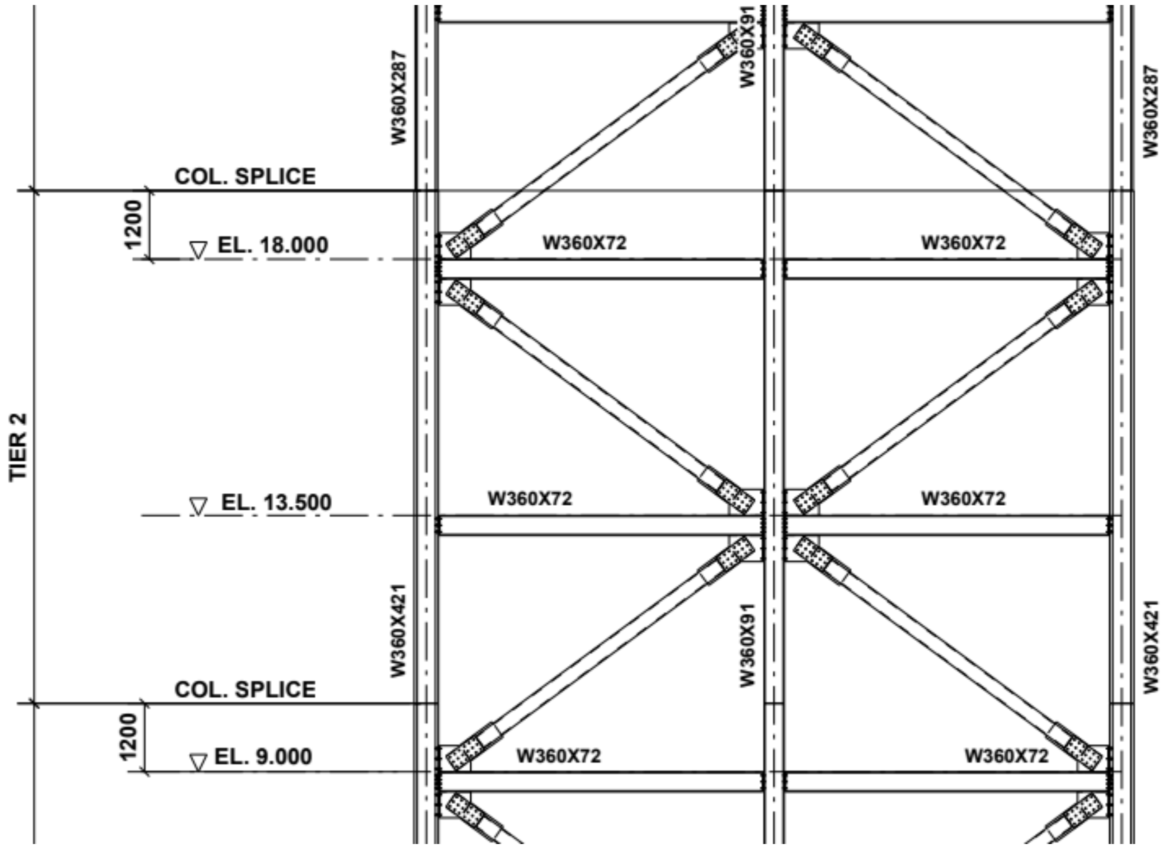

Figure 11: 20-Storey Steel Braced Frame Core Structure Section

5.2 Cost Framework

To understand the opportunity cost of each material and system many different factors were analyzed. The most important factors from a cost perspective include material cost, labour cost and schedule. Core walls often house mechanical and electrical risers and elevators where the consideration of acoustical and environmental separation is important. All the various factors were reduced to a cost per gross floor area (GFA) number. The following table shows the overall building characteristics.

Table 17: Geometry for Timber Towers @ 10, 20 & 30-Storey

Loft 1 Building Characteristics		
Gross Floor Area (GFA)	8,000	sq. ft.
Length	100	ft
Width	80	ft
10 Storey (GFA)	80,000	sq. ft.
20 Storey (GFA)	160,000	sq. ft.
30 Storey (GFA)	240,000	sq. ft.
Core Wall: Surface Area	1554.85	sq. ft.
Floor Height	14.76	ft
Perimeter	105.3	ft

An 8000 square foot floor plate is close to the suggested 8072 square foot typical floor plate laid out in the "Tall Building Design Guidelines", a document put together by the City of Toronto to provide design parameters for developers. This cost matrix serves more as a comparative tool and so the most important factor is the relative cost between the different options. The below factors are detailed further in the following sections:

- Material & Labour
- Schedule
- Assemblies and Systems Integration
- Environmental Sustainability

5.3 Material & Labour

Below is a summary of the material and labour cost associated with each system.

Table 18: Material & Labour Cost for Various Structural Options @ 10, 20 & 30-Storey

Structure Cost Calculations	*Units*	***CIP Concrete***	***Steel***	***Timber***	***Precast***
10-Storey	(GFA) $ / sq. ft.	**$5.13**	**$5.62**	**$11.22**	**$6.92**
Quote Units	$ / Sq Ft (Wall Area)				$35.00
Lump Sum	$ /Per Floor	$25,790	$42,970	$89,200	$54,419
Crane Cost	$ /Per Floor	$15,236	$1,951	$554	$937
20-Storey	(GFA) $ / sq. ft.	**$5.39**	**$8.24**	**15.01**	**$7.88**
Quote Units	$ / Sq Ft (Wall Area)				$40.00
Lump Sum	$ /Per Floor	$29,635	$63,956	$119,600	$62,193
Crane Cost	$ /Per Floor	$13,478	$1,951	$511	$820
30-Storey	(GFA) $ / sq. ft.	**$6.84**	**$8.53**	**N/A**	**N/A**
Quote Units	$ / Sq Ft (Wall Area)			N/A	N/A
Lump Sum	$ /Per Floor	$41,852.76	$66,337.51		
Crane Cost	$ /Per Floor	$12,892	$1,933		

The concrete and precast are contractors competing locally in the Ontario market, and therefore had a good understanding of pricing quite quickly. They did not generally spend much time assessing the structural characteristics, but rather gave an estimate based on comparable projects. There is some inherent risk with this method of cost estimating and the quotes are likely inflated to incorporate additional risk. Also, not having a true structural analysis creates additional risk, as this type of timber construction will surely be unlike any other project performed previously. Though the precaster did provide rough pricing for the 30-storey tower at $35 per square foot for material and $10 per square foot for installation, it seemed unlikely that the complexities of the structure would allow reasonable certainty around the price quoted.

The specialized timber design firm first analyzed the 10-storey structure, and after realizing that the frequency of the structure would warrant a dynamic analysis, they added post tensioning to the 10-storey option to be included in the price. On top of the post tensioned timber walls (either cross laminated timber (CLT or mass plywood panels (MPP)), the 20-storey option required the use of an outrigger truss. This truss system would be pin tied to the outer columns, allowing the lateral loading to be transferred down through these outer columns (similar to a human using a cane as support). These timber systems, though feasible, have not yet been tested at scale and therefore have inherent risk and developmental time and cost associated with their use.

The structural steel supplier also performed a structural analysis and provided a diagram with connection and element sizing with their pricing for the 10 and 20-storey options. Pricing for the 30-storey option was provided, however, based on the relatively linear increase in cost from the 20-storey option. The linear increase may be due to the type of analysis performed in which building drift was the governing factor as opposed to the lateral acceleration. It is likely the extremely light-weight timber-steel composite structure will be governed by the lateral accelerations, and so this linear increase would show a very optimistic estimate since the overall stiffness in the system would need to be increased. There would no doubt be cost implications in designing a stiffer system, which could only be achieved through larger sections or a tuned mass damper. In any case the cost for the 30-storey option is likely underestimated.

Concrete systems are typically known to be the least cost solution. Steel systems, though much faster that CIP concrete, are generally about double the cost of concrete. The precast numbers likely have a large margin of error within them, they would typically be more expensive then CIP concrete but less than steel solutions. These types of timber systems are understandably more expensive due to the material premium and due to the innovation and risk, having not yet been tested in practice.

