# SEATTLE MASS TIMBER TOWER

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Feasibility Study
Design and Construction Analysis

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# FOREWORD

When asked to consider writing a Foreword for this important project, I was more than happy to do so. Affordability and sustainability are the two most important conversations in which our community should be engaged. We have made huge strides as an industry on the sustainability front, but when I look back a decade or so we were talking about solutions well beyond conventional wisdom and it was expensive, difficult and risky, yet we forged ahead and have indeed made progress. I don't think that journey is over, but we have learned valuable lessons along the way and found new opportunities in the process. Now the challenge has become more complex. It is a three dimensional Rubik's cube—sustainability, thoughtful design and affordability. Perhaps not new cohorts, but the amplitude of each is significantly greater.

So now here we are at the beginning of the discussion about how wood and wood fiber in taller structures might in fact contribute to all three of these elements in a new and hereto for untested way. The premise of pushing the height limits of wood structures is not new as there are a few projects underway in the US, more in British Columbia and still more in Europe. Early results would suggest this technology is legitimate and a potential key to solving the challenge. The Pacific NW should absolutely be part of this discussion- we are pioneers and should be leading, we reside in one of the greatest "wood baskets" in the world given the extent of our Douglas Fir Forests and manufacturing capabilities and finally or vibrant economy has been a strength, but is creating an unintended consequence as affordability slips further and further from our grasp.

So let the discussion begin...This report is not an answer, it is a stimulant to the dialogue we as a community should be having. I am thankful we have the kind of Design firms in this community who would take it upon themselves to fund this R&D work. To be sure they will benefit, but their objective is bigger. We have to start somewhere and putting a thoughtful idea forward that is specific and detailed means we can have a more robust debate about both the opportunities and concerns. I know we have opportunities to sequester more carbon, build faster, build safer, build more affordably and build structures that meet our expectations for design- but we have to begin the discussion and this proposal will help focus the debate.

Bravo and thank you to all those who gave of their time and expertise to help us begin the conversation.

#### Peter Orser

Director Runstad Center for Real Estate Studies, College of the Built Environments, University of Washington

# **EXECUTIVE SUMMARY**

Mass timber construction (MTC), including engineered woods such as cross laminated timber (CLT), nail laminated timber (NLT), and associated variables, is currently promoted by the global wood industry for use in buildings above ten stories. While the technology is capable of developing highly sustainable solutions to today's exponential urban growth, the financial, regulatory and constructibility implications of this technology for taller buildings in the 30 to 40 story range are not well understood or currently accepted by the building community at large.

CallisonRTKL has taken the initiative to explore these possibilities and this report articulates the design and feasibility of the construction of a 40-story (420' / 128-meter) tall residential tower using MTC as the primary structural material and technology of choice for all floor assemblies, beams, partitions, and upperlevel columns. The research process ultimately alluded to a hybrid and composite format of construction as the optimal solution for a structure of this magnitude although MTC still remains the predominant component of the structure. The tower core, two extending outrigger walls, and the foundation are the only components that are constructed in-situ with reinforced concrete. Lower floor columns are fabricated in steel and two other outrigger walls in carbon fiber, using the structural performance advantages of new, lightweight carbon fiber strands in a hexagonal net configuration for wind-load resistance. The material-specific advantages of MTC, reinforced concrete, and carbon fiber are strategically put to work to form an innovative high-performance hybrid structural system for tall buildings.

On a parallel note, although the primary intent of this study is to demonstrate the structural and financial viability of this technology, the notion of solving the current paucity of affordable accommodation within Seattle's core is also addressed. This is done by defining a clear blueprint for density and affordability in the form of smaller, compact and flexible unit typologies that constitute the DNA of the structure.

The design process was a coordinated effort between engineering consultants, construction contractors, and cost estimators to validate the structural and cost competitiveness of a real-time solution via performance benchmarking. Using relevant industry research and three-dimensional explorations, we developed the study as a prototype solution responding to a specific site opportunity in downtown Seattle, developer and client needs, and regulatory constraints. Beneficiaries of this study include regional real estate development communities, venture capitalists, local timber industries, and the political arena.

The primary program use for the tower is housing, i.e. self-sufficient studio and one bedroom units for individuals and couples who represent a growing demographic in cities around the nation. Units are outfitted with prefabricated kitchen and powder room modules. The proposed location for this tower is an urban renewal and infill site in downtown Seattle. The site is within walking distance to Amazon headquarters, high-tech firms and institutes for higher education. The design concept corresponds with applicable building code requirements including zoning, seismic, and energy code regulations.

#### Advantages

The use of MTC in high-rise construction combines the potential advantages of modular, flat-pack prefabrication at a new industry scale, rapid construction, lower embodied energy, sequestration of carbon for a building's lifetime, and overall widespread market appeal due to the scientifically-proven positive cognitive and physiological effects of wood structures on humans and society as a whole.