5.4 Schedule

Schedule Comparison: The Cost of Time

The schedule on a project has several major cost implications, the most significant of which are the cost to run the site or "General Expenses" and the potential revenue that could be generated once the project is complete. These factors add up to significant dollars, and therefore schedule acceleration has a major impact on the bottom line of the project. The following table shows approximate costs and revenue on a weekly basis:

Table 19: Main Value Drivers Related to Schedule

Major Costs Affected by Schedule		*(MONTHLY)*
General Expenses:	$/mo	$ 150,000
Rentable Office	$/SqFt	$ 3.33
Residential Rent	$/SqFt	$ 4.60
Blended Rate	$/SqFt	$ 3.97

The major costs were used to calculate the weekly opportunity cost of speeding up the construction schedule. General expenses are costs associated with running a construction site, which are made up of staff, utility, insurance, office rental and other soft and hard costs that are not recoverable. In this case costs associated with a tower crane were taken out, since they were already accounted for in the Material and Install Cost. Due to the high cost of running a construction site and the high value of renting real estate in the Toronto market, the value associated with a reducing the schedule by a month is a very substantial value and can justify more expensive lateral systems in some cases. The value of completing projects early is compared directly in the below table:

Table 20: Schedule Opportunity Cost for Various Structural Options @ 10, 20 & 30-Storey

SCHEDULE	Units	Cost per Week	CIP CONCRETE	STEEL	TIMBER	PRECAST
10-Storey	$/ sq. ft. GFA		**$7.30**	**$1.46**	**$1.46**	**$1.46**
Lump Sum	$	$129,333	$646,666	$129,333.33	$129,333.33	$129,333.33
Critical Path Affect	Weeks		5	1	1	1
Full Schedule*	Weeks		14.6	5.3	4.1	4.4
20-Storey	$/ sq. ft. GFA		**$6.13**	**$1.23**	**$1.23**	**$1.23**
Lump Sum	$	$208,666	$1,043,333	$208,666.67	$208,666.67	$208,666.67
Critical Path Affect	Weeks		5	1	1	1
Full Schedule*	Weeks		29.0	11.3	11.1	11.6
30-Storey	$/ sq. ft. GFA		**$9.18**	**$1.15**		
Lump Sum	$	$288,000	$2,304,000	$288,000.00	N/A	N/A
Critical Path Affect	Weeks		8	1	1	1
Full Schedule*	Weeks		42.7	17.7	N/A	N/A

There are two different schedules by which you could measure the performance of the lateral load resisting systems, named here the, "Full Schedule" and the "Critical Path Schedule". The full schedule indicates the total time the structure would take to complete (timber superstructure and lateral load resisting core). Since the critical path is the time which would affect the final occupancy date, that was the time period used in calculating to cost impact with respect to the schedule. A zero cost would be associated with a lateral load resisting system built in no time, therefore the faster a system can be built, the less financial impact it will have on cost.

Each system would be constructed somewhat differently. The CIP concrete tower would ideally be constructed continuously and as quickly as possible starting from the foundation until topping off. For the 10-storey option, it was assumed that a tower crane would be used to install each floor in about 1 week, and there would be 2 subgrade floors and 11 above grade floors. The timber superstructure would then begin so that it's completion would coincide with the CIP core completion. Since both of these systems utilize a crane for construction, either a second crane would need to be brought onsite, or the timber tower would be slowed down, the latter was assumed for this exercise.

For the 20 and 30-storey options, self-climbing formwork was found to be feasible. This system takes about 2 weeks to setup and so it is not typically used on lower buildings (20-storeys is near the bottom of its economical limit). This self-climbing formwork system does not use the crane and can typically complete a floor in about 4 days. This is how the gap is closed between the 10 and 20-storey buildings.

It was assumed that the steel system would be erected simultaneously with the timber, having some effect on the crane time. The precast options would be constructed 3 storeys at a time, with the timber structure chasing it. These 3 storey lifts were confirmed to be completed in single day increments.

The 10-storey timber cores would be constructed in line with the timber superstructure. Since this construction would be within one trade, the lower required coordination is expected to save time. The 20-storey timber schedule, which would utilize the outrigger truss system, would be slowed down significantly on the outrigger floors, taking an estimated 2 weeks longer approximately. Appendix B shows a simplified schedule with typical construction times for the different systems as described in the previous passage.

5.5 Assemblies and Systems Integration

Though the material, labour and schedule costs are by far the most significant, other factors do contribute to the feasibility of the different systems. Not only do these factors contribute to the underlying cost, but they speak to the underlying risks associated with the different systems as well. These risks are associated with fire, moisture, sound, and the coordination between subtrades.

5.5.1 Assemblies: Fire, Acoustic and Environmental Separations

Achieving adequate fire suppression is critical for timber structures, especially within the shafts which act as egress paths in an emergency scenario. The interiors of the shafts must achieve a flame spread rating of 25, which is essentially non-combustible, to allow building occupants a safe path of escape and to avoid contributing to fires, through the stack effect[2]. Structural elements must have 2-hour fire ratings.

Many of these same assemblies also serve to reduce sound transmission between space. The main forms of acoustical nuisance are measured through the Sound Transmission Class (STC), airborne sound which can travel through walls, Impact Insulation Class (IIC) which occurs mainly through heavy footsteps and other impacts, and through flanking where vibrations are transferred through stiff structural members. All three of these factors must be considered, especially in cores, where stairs, elevators, garbage shoots, and shafts exist below building equipment which is often housed at the tops of towers.

The following paragraphs summarize the likely treatment of each material used in shaft walls:

[2] The movement of air due to buoyancy of air density from temperature change

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Thursday, April 25, 2019

Timber

CLT walls have higher flame spreads, and by code they require encapsulation on the interior walls. Since timber is comparatively light, acoustics can pose issues in terms of impact sound and flanking transmission paths. Floor vibrations can also be higher than what occupants are typically used to, if not addressed properly in design.

Steel

Steel, though non-combustible, becomes more ductile and loses strength with increased temperature, and this behavior is highly unpredictable. The Steel would require heat insulation through the use of intumescent paint, a concrete or insulation covering, or by building fire-rated shaft walls. The steel requires a 2 hour fire barrier, and because shafts cannot be left open for safety reasons, this assembly was also able to pick up the sound and moisture barrier and so there was no additional cost charged for an acoustical separation.

Precast Concrete

Concrete, being a ceramic, is resistant and insulating, and a cover layer over the reinforcing steel insulates the steel from temperature fluctuations. The precast to precast and precast to CLT (Slab) connections would require a fire rating as these are usually built from plate steel and either bolted or welded. This fire rating is usually achieved through a layer of grout being installed over all connections. Precast, being a heavy mass with thick walls has inherent sound insulating properties, however, in order to meet the best practices, another barrier is built for sound insulation.

CIP Concrete

CIP concrete has the same cover layer over the entire surface, and since each floor is poured monolithically there is no exposed steel or rebar from a structural perspective, meaning that the fire protection is inherent to the system. Cast-in-Plates[3], used to support the CLT slabs and elevator equipment would need to be protected with a two hour fire-rating which could be a drywall assembly or encapsulated with Timber. The CIP concrete is similar to the Precast concrete walls, and the same acoustical rating was therefore used.

These different systems have relatively minor impact on cost, but it is still significant enough to consider. These costs are summarized in the following table:

Table 21: Fire Rating Cost for Various Structural Options @ 10, 20 & 30-Storey

FIRE-RATING	*Units*	***CIP CONCRETE***	***STEEL***	***TIMBER***	***PRECAST***
COST/ FLOOR	$ / sq. ft. GFA	**0**	**$2.18**	**$1.56**	**$0.03**
Unit Rate of Assembly	$ / sq. ft. (Wall)		$11.24	$8.01	$2.00
Lump Sum Per Floor			*$17,478.09*	*$12,461.05*	*$210.63*
Notes:		- Not Required: Concrete Non-Combustible Ceramic	-Fire Rated Assemblies and Covered Connections	-Fire Rated Assemblies or Char Layer and Covered Connections	-Fire Rated Connections
Assembly Type 1		N/A	Type P - 6A Shaft Wall (64mm Stud, 25mm Liner & 16mm Type X Drywall + Insul.)	Encapsulation (3 Layers of Drywall)	Mortar Covering

[3] Cast in place structural steel elements

Table 22: Acoustical Separation Cost for Various Structural Options @ 10, 20 & 30-Storey

ACOUSTICS	*Units*	***CIP CONCRETE***	***STEEL***	***TIMBER***	***PRECAST***
COST/ FLOOR	$ / sq. ft. GFA	**$0.70**	**$0.00***	**$0.83**	**$0.70**
Unit Rate of Assembly	$ / sq. ft. (Wall)	$3.58	$11.24	$4.29	$3.58
Lump Sum Per Floor		$5,561.21	*Accounted for in Fire Rating	$6,673.45	$5,561.21
Inherant STC Ratings	Code 55	58	0	39	58
Inherant IIC Ratings	Goal 55	34	0	35	34
Notes:		-Acoustic Assembly w/ Isolation Pads	-Acoustic Assembly w/ Isolation Pads -Additional Build ups likely required	-Acoustic Assembly w/ Isolation Pads -Additional Build ups likely required	-Acoustic Assembly w/ Isolation Pads
Assembly Type 1		Type P - 1A (41mm. Stud c/w 15mm Drywall on 1 Side & Insul)	Type P - 6A Shaft Wall (64mm Stud, 25mm Liner & 16mm Type X Drywall + Insul)	Type P - 1 (41mm. Stud c/w 15mm Drywall on 2.Sides)	Type P - 1A (41mm. Stud c/w 15mm Drywall on 1 Side & Insul)
Additional STC Ratings		44	59	45	44

5.6 Environmental Sustainability: Carbon Equivalents

The environmental sustainability of different materials is a very complex field of study. The full lifecycle of each material must be considered, which include primary resource extraction, transportation, energy embodied during manufacturing and construction process, the performance during use and end of life considerations. Additionally, variables within with each of these phases of life must be considered, including the impact on the earths carbon cycle, longevity and durability, end of life and waste due to use. Not all aspects of this field were quantified, the single largest impact, the carbon footprint, was used as a proxy to weigh the sustainability of the different materials. First, a Life Cycle Assessment (LCA) methodology was used to quantify the embodied carbon within each material. With these carbon equivalents calculated, future carbon pricing rules, recently presented by the federal government of

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Thursday, April 25, 2019

Canada, were used to understand the cost of the new carbon tax. The carbon tax is to come into effect in 2019 and will begin at $10 / tonne and increase at $10 per year for 5 years reaching $50 in 2023. The full escalation pricing was used to demonstrate the steady state cost of carbon.

Table 23: The Carbon Cost for Various Structural Options @ 10, 20 & 30-Storey

THE COST OF CARBON	Units	CIP CONCRETE	STEEL	TIMBER	PRECAST
COST / FLOOR	$ / sq. ft. GFA	**$0.27**	**$0.03**	**-$0.21**	**$0.07**
Carbon Tax (at full escalation)	$ / Tonne	$50	$50	$50	$50
Floor Area	sq ft	8000	8000	8000	8000
Carbon Equivalent	Tonnes CO2	42.7	4.9	-33.4	11.9
Carbon Footprint	KgCO2 / KgMaterial	0.36	0.81	-1.249	0.12
Weight / Floor	Tonne	118.6 237*	6.0	26.7	98.8
Volume of Core	m^3	51.9	0.769	51.9	41.2
Density of Material	Kg/m^3	2400	7849	515	2400

*Concrete at 600mm wall thickness

Calculating the carbon cost impact of different materials is no simple task; the full lifecycle of products must be considered. Some of the questions complicating the carbon equation include at what phase counting carbon output begins, what process/practice can different companies perform these tasks differently, where in the world the products originate from and how accurately can end of life carbon be predicted? The carbon footprint numbers listed above were from a third-party company without any apparent bias towards one material (Ruuska, 2013).

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5.7 Other Design Factors

5.7.1 Connections

Though all connections were included within individual estimates for each system, they did not include connection details to the timber systems. There are well known connection details used in steel, precast and even CIP concrete and all mainly use steel plates or dowels. Major timber systems use steel plates or dowel connections to transfer loads as well, however, there are major innovations continuing to change the timber connection landscape. Due to the great variety and continuously changing timber connection landscape, this part of the analysis was not evaluated in great detail.

5.7.2 Elevator Integration

Elevators affect the building's overall cost by taking up more or less usable square footage per floor and also through differences in construction scheduling. Construction elevators are common on typical construction projects, but the situation changes when the construction timeline is drastically shorter and many of the finishes are complete offsite.

Prefabricated elevators are elevator runs typically built horizontally in a factory and then dropped onto site where connections are made quickly, and commissioning is generally accelerated. Jump lifts are essentially construction elevators which utilize the rails and the base of the unfinished cabin to deliver material and people during construction, replacing temporary hoist lifts.

All of these core wall options could accommodate most different elevator strategies, but some could add more value than others. In theory streel braced frames could be built into a lattice structure which both acts as the lateral load resisting system and has many elements prefabricated into them, including elevator rails. Typically, precast elements have cast-in-plates where rails are field welded and leveled. Timber Elements could have a level of prefabrication similar to precast. For Cast-In-Place concrete core walls, it would be difficult to prefabricate elevators, without building wider shafts and dropping in steel structures, reducing the efficiency of the floor plate.

5.7.3 Coordination Risk

A major risk during the design and construction process is the risk associated with coordinating exact prefabricated elements within the correct tolerance and schedule. Increasing the number of contractors by nature will increase the risk of human error. There is also a risk associated when mating different materials together as typically different materials have different tolerances. Even if care is taken while preparing members, timber, concrete and steel all have different thermal and, in the case of wood, moisture expansion characteristics.

5.7.4 Maintenance

Long term maintenance cost of each system will vary, which can change the operational cost. This impact can be material, especially when considering the more innovative systems. Steel and concrete have been used extensively, however; timber is a fairly new material being used in taller modern buildings. As such, the International Building Code has outlined more stringent monitoring considerations for this natural material. The reason behind the enhanced monitoring are related to long term differential movement, moisture related issues as well as human interference, such as drilling into the structural elements.

5.8 Conclusion

The cost comparison between the different lateral structural systems is presented in Table 24 below. These factors are sorted by systems having the greatest impact on cost, with the total cost of each system presented..

Table 24: Structural System Cost Comparison Matrix Summary

		CIP CONCRETE	**STEEL**	**TIMBER**	**PRECAST**
SYSTEM TYPE		*Concrete Cores*	*Steel Braced Frame*	*-CLT Core - PT -Outriggers*	*Precast Cores*
	TOWER	$ / Sq Ft	$ / Sq Ft	$ / Sq Ft	$ / Sq Ft
MATERIAL & LABOUR	*10-Storey*	$5.13	$5.62	$11.22	$6.92
	20-Storey	$5.39	$8.24	$15.01	$7.88
	30-Storey	$6.84	$8.53*	- - -	- - -
SCHEDULE	*10-Storey*	$7.30	$1.46	$1.46	$1.46
	20-Storey	$6.13	$1.23	$1.23	$1.23
	30-Storey	$9.18	$1.15	- - -	- - -
FIRE RATING		$0.00	$2.18	$1.56	$0.03
ACOUSTICS		$0.70	0.00	$0.83	$0.70
SUSTAINABILITY		$0.27	$0.03	-$0.21	$0.07
		$0.53			
TOTAL	*10-Storey*	**$13.39**	**$9.29**	**$14.86**	**$9.18**
	20-Storey	**$12.75**	**$11.68**	**$18.42**	**$9.90**
	30-Storey	**$16.99**	**$11.90***	*Unknown*	*Unknown*

By viewing the result strictly from a cost perspective, it appears that the precast option is the best solutions for 10 and 20-storey buildings and the CIP Concrete option is the best option for 30 storey structures. One major detail which requires further study are the connection details used in the prefabricated precast, timber and steel solutions. These connections could increase the cost substantially with respect to complexity and therefore time.

CIP concrete is the lowest cost solution when considering the pure material and labour cost of the different systems, however when considering this cost with schedule implications this changes drastically. Downtown Toronto real estate value is accelerating at a pace that is among the fastest in the world and with rental prices to match this acceleration, it is among the most expensive cities. The steel option shows the extreme advantage building quickly can have. As stated previously, it appears that the steel 30 storey option has been underestimated from a cost perspective, however, at $5.09 per square foot there is an almost $1.4 million buffer between the concrete option. Though in North America, many of the tall timber buildings have used concrete core walls as their main lateral load resisting systems, exploring different structural systems which can be produced offsite can not only speed the construction process but offers an opportunity to integrate other building systems to further improve efficiencies.

Though this study attempts to compare these systems on an “apples to apples” basis, it is clear that the advantages of the different systems can vary based on the site specific outcomes desired. These outcomes include the programmatic use, the building massing, the floor layout and in the case of timber, the system type, for example post and slab, post and beam, or a panelized system. Revisiting the case studies can better illustrate this as three quarters of Mid-Rise timber buildings up to 10 floors use a panelized system, and but the majority of these had residential programs. The post and beam/slab systems typically provide more flexible and open floors and they are more often used in taller structures. As buildings grow in height, the gravity load baring element cross sections must also grow, and in the case of panelized walls, this disproportionately reduces the usable square footage of the floors. Only one out of sixteen of the high-rise building systems above 10-storeys used a panelized system as the main structural supports. These nuances of timber construction indicate an approach which is more unique; steel, precast and concrete have their own nuances. In typical construction projects each system is designed on a one-off nature, but when trying to prefabricate assemblies into modular building systems the need for standardization becomes more important. It is no surprise that this work has brought out inefficiencies with respect to the design of certain systems, namely the timber option. Table 24 does, however, justify the advantages of hybrid tall timber towers, demonstrating that materials should be used where they can provide the most advantageous effect.

Major assumptions were made with respect to construction phasing plans. More detailed information is required the level of prefabrication within the whole process in order to better optimize and understand a phasing plan. Factors such as time constraints placed on cranes, the time required to install different connections, can affect the overall schedule to a large degree. The margin of error within the schedule and man and material cost numbers presented and could easily swing the lowest cost option of the results to any of the different systems. The fact that these systems do compete so closely on total cost is encouraging, as all of the options presented have been used previously typically under normal market conditions.