#### Market demand

The market demand for MTC in the United States has been limited to 6 to 10-story structures, mainly due to the lack of acceptance of engineered timber composite solutions that address the structural requirements for high-lateral load resistance as a function of highwind loads in tall buildings. European countries have developed and executed engineered wood and concrete composite systems that achieve composite action and structural integrity at height - most notably, a 14-story CLT apartment building that was recently completed in Norway and a 34-story mass timber tower that passed construction permitting in Stockholm, Sweden earlier this year. In 2015 about 15 tall wood buildings were completed in Australia, Canada, and Europe.

In the United States, fire-resistance performance tests have been positive and cleared the way for the construction of a 10-story tower in Manhattan and a 12-story tower in Portland, Oregon. The forest and timber industries in Washington State are on the cusp of renewal due to newfound uses for timber in engineered woods and the wide market and broad cultural appeal of timber design. The City of Seattle has recently taken on this challenge and is actively pursuing changes to the regulations that allow for the usage of MTC in loadbearing walls and floors.

Economically speaking, the technical competitiveness with conventional models of structural, acoustic, and fire protection are all prerequisites for success; the advantages of MTC in high-rise construction will be evident when this technology is fully integrated with other building systems. Cost efficiency related to hybrid material efficiencies, procurement, and the supply chain is the main driver. Sound and well-engineered timber concrete composite slabs and slab-to-beam connections are key to achieving a cost-efficient structure. According to a 2014 research paper published by the Council on Tall Buildings and Urban Habitat (CTBUH), MTC slabs can match the performance criteria of concrete at about half the weight and half the embodied carbon.

In the architecture, engineering, and construction industry, a convergence of changes in technology, building codes, procurement strategies, market conditions, and cultural norms are underway which will undoubtedly render the realization of an engineeredwood high-rise building in the United States as a viable option to conventional systems while also providing the distinct advantages of a performance driven and sustainable design strategy. Architects, developers, engineers, regulatory agencies, and supply industries are approaching initiation and implementation.

### ABSTRACT

Ever since humans began building their first dwellings, timber has been the construction material of choice. In the 21st century, mass timber technology offers an engineered wood product of choice that is recognized for superb structural strength and superior fire resistance over steel. MTC provides opportunities to explore a new design aesthetic and, most importantly, the technology comes at a time when the realities of climate change require the repositioning of forest, timber, manufacturing, and construction industries toward resourceful, renewable, sustainable processes and products that promote health and wellness.

The design tactics and cost analysis included in this study identify opportunities for strategic integration of mass timber products into the construction assembly of tall buildings. Significant advantages exist relative to environment, business and industry, cost, and the occupant. The outcome is a new typology for tall building systems and assemblies that can be prefabricated in part from renewable building materials—with the most visible results being construction time reduction and superior quality. The implications of this new technology are of a global magnitude. Mass timber designs will impact business and manufacturing streams and construction where timber is available and can be sourced regionally in close proximity of the project site.

### INTRODUCTION

#### Why Mass Timber?

Mass timber products such as CLT or NLT are renewable materials, have a lower embodied energy footprint than concrete or steel, and capture carbon dioxide rather than emitting greenhouse gases during their production.

North American forests comprise large areas of previously unusable small growth trees and softwoods,

a primary source of mass timber products. Creating an economic use for this plant material will free up vast amounts of forest lands for sustainable and managed forestry. In forest-rich states such as Washington State, mass timber technology is seen as a game changer by the timber and manufacturing industries as they are eager to reinvent and reposition themselves after decades of decline.



Pacific Northwest Forests

Regarding the harvest impact, statistics show that in the past 50 years the North American annual timber harvest rate was at 2% compared with an annual tree growth rate of 3%. Moreover, mass timber products have the potential to make use of small-size softwoods and trees felled by beetle kills, which result in increased carbon release during decay.

The use of mass timber construction offers distinct performance advantages over conventional cast-in-place concrete construction technologies with implications for environmental, economic, and social sustainability, including:

- Equal or lower price point as compared to conventional construction
- Shorter construction times
- Commercialization of carbon sequestering
- Commercialization of reduced embodied energy
- Scientifically substantiated positive effects on health

- Reinvigoration of local forest, timber and manufacturing industries in Washington State
- Marketability of 'Made Locally'
- Scalability and robustness of engineered product
- Consistency and higher quality control through factory pre-fabrication
- Reduced construction tolerances and high architectural finish control
- Reduced on-site labor alleviates Seattle's construction labor shortages and cost
- Very clean and quiet construction site contributes to maximum safety
- Significant reduction in construction waste
- Significant reduction in structural weight, pilings and foundations
- Seismic applicability and structural integrity
  Mosts performance fire safety standards and other

Meets performance fire safety standards and other code requirements in jurisdictions of major advanced countries and world capitals

Capitalizing on these performance advantages of engineered wood was key for our design proposal and cost feasibility study. The design goal is to maximize the use of engineered wood in tall building design and in assemblies and building components that yield the greatest economic benefits as compared to conventional means of construction.