Conclusions from this study are most powerful when quantitative factors are considered with the qualitative, risk factors and with specific goals in mind. These risk considerations will be considered in the concluding chapter of this report.

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Chapter 6: Conclusions & Next Steps

It is becoming clearer that current development practices are environmentally unsustainable, but better practices are emerging. Urban development must be delivered at an accelerated rate as the populations of cities balloon; an estimated two thirds of the future 9 billion human population will be moving to cities by 2050. The real estate industry is beginning to shift, developers are continually seeking opportunity to provide solutions to the above trends and all the issues which follow.

In Toronto, for example, vacancy rates for commercial real estate are at an all-time low and individuals struggle to find affordable places to live. Designers seek to create better products but are often pinched by financial goals constraints developers face to remain competitive and the standardization regulators enforce due to their lack of resources. Regulators are working to improve processes which could increase supply, but it is difficult to change directions in large organizations and they have the added difficulty of being public facing while facing four-year intervals of political change. The margins general contractors currently accept are quite low, and they've been getting pinched on cost even more in recent years. All these factors lead to more of the same short term thinking which as lead to non-existent productivity growth over the past decades.

The design process for a traditional development occurs in a waterfall format, where developers state objectives, architects provide massing and programming diagrams, then the documents cascade down to structural engineers, mechanical and electrical engineers each taking weeks to add their parts missing valuable opportunities to influence decisions early. Construction managers generally receive these documents at the of the process, without having had much, if any influence. Prefabricated buildings must take a fundamentally different approach to the design and construction process in order to achieve success. This paper compares potential lateral load resisting systems which would support innovative prefabricated timber buildings. By integrating all disciplines at an early stage, a systems approach can be taken to achieve maximum efficiency, reduce coordination and construction risk and create innovative solutions to achieve superior cost and performance. Cost should, however, be viewed by incorporating an understanding of underlying risk. Risk in this situation includes: 1) coordination risk between subtrades, 2) risk in using innovative systems, as well 3) cost premiums associated with insurance and 4) regulatory hurdles in developing innovative systems. As the next step in the costing work the risk level should be view quantitatively, however, the following sections describe the qualitative risk associated of each Lateral Load Resisting Systems within the timber gravity structure.

Timber

Qualitatively, it is clear that the timber options hold the most risk, it is a new system being proposed, regulatory and insurance bodies are unfamiliar with this system and how it performs from a structural, fire safety and moisture perspective. The advantage from a risk perspective is that the entire structural system can be installed by the same contractor group which significantly reduces the coordination requirements and risk.

Steel

Steel has been combined with timber for the longest periods of time when considering the connections and hybrid systems that existed in the past, however, those solutions existed in the 10-storey building height range. The properties of steel are more uniform compared to concrete and timber, reducing risk by simply using a predictable material. Lateral load resisting steel systems are regularly used in the construction of taller structures, albeit, usually in jurisdictions with higher seismic demands. The coordination between the timber subtrade and steel subtrade would likely be greater than with an all timber solution but still lower than using concrete options since all connections are made of steel regardless.

Precast Concrete

Precast is not typically used on taller towers, and connections with the timber superstructure have no precedents at these taller heights. Regulators and insurance companies would therefore be less comfortable with the structural implications for taller buildings. Although the non-combustible nature would allow some comfort, structural connections must still be fireproofed the connections are steel. Precast is prefabricated and so coordination between these subtrades, would likely be less onerous than cast in place concrete, but greater than steel and timber.

Cast in Place Concrete

Concrete structural systems are used regularly in the Toronto jurisdiction, and in other regions are often combined with tall timber structures, for example Brock Commons in Vancouver (18 storeys) and Hoho in Vienna(24 storeys), which both use reinforced concrete for lateral support as well as a non-combustible egress option. Combining CIP concrete with a prefabricated timber can create tolerance and connection issues due to the high inconsistency with onsite construction. The coordination between CIP concrete and Timber would likely not be a huge issue since the walls are typically completed prior to timber commencing, however, this extends the schedule dramatically. Both contractors require significant crane time, if the phasing were to be overlapped careful attention to the phasing plan would be required, as well as additional crane costs. If the activities were overlapped it would also cause potential safety concerns with respect to overhead work.

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Buildings Innovation

The next Industrial Revolution (4.0) promises to combine artificial intelligence and more advanced mechatronics to create ultra-efficient manufacturing practices, and so the question becomes: what is the opportunity cost of choosing a status quo option? There is inherent risk in not acting to create more efficient processes, since certain companies could altogether disrupt industries by quickly scaling and taking market share. Based on many of the trends it appears that companies are placing huge bets on prefabrication as an option to improve productivity in the construction sector. There is great potential upside in contributing to the advancement of such technologies.

The Buildings Innovation team at Sidewalk labs had four main goals, to create **adaptable** and **sustainable** buildings, which improve **affordability** without compromising on world class **design**. Through prefabricated timber buildings, assemblies can be efficiently manufactured in a factory setting, by taking advantage and building on existing technologies such BIM and Industry 4.0, through a systems approach to construction.

Recommendations

This report has explored the effect that wind loading has on innovative tall timber buildings with different lateral load resisting systems. It compared one onsite solution, CIP concrete, to three prefabricated solutions, precast concrete, timber and steel. Each system performs well when measured by different goals but by viewing the systems through the Sidewalk Labs lens a modular steel system appears the most attractive. Sidewalk Labs aims to reduce cost through creating innovative systems, which means that it is important to consider both the short and long-term view of cost savings. CIP concrete has many precedents in tall timber buildings and reduces the regulatory risk and competes very well on cost, but does nothing towards the prefabrication strategy, nor does it offer future innovation potential. Precast is modular but has few or no completed precedents in a timber tower and again it would be difficult to prefabricate other systems into it. The all timber solution is potentially attractive as it is light and versatile enough to prefabricate other system into, however the system is less interesting to use in lateral load resisting systems due to the relatively low stiffness inherent to the material.

Prefabrication

A construction project on its own can only reduce cost through more efficient processes, whereas factories can reduce cost through both efficiency and scale, since the capital cost of a factory can be split over all units that factory produces. Steel systems, through a prefabricated modular methodology, are the most versatile of those proposed. Many additional building systems, such as electrical closets, stairs, elevators, garbage shoots, prefabricated bathroom and kitchen modules and more can be accommodated within the overall steel lateral system.

Steel is the second most sustainable material proposed, behind timber. Steel is the most recycled material in the world, and if used in this way the sustainability of the material improves significantly.

The key to success for prefabricated buildings is the replicability of similar elements used in many buildings. If the massing of the building is changed in the future, steel frame elements are highly modular could be accommodated into the walls of several of the previously listed systems, allowing for additional strength. Steel frames could also be incorporated the exterior of the building structure in an exo-skeleton format which can more extreme loading conditions.

Due to the many short-term benefits and long-term potential of steel, a prefabricated steel system is the recommended approach to bring forward to a deeper level of design.

Future Work

Both the cast-in-place concrete and the prefabrication steel options are worth carrying forward to gain a more detailed understanding of the design and cost. The "Kit-of-Parts" methodology, will allow for a more effective manufacturing strategy, and so the following parametric model help to generate a solution from the matrix of viable lateral structural options.

Table 25: Parametric Structural Model

A	B	C	D	E	F	G	H
Building Shape	**Program**	**Grid (ft.)**	**# Floors**	**Floor Area**	**FL To FL (m)**	**LOADING OUTPUT**	**LATERAL OPTIONS**
Insert Drop Down Toggle on This Line						1. Gravity Load	
Square "Point Form"	**RESIDENTIAL**	20X20	22	17,265	3.4	2. Lateral Load -Deflection -Acceleration	I CIP Concrete
Rectangular "Bar Form"		20X24					II Prefab Steel
Hybrid Shapes		24X24					III External Braces (Steel or Timber)
	OFFICE	20X40	5	25,532	4.0		IV Outrigger Truss
		40X24					V Transfer Floors
		20X48					
		40X24					
	Retail	40X40	2	25,532	5.0		
		40X48					
		48X48					

This matrix shows the important factors which provide initial loading to the structure, these are chosen based on the site shape and programming factors. This matrix provides the initial iteration for choosing structural options. This paper only studied core options, however, these can be paired with other systems such as externally braced frames or exo-skeletons, as well as outrigger-truss systems. Furthermore, this study used lateral deflection as a proxy for sizing elements. The acceleration becomes important for light and tall buildings, as indicated by the calculated frequencies of the different options in this study, and so this factor must be studied in more detail. As future work, these options should be evaluated in more detail and a parametric model could be created as part of a generative design model for quickly generating efficient structural options.

A second iteration of this parametric model would be required to begin generating a more accurate design. Within this next iteration, detailed information on the building assemblies and their characteristics should be studied. Some of these assemblies include the modular cores, housing the main building systems, prefabricated kitchen and bathroom modules, the floor and wall modules. Detailed information including weights, connection details, acoustical, fire and moisture properties would be required to generate a more detailed structural model, but also to generate more accurate cost information.

For the purposed of this study all connections were idealized as rigid. Though this approximation is fair at this level of detail, it is likely an overly optimistic picture, especially for the timber system. There will likely be additional ductility in the timber connections especially if the fastening system is screws and nails. Connections are extremely important and should be For timber buildings above 10-storeys. Differential shortening of structural elements can become a significant factor that must be accounted for in the design. The short and long-term shortening characteristics of mass timber will vary from steel and concrete so these factors should be considered when sizing elements.

Torsional effects, though taken into account though different wind load combinations, should be reviewed closely. Timber buildings, due to their typical natural frequency range, can be more sensitive to this failure mode at taller heights. The torsional failure mode is sudden with very little warning and is therefore must be limited. Bracing through walls or diagonal members may be required at the outer edges to ensure this mode is avoided.

Considerations for fire and vibration can be significant for timber structures, in some cases actually governing the sizing of members. If the vibration of floor structures is too great then oversizing of beam and floors may be required for this serviceability component and this increased localized stiffness will change the characteristics of the overall building. If the timbers are to be exposed, an additional char layer is required to achieve a 2-hour fire rating. This additional structure is significant and can improve the stiffness characteristics and add additional mass to the overall structure. As indicated by the green box in figure 12, only a preliminary structural analysis was performed, the factors discussed previously should be studied further.

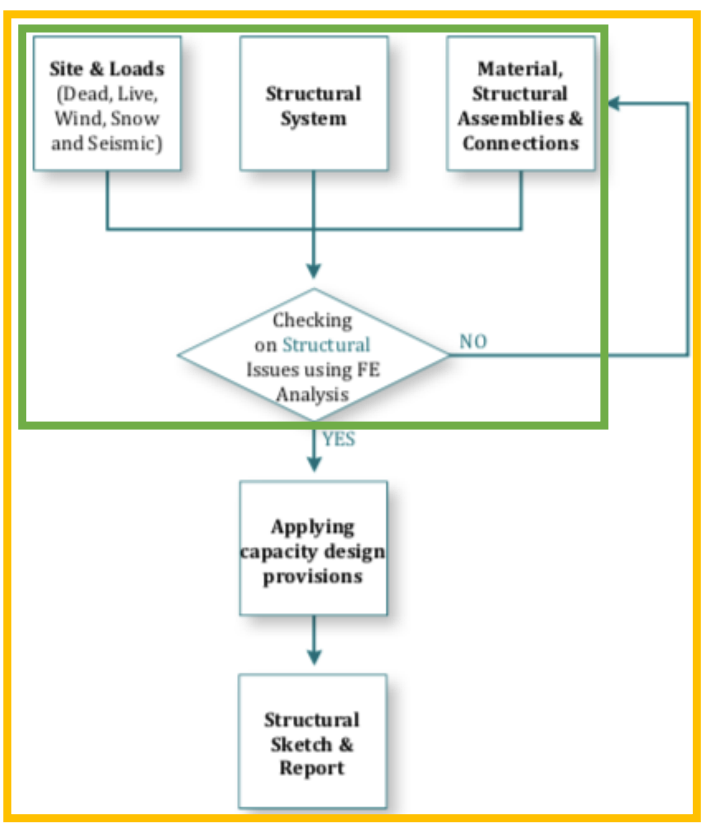

Figure 12: Structural Design Flow Chart

After completing the more detailed structural design, experimental testing of assemblies for fire and structural performance should follow, as well as a wind tunnel test to better understand the empirical acceleration and deflection data.

Time-scale modelling should be performed to understand the actual assemble time for building components, and with this real-world testing, greater confidence can be placed behind schedules of these novel buildings. This is an extremely important step since, as shown in this study, the cost of time can be enormous, and so a great part of the benefit of prefabricated systems is the schedule reduction.

Through this study several interesting core systems, available on the market, were discovered which are being tested and piloted. One such system, named SpeedCore, is composed of a permanent steel forms combined with concrete to form a stiff yet ductile composite. Creating relationships with innovative industry partners is essential to a successful innovation strategy. Innovation in construction, as described in this paper, is very difficult to foster due to many factors. Companies within Silicon Valley have created a geographic ecosystem which has helped to foster and supercharge the advancement of technology. Similarly, companies and individuals willing to push the boundaries must build an ecosystem which can help advance the construction industry, and this is done through building relationships and working together. Sidewalk Labs have proposed an "Idea District", which will help to create a geographic location in which an urban innovations industry can foster and thrive. Waterfront Toronto have begun to set the stage by attracting some of the world's most innovative partners. To this end, the City of Toronto, already a microcosm of global culture and urban issues, can meaningfully contribute to the next chapter of urban success.

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Bibliography

(n.d.). Retrieved from http://www.woodworks.org/wp-content/uploads/17DS08-GUEVARA-T3-Minneapolis-WDS-171116.pdf

Abrahamsen, R. (2017). Mjøstårnet - Construction of an 81 m tall timber building. *Internationales Holzbau-Forum.*

AWC. (2019). *Understanding the Mass Timber Code Proposals: A guide for building officials.* Mass Timber Code Coalition.

Bergeron, D. D. (2004). *The Origin and development of Canada's objective-based codes concept.* National Research Council.

Block, I. (2018, September 7). *dezeen*. Retrieved from Anders Berensson Architects proposes "wooden skyscraper city" for Stockholm: https://www.dezeen.com/2018/09/07/anders-berensson-architects-wooden-skyscraper-city-stockholm-sweden-architecture/

Bouchet, M., Liu, S., Parilla, J., & Kabbani, N. (2018). *GLOBAL METRO MONITOR.* Brookings.

Browning, W., Ryan, C., & Clancy, J. (2014). *14 patterns of biophilic design Improving Health & Well-Being in the Built Environment.* New York: Terrapin Bright Green.

Canadian Wood Council (CWC). (2017). *Brock Commons Study.* Retrieved from Wood Works: http://wood-works.ca/wp-content/uploads/CS-BrockCommon.Study_.23.lr_.pdf

City of Toronto. (2013). *TALL BUILDING DESIGN GUIDELINES.* Toronto: City of Toronto.

CTBUH. (2017, June). *Tall Buildings in Numbers Tall Timber: A Global Audit*. Retrieved from Council on Tall Buildings and Urban Habitat: http://www.ctbuh.org/Publications/CTBUHJournal/InNumbers/TBINTimber/tabid/7530/language/en-US/Default.aspx

CWC. (2016). *ORIGINE POINTE-AUX-LIÈVRES ECOCONDOS QUEBEC CITY.* Retrieved from Wood Works: http://cwc.ca/wp-content/uploads/2018/05/Origine-Case-Study.pdf

Dobbs, R., Smit, S., Remes, J., Manyika, J., Roxburgh, C., & Restrepo, A. (2011). *Urban world: Mapping the economic power of cities.* McKinsey Global Institute.

Dr. Moses, D., Alexander, M., & Dr. Craft, S. (2017). *Ontario's Tall Wood Building Reference: A Technical Resource for Developing Alternative Solutions Under Ontario's Building Code.* Toronto: Ministry of Natural Resources and Forestry.

Drew, R., Karsh, E., Harmsworth, A., Dr. Nadim, M. A., D'Ambra, S., Dr. Chen, Z., . . . Medin, A. (2015). *Application of Analysis Tools from NEWBuildS Research Network in Design of a High-Rise Wood Building.* Vancouver: WoodWORKS!

Filipe Barbosa, J. W. (2017, February). *Reinventing construction through a productivity revolution*. Retrieved from McKinsey Industries: Capital Projects and Infrastructure: https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/reinventing-construction-through-a-productivity-revolution

Foster, R. R. (2016). "Proposal for defining a tall, timber building", . *J. Struct. Eng.*

Global Construction Outlook to 2022 . (2018, July 17). Retrieved from Business Insider: https://markets.businessinsider.com/news/stocks/global-construction-outlook-to-2022-1027375492

Government of Canada. (2017, 07 26). *Forest certification in Canada*. Retrieved from Natural Resources Canada: https://www.nrcan.gc.ca/forests/canada/certification/17474

Guevara, A. (2017, November 16). *T3 Minneapolis.* Retrieved from Wood Works: http://www.woodworks.org/wp-content/uploads/17DS08-GUEVARA-T3-Minneapolis-WDS-171116.pdf

Hawk, T. (2016, May). *A short history of tall buildings: the making of the modern skyscraper.* Retrieved from The Conversation: http://theconversation.com/a-short-history-of-tall-buildings-the-making-of-the-modern-skyscraper-56850

Jones, R. (2014, November). *Tall Wood Buildings:The Canadian Experience.* Retrieved from Natural Resources Canada (NRCan) : http://www.woodworks.org/wp-content/uploads/TTBW-Jones-canadian-tall-wood-competition.pdf

K. A. Malo, R. B. (2016). Some structural design issues of the 14-storey timber framed building "Treet" in Norway. *Eur. J. Wood Prod.* , 74: 407.

Khan, F. (1969). Recent Structural Systems in Steel for High-Rise Buildings. *Conference on Steel in Architecture.* London: The British Constructional Steel work Association.

Koo, K. (2013, May). *A Study on Historical Tall-Wood Buildings in Toronto and Vancouver.* Retrieved from FPInnovations: https://fpinnovations.ca/Documents/a-study-on-historical-tall-wood-buildings-in-toronto-and-vancouver.pdf

Kusisto, L. (2018, July 31). *Young People Don't Want Construction Jobs. That's a Problem for the Housing Market.* . Retrieved from The Wall Street Journal: https://www.wsj.com/articles/young-people-dont-want-construction-jobs-thats-a-problem-for-the-housing-market-1533029401?mod=e2fb

Lynn Embury-Williams, E. K. (2013). *Application of Analysis Tools from NEWBuildS Research Network in Design of a High-Rise Wood Building.* British Columbia: WoodWorks.

Magne Aanstad Bjertnæs, K. A. (2017). WIND-INDUCED MOTIONS OF "TREET" - A 14-STOREY TIMBER RESIDENTIAL BUILDING IN NORWAY. *World Conference on Timber Engineering.* Quebec City.

McDonnell, R. Z. (2017). Framework - A tall re-centering mass timber building in the United States. *NZSEE Conference.* Portland: KPFF Consulting Engineers.

mgb ARCHITECTURE + DESIGN, Equilibrium Consulting, LMDG Ltd, BTY Group. (2012). *THE CASE FOR Tall Wood BUILDINGS.* Vancouver.

Moudgil, M. (August 2017). *Feasibility study of using Cross-Laminated Timber core for the UBC Tall Wood Building* . Vancouver: THE UNIVERSITY OF BRITISH COLUMBIA.

Naturally Wood. (2015, June). *Wood Innovation and Design Center.* Retrieved from Naturally Wood: https://www.naturallywood.com/sites/default/files/documents/resources/wood-innovation-design-centre_0.pdf

Robert Foster, T. R. (2016). Proposal for defining a tall, timber building. *Journal of Structural Engineering*.

Robert M. Foster, M. H. (2016). Briefing: Super tall timber–Oakwood Tower. *ICE: Institution of Civil Engineers*.

Ruuska, A. (2013). *Carbon footprint for building products.* Finland: VTT TECHNOLOGY 115.

Sidewalk Labs. (2018). *PROTO MODEL | TOOLKIT.* Toronto: Sidewalk Labs.

SOM, LLP. (2013). *Timber Tower Research Project.* Chicago: Skidmore, Owings & Merrill, LLP.

Stephen R. Kellert, J. H. (2013). *Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life.* Wiley.

The Beck Group. (2018). *Mass Timber Market Analysis.* Portland: The Beck Group.

The Skyscraper Center. (2017). *HoHo*. Retrieved from The Global Tall Building Database of the CTBUH: https://www.skyscrapercenter.com/building/hoho/18763

Thomas Connolly, C. L. (2018). Feasibility Study of Mass-Timber Cores for the UBC Tall Wood Building. *Buildings*.

Timber Technology and Design. (2017). *REACH HIGHER WITH WOOD: 84 METER, 24-STOREY 'HOHO' TOWER*. Retrieved from Timber Design and Technology: http://www.timberdesignandtechnology.com/reach-higher-with-wood%E2%80%A8-84-meter-24-storey-hoho-tower/

United Nations. (2018, May). *2018 Revision of World Urbanization Prospects.* Retrieved from UNITED NATIONS: https://www.un.org/development/desa/publications/2018-revision-of-world-urbanization-prospects.html

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APPENDICES

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Appendix A: Glossary of Timber Products

(Naturally:Wood, 2019)
(Designing Buildings Wiki, 2018)

	Light Wood-Frame	Wood framing, or light frame construction, is the assembly of dimensional lumber that is regularly spaced and fastened together with nails to create floor, wall and roof assemblies. Wood is the most common material used within the construction industry today. The limit of this type of construction is typically 6 storeys
	Post & Beam	Timber post and beam construction is a building method that comprises vertical structural posts and horizontal beams, jointed to form a structural frame into which walls are 'placed'. As this frame is structural, and carrying the roof load, the number of interior walls can be reduced, making it suitable for creating open plan spaces. Timber post and beam construction differs from the technique referred to as 'timber frame' construction, which is a system of panelised structural walls and floors constructed from small section timber studs and clad with board products. For more information, see Timber frame.
MT	Mass Timber	Mass timber construction uses large prefabricated wood members for wall, floor and roof construction. Some of these products include glue-laminated timber (glulam), cross-laminated timber (CLT) and nail-laminated lumber (NLT). They are diverse with proven performance and safety, showcasing the wide range and variety of opportunities with wood products. They are listed below:
CLT	Cross Laminated Timber	CLT is an engineered wood panel typically consisting of three, five, or seven layers of dimension lumber oriented at right angles to one another and then glued to form structural panels with exceptional strength, dimensional stability and rigidity. Because of CLT's structural properties and dimensional stability, this mass timber product is well suited to floors, walls and roofs used in mid-rise and tall wood construction. The wall and floor panels may be left exposed in the interior which provides additional aesthetic attributes. The panels are used as prefabricated building components which can speed up construction practices or allow for off-site construction.
Glulam	Glue Laminated Timber	Glulam is composed of individual wood laminations (dimension lumber), specifically selected and positioned based on their performance characteristics, and then bonded together with durable, moisture-resistant adhesives. The grain of all laminations runs parallel with the length of the member. Glulam can be used in horizontal applications as a beam, or vertically as a column. Glulam has excellent strength and stiffness properties and pound for pound, it is stronger than steel. It is available in a range of appearance grades for structural or architectural applications.

NLT	Nail Laminated Timber	NLT is created by fastening individual dimensional lumber (2x4, 2x6, 2x8, 2x10 or 2x12), stacked on edge, into one structural element with nails. In addition to being used in floors, decks and roofs, NLT panels have been used for timber elevator and stair shafts. NLT offers a consistent and attractive appearance for decorative and exposed applications. Sheathing can be added to one top side to provide a structural diaphragm and allows the product to be used as a wall panel element.
DLT	Dowel Laminated Timber	DLT is the only all wood mass timber product. It can be used for floor, wall, and roof structures. Hardwood dowels are used to friction fit pre-milled boards together on edge, creating a panel which is particularly efficient for horizontal spans and allows for much architectural flexibility.With no metal fasteners, the panels can be easily processed using CNC machinery creating a high tolerance panel which can also contain pre-integrated acoustic materials, electrical conduit, and other service interfaces.
MPP	Mass Plywood Panels	MPP is similar to LVL products but can be made into wider sections which make up either wall or floor panels in to compete again similarly dimensioned CLT type products.
PSL	Parallel Strand Lumber	PSL is manufactured from veneers clipped into long strands laid in parallel formation and bonded together with an adhesive to form the finished structural section. It is well suited for use as beams and columns in post-and-beam construction, and for beams, headers and lintels in light framing. Visually attractive, PSL is suited to applications where finished appearance is important, as well as structural applications where appearance is not a factor.
LVL	Laminated Veneer Lumber	LVL is made up of dried softwood veneers, bonded together with adhesives so that the grain of all veneers is parallel to the long direction. With a very high strength-to-weight ratio, LVL columns, beams and lintels are often chosen to replace dimension lumber or glulam as columns, beams and headers. The many uses of LVL include headers and beams, hip and valley rafters, rim board, scaffold planking, studs, flange material for prefabricated wood I-joists and truss chords.
LSL	Laminated Strand Lumber	LSL is made by aligning thin chips or strands of wood and then gluing them under pressure. The wood grain of the strands is oriented parallel to the length of the member and then the wood member is machined to consistent finished sizes. It is strong when either face- or edge-loaded, but typically has lower strength and stiffness properties than LVL. LSL is commonly used in a variety of applications, such as beams, headers, studs, rim boards and millwork components.
OSL	Oriented Strand Lumber	Similar to LSL, OSL is also made from flaked wood strands. Panels are made from narrow strands of fibre oriented length-wise and then arranged into layers at right angles to one another, laid into mats and bonded together with waterproof, heat-cured adhesives.

Appendix B: Alternative Solutions Code Statements

Division A
1.2.1.1 Compliance with Division B
(1) Compliance with Division B shall be achieved,
(a) by complying with the applicable acceptable solutions in Division B, or
(b) by using alternative solutions that will achieve the level of performance required by the applicable acceptable solutions in respect of the objectives and functional statements attributed to the applicable acceptable solutions in MMAH Supplementary Standard SA-1, "Objectives and Functional Statements Attributed to the Acceptable Solutions".
(2) For the purposes of Clause (1)(b), the level of performance in respect of a functional statement refers to the performance of the functional statement as it relates to the objective with which it is associated in MMAH Supplementary Standard SA-1, "Objectives and Functional Statements Attributed to the Acceptable Solutions".

Division C
2 2.1.1. Documentation of Alternative Solutions
2.1.1.1. Documentation
(1) The person proposing the use of an alternative solution shall provide documentation to the chief building official or registered code agency that,
(a) identifies applicable objectives, functional statements and acceptable solutions, and
(b) establishes on the basis of past performance, tests described in Article 2.1.1.2. or other evaluation that the proposed alternative solution will achieve the level of performance required under Article 1.2.1.1. of Division A.
(2) The documentation described in Sentence (1) shall include information about relevant assumptions, limiting or restricting factors, testing procedures, studies or building performance parameters, including any commissioning, operational and maintenance requirements.
More info in: Appendix A of OBC under A-1.2.1.1.(1)(b).
2.1.1.2. Tests
(1) Where no published test method to establish the suitability of an alternative solution proposed under Article 2.1.1.1. exists, then the tests used for the purposes of that Article shall be designed to simulate or exceed anticipated service conditions or shall be designed to compare the performance of the material or system with a similar material or system that is known to be acceptable.
(2) The results of tests or evaluations based on test standards, other than as described in this Code, may be used for the purposes of Sentence (1), if the alternate test standards provide comparable results

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Appendix C: Redundancy for Timber Frame Construction For Fire Design

1. Requirements for Combustible and Non-Combustible
    a. Building area that must be much smaller that of non-combustible buildings
    b. Smoke alarms in all apartment suites and fire detectors in exit stairways and corridors
    c. Fire hose cabinets on each floor and two independent sets of stairs
2. Use Type Restriction:
    a. Group C
    b. Group D
3. Sprinklers of all balconies over 610mm (2 feet) deep
4. Combustion Resistance
    a. Non-combustible exit stairwell enclosures
    b. Exterior Cladding - Non-Combustible or Combustion Resistant
    c. Roof covering must be combustion resistant class A, or non-combustible
    d. Large concealed spaces must have additional compartmentalization, even when sprinklered
    e. Plumbing must be combustion-resistant
5. Site/Building Logistics
    a. Min 10% of the building perimeter to have fire access route within 15 metres of building exterior.
    b. No partial occupancy permits allowed; building must be complete and fire safety systems operational before occupancy
    c. If a five and six storey wood frame building is constructed in direct contact with an existing unsprinklered building, the firewall separating them must be masonry or concrete
6. Structural Requirements
    a. Mid-rise buildings must have the capacity to resist increased seismic loads

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Appendix D: Equations for Calculating Acceleration Due to Wind

Acceleration Across-Wind Direction: $\boldsymbol{a_w = f_{nW}}^{\boldsymbol{2}} \boldsymbol{g_p} \sqrt{\boldsymbol{Wd}} (\frac{\boldsymbol{a_r}}{\boldsymbol{\rho_b g \sqrt{\beta_w}}})$ (m/s^2)

$\boldsymbol{f_{nW}}$ – Lowest Natural Frequency Across-Wind Direction

Lowest Natural Frequency: $f_n = \frac{1}{2\pi} \sqrt{\frac{\sum_{i=1}^{n} F_i X_i}{\sum_{i=1}^{n} W_i {X_i}^2}}$=-=

n – Storey Number
F_i – Associated Wind Force of Each Storey (in Newtons)
X_i – Horizontal Deflection of each storey caused by F_i computed using FE Analysis under static wind load (in meters)
W_i – Associated Mass of each storey (in Newtons)

$\boldsymbol{g_p}$ – Statistical Peak Factor for Loading

$$g_p = \sqrt{2 \ln 3600v)} + \frac{0.577}{\sqrt{2 \ln 3600v)}}$$

v – Average Fluctuation Rate

$$v = f_n \sqrt{\frac{sF}{sF + \beta B}}$$

B – Background Turbulence Factor

$\boldsymbol{w}$ & $\boldsymbol{d}$ – Across wind effective Width and Depth of the overall building footprint

$\boldsymbol{a_r}$ –

$$a_r = 78.5x10^{-3} \left({}^{V_H}/_{f_{nW}} \sqrt{wd} \right)^{3.3} \quad \text{N}/m^3$$

V_H – Mean Wind Speed m/s

$\boldsymbol{\rho_b}$ – Average Density of the Building kg/m^3
$\boldsymbol{g}$ – Acceleration due to gravity (9.81 m/s^2)
$\boldsymbol{\beta_w}$ – Critical Dampening Ratio (assumed to be 1% based on experimental evidence)

- Use: 0.015

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Acceleration Along-Wind Direction: $\boldsymbol{a_D = 4\pi^2 f_{nD}{}^2 g_p \sqrt{\frac{KsF}{C_{eH}\beta_D}\frac{\Delta}{C_g}}}$ (m/s^2)

$\boldsymbol{f_{nD}}$ – Lowest Natural Frequency Along-Wind Direction

Lowest Natural Frequency: $f_n = \frac{1}{2\pi}\sqrt{\frac{\sum_{i=1}^{n} F_i \frac{X_i}{X_n}}{\sum_{i=1}^{n} W_i (\frac{X_i}{X_n})^2}}$

n – Storey Number
F_i – Associated Wind Force of Each Storey (in Newtons)
X_i – Horizontal Deflection of each storey caused by F_i computed using FE Analysis under static wind load (in meters)
W_i – Associated Mass of each storey (in Newtons)

$\boldsymbol{g_p}$ – Statistical Peak Factor for Loading

$$g_p = \sqrt{2\ln 3600v)} + \frac{0.577}{\sqrt{2\ln 3600v)}}$$

v – Average Fluctuation Rate

$$v = f_n\sqrt{\frac{sF}{sF + \beta B}}$$

B – Background Turbulence Factor

$\boldsymbol{F}$ – Gust Energy Ratio

$$F = \frac{x_o{}^2}{(1 + x_o{}^2)^{4/3}}$$

$$x_o = \frac{1220 f_n}{V_H}$$

$\boldsymbol{Ks}$ – Factor related to surface roughness coefficient
$\boldsymbol{C_{eH}}$ – Exposure Factor (From NBCC)
$\boldsymbol{\beta_D}$ – Critical Dampening Ratio (assumed to be 1% based on experimental evidence)

- Use: 0.015

Δ – Maximum wind-induced lateral deflection at the top of the building in the along wind direction (m)
$\boldsymbol{C_g}$ – Gust Factor (From NBCC)

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Appendix E: Steel Sections for 10, 20 & 30-Storey Core Walls

Steel Elements	***W360x***															***HSS203x 203x***	
	64	**74**	**91**	**122**	**147**	**179**	**216**	**262**	**314**	**382**	**421**	**509**	**592**	**677**	**744**	**8**	**16**
Area (cm2)	81.4	91	116	155	188	228	276	335	399	487	537	649	755	863	948	60.5	112
Height	4.5 m																
Element Volume	0.04	0.04	0.05	0.07	0.08	0.10	0.12	0.15	0.18	0.22	0.24	0.29	0.34	0.39	0.43	0.03	0.05
# Elements																	
10 Storey	12	70	32	8	8											80	
20 Storey	12	140	32	8	8	16	8	20	8	8						160	
30 Storey	12	210	32	8	8	16	8	20	8	8	16	8	20	8	8	160	80
Volume by Elements (m3)																	
10 Storey	0.44	2.56	1.17	0.29	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.93	0.00
20 Storey	0.44	5.13	1.17	0.29	0.29	0.59	0.29	0.73	0.29	0.29	0.00	0.00	0.00	0.00	0.00	5.86	0.00
30 Storey	0.44	7.69	1.17	0.29	0.29	0.59	0.29	0.73	0.29	0.29	0.59	0.29	0.73	0.29	0.29	5.86	2.93

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Appendix F: Loading Assumptions

Loading Data		***Value***	***Units***	***Source***
Dead Load				
Roof		1.12	kPa	Assumption
Floor		0.7	kPa	Assumption
Partition		1	kPa	Assumption
Live Load				
Floor		4.8	kPa	Assumption
Ground Snow Load	S= Is x (Ss x (Cb x Cw x Cs x Ca) + Sr)			
Importance Fatcor, Is	ULS	1		Table 4.1.6.2*
Importance Fatcor, Is	SLS	0.9		Table 4.1.6.2*
Ss		0.9	kPa	Table C-2*
Sr		0.4	kPa	Table C-2*
Wind Load	p= Iw q Ce Ct Cg Cp			
Importance Factor, Iw	ULS	1		Table 4.1.7.1*
Importance Factor, Iw	SLS	0.75		Table 4.1.7.1*
Hourly Wind Pressure	1/10	0.34	kPa	Table C-2*
Hourly Wind Pressure	1/50	0.44	kPa	Table C-2*
Earthquake Load				
Importance Factor, Ie	ULS	1		Table 4.1.8.5*
Importance Factor, Ie	Sa(0.2)	0.257		
Spectral Acceleration (5%)				Table C-3*
	Sa(0.5)	0.129		
Spectral Acceleration (5%)	Sa(1.0)	0.063		Table C-3*
Peak Ground Acceleration	Sa(2.0)	0.03		
	PGA	0.166	g	

Appendix G: Full Schedule for Gravity and Lateral Structural Systems

	Lateral Structure				**Gravity Structure**				
					Glulam Members				
LEVEL	CIP Concrete	CLT Panels (Days)	Precast (Days)	Structural Steel (Days)	Columns (hrs)	Beams (hrs)	CLT Floor Panels (hrs)	Total (Days)	Facade Panels
1	5			0.75	2.8	2.57	2.40	0.97	0.64
2	5	0.57	1	0.75	2.8	2.57	2.40	0.97	0.64
3	5			0.75	2.8	2.57	2.40	0.97	0.64
4	5			0.75	2.8	2.57	2.40	0.97	0.64
5	5	0.57	1	0.75	2.8	2.57	2.40	0.97	0.64
6	5			0.75	2.8	2.57	2.40	0.97	0.64
7	5			0.75	2.8	2.57	2.40	0.97	0.64
8	5	0.57	1	0.75	2.8	2.57	2.40	0.97	0.64
9	5			0.75	2.8	2.57	2.40	0.97	0.64
10	5			0.75	2.8	2.57	2.40	0.97	0.64
11	5	0.67	1	0.8	4	3.67	3.30	1.37	0.75
12	5			0.8	4	3.67	3.30	1.37	0.75
13	5			0.8	4	3.67	3.30	1.37	0.75
14	5	0.67	1	0.8	4	3.67	3.30	1.37	0.75
15	5			0.8	4	3.67	3.30	1.37	0.75
16	5			0.8	4	3.67	3.30	1.37	0.75
17	5	0.67	1	0.8	4	3.67	3.30	1.37	0.75
18	5			0.8	4	3.67	3.30	1.37	0.75
19	5			0.8	4	3.67	3.30	1.37	0.75
20	5	0.67	1	0.8	4	3.67	3.30	1.37	0.75

21	5			0.9	5.2	4.77	4.20	1.77	0.86	
22	5			0.9	5.2	4.77	4.20	1.77	0.86	
23	5	0.77	1	0.9	5.2	4.77	4.20	1.77	0.86	
24	5			0.9	5.2	4.77	4.20	1.77	0.86	
25	5			0.9	5.2	4.77	4.20	1.77	0.86	
26	5	0.77	1	0.9	5.2	4.77	4.20	1.77	0.86	
27	5			0.9	5.2	4.77	4.20	1.77	0.86	
28	5			0.9	5.2	4.77	4.20	1.77	0.86	
29	5	0.77	1	0.9	5.2	4.77	4.20	1.77	0.86	
30	5			0.9	5.2	4.77	4.20	1.77	0.86	
10 Storey	55.0	2.4	4.0	8.3				11.08	7.13	=18.2
20 Storey	105.0	15.4	7.0	16.7				25.19	14.74	=39.9
30 Storey	150.0	6.7	10.0	24.8				41.13	22.50	=63.6

	Full Schedule: Gravity & Lateral Structure				
(days)	**CIP Concrete**	**Timber**	**Precast**	**Structural Steel**	Timber Gravity Structure
10 Storey	**73.2**	**20.6**	**22.2**	**26.5**	18.2
20 Storey	**144.9**	**66.3**	**46.9**	**56.6**	39.9
30 Storey	**213.6**	**70.3**	**73.6**	**88.4**	63.6

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Thursday, April 25, 2019

Background on Timber Outrigger Truss

CLT Panels	Outrigger Truss												
20.6				# of Bays Truss	Elements / Bay		Pick Time (mins)	Connections		Truss Install (Day)	# of Floors	Building Truss Time (Days	
55.3	11	# of Bays N-S	5	2	1	10	20	60	800	2			
70.3		# of Bays E-W	6	2	1	12	20	60	960	2			
										4	3	11	2.2
										4			

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Appendix H: Background on Cost Model

Appendix I: Concrete Takeoff

Core Walls & Shear Walls Above Grade:	10 Storey	20 Storey	30 Storey	30 Storey
Sq Ft.	80,000	160,000	240,000	240,000
Concrete Supply, 30 MPa 326 cm 160.00 03 31 00	$52,177.00	$133,517.00	$203,789.00	$305,683.50
Concrete Supply, 40 MPa 46 cm 170.00 03 31 00	$7,761.00	$19,861.00	$30,314.00	$45,471.00
E/O. Supply of High Early 372 cm 45.10 03 31 00	$16,766.00	$42,904.00	$65,485.00	$65,485.00
E/O. Supply of Super P 372 cm 16.50 03 31 00	$6,134.00	$15,697.00	$23,958.00	$35,937.00
E/O. Supply of Heated Concrete 155 cm 19.80 03 31 00	$3,067.00	$7,848.00	$11,979.00	$17,968.50
Allowance For Concrete Waste 1 3.00% --- ---- Included Above 03 31 00				
Winter Heat & Protection 155 cm 45.32 03 11 00	$7,020.00	$17,964.00	$27,419.00	$27,419.00
Fwk. General Accounts 372 cm 44.90 03 11 00	$16,692.00	$21,821.00	$24,299.00	$29,158.80
Place Concrete To Shear Walls 372 cm 42.90 03 11 00	$15,949.00	$40,811.00	$62,291.00	$93,436.50
Fwk. To Shear Walls 242 sm 86.25 03 11 00	$20,835.00	$20,835.00	**$20,835.00**	**$25,002.00**
Formwork Material 242 sm 36.82 03 11 00	$8,895.00	$8,895.00	$8,895.00	$8,895.00
Reinforcing Steel 43 mt 2,400.00 03 21 00	$102,606.00	$262,561.00	$400,751.00	$601,126.50
	$257,902.00	$592,714.00	$880,015.00	$1,255,582.80
	$3.22	**$3.70**	**$3.67**	**$5.23**
Hoisting & Concrete Pump 372 cm 1,894.22 03 11 00	$704,197.00	$762,736.00	$778,826.00	$778,826.00
	$8.80	$4.77	$3.25	$3.25

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Thursday, April 25, 2019

Appendix II: Cost of Fire Rating Timber

Cost of Fire Rating Through Char Layer				
Charring Rate =	0.7	mm/min		
2hr Rating=	84	mm		
Standard Cross Section=			Volume Sacrificed	% Per Member
Girders	315	495	53928	34.59%
CLT		245	6468	34.29%
DLT		235	5628	35.74%
10 Storey Col	365	380	48468	34.94%
20 Storey Col	430	684	79464	27.02%
30 Storey Col	530	836	100632	22.71%
Source				
https://www.designingbuildings.co.uk/wiki/Sacrificial_timber				

3 Layers of Gypsum Wall Board Fire Rating	
Timber	Building 1
Encapsulation Cost	$4,382,683.00
Exposed Area Glulam	306,948.93
Exposed Area CLT	239,907.32
Total	546,856.25
Cost per Sq Ft	$8.01

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Thursday, April 25, 2019

Appendix III: Cost of Fire Rating Steel

Shaft Wall Type
Type P - 6A Shaft Wall (64mm Stud, 25mm Liner & 16mm Type X Drywall + Insul)
Cost: $11.24

Appendix A: Shaft Walls		
Floor To Floor Height	14.76	ft
Side A	40.02	lin. ft
Side B	20.01	lin. ft
Side C	20.01	lin. ft
Side D	25.26	lin. ft
Total Surface Area of Walls Per Floor	1554.84	

Appendix IV: Crane Cost

Appendix G: Crane Cost		
Crane Rental - Equipment	15000	Monthly
Crane Rental - Labour	26400	Monthly
Crane Rental - Setup+Dismantle	65760	1 time
Insurance + Variable Exp.	Assume Inc. in Eq. Rental	
Evan Reidel Market Est.	$46,880.00	For 1 Year Avg.
Crane Cost (Per Month)	$46,880.00	
Crane Cost (Per Day)	$2,344.00	
Crane Cost (Per Hour)	293.00	

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