# MASS TIMBER CONSTRUCTION

#### What Is It?

Mass timber is the only renewable structural building material of scale and has the lowest energy consumption across its life cycle. It is sourced from sustainability managed forests. Panels are made from cheap, sustainable softwood. In CLT, panels are glued together in precise layers of alternating fiber direction. Planks of kiln-dried, finger-jointed softwood are sorted and cut into sheets of 54 feet x 10 feet (16.5 meters x 2.95 meters). The sheets are then stacked and glued under high pressure in perpendicular layers. The process involves a high-pressure bonding system which allows the use of polyurethane adhesive solvent, keeping the boards formaldehyde-free. Crosswise gluing at high pressure reduces the wood's potential for expansion and shrinkage. CLT panels are cut and processed using CNC technology to quickly and accurately produce multiple panels of the precise dimensions needed.

In NLT, layers of wood are arrayed side-by-side and pinned together. Panels possess excellent structural stability. The raw material itself may be of varying thickness, quality and strength as the panels are engineered for performance properties identical to or even stronger than concrete. The minimum cross section of raw material is .75" x 3.5"; or 19 millimeters by x 89 millimeters, thus including a wide growth range of timber species.



Cross Laminated Timber Source: Binderholz

MTC technology led to innovative uses in the sphere of architecture and design; today, successful real estate developments serve as show-and-tells in Canada, Japan, Northern and Central Europe, and Australia. In these regions, performance-based testing and code compliance satisfy the requirements for cost-competitive construction of most types, sizes, and scale. In the US, the first tall building is now under construction in Portland, Oregon. Framework is a 12-story, mixed-use tower in Portland's Pearl District using CLT and other engineered wood products. Forte is a 12-story apartment building in Melbourne, Australia, made entirely in wood with the exception of the concrete pad.



### SITE CONTEXT

The site is located in the immediate vicinity of the northern border of the Denny Triangle Urban Center, just to the south of Denny Way. The height limit for residential developments in this downtown mixedcommercial zone is 420 feet, per DMC 240/290-400.

This design and feasibility study is for the select use of mass timber systems and building assemblies in the design and construction of a proposed 37-story tower with a two-story podium (24,000 square feet each), a third-level amenity floor (10,600 square feet), and below grade parking. The project yields approximately 650 residential apartment units varying in size and averaging 460 square feet. The below-grade parking structure offers approximately 500 parking stalls. Although we have chosen for this study to include smaller units in order to provide more affordable housing within the downtown area, the design could easily be modified to provide larger units or a combination of unit sizes in order to meet the needs of a variety of markets.

Vehicular access from Interstate I-5 is via Mercer Street exits and through principal arterials Westlake Avenue and Denny Way and minor arterial Fairview Avenue. The site is in close proximity of Metro bus routes 8, 40 and 70 and a 10-minute walk from the closest Link light rail station at Westlake Center.

# DESIGN GOALS

The key objective of this design is to showcase both the applied technology and the benefits of mass timber construction in high-rise design, specific to the Pacific Northwest region of the United States. Exploration of price competitiveness over conventional structural systems has been the premise and the established prerequisite of this analysis.

Recent advances in mass timber technologies over the last three decades have led to major market successes and have been applied to a wide variety of building types, predominantly in European countries. Not until now has this technology been introduced to construction projects in North America. Canada and, to some extent, Oregon are at the frontier of pushing mass timber technologies into the mainstream.

The vernacular of European timber-framed houses serves as a reference for design aesthetics and orientation for the mass timber tower in Seattle. True to the expectation that a timber high-rise building should convey the particular aesthetic characteristics of wood as a building material, the tower's enclosure borrows from the formal design language of timber-frame construction, creating a reinterpretation with contemporary building materials. In traditional architecture, timber framing, or half-timbering, is the method of creating framed and





Timber-framed House, Grossholbach, Germany, 18th Century



Timber-framed Houses, Germany

exposed structures of heavy timber members joined together with pegged mortise and tenon joints. Diagonal bracing provides structural rigidity. Framing members are typically 6-inch x 6-inch, 8 inch x 8-inch and 10-inch x 10-inch square sections, and the framed areas are usually filled with a wood and clay composite or brickwork. The framework construction (German: Fachwerk) was popular from the Middle Ages to the 19th century and one of the predominant construction methods north of the Alps and in parts of Asia. The enclosure design of our mass timber tower echoes the exposed delineation of the bracing and its circumscribed areas through means of color contrast and proportion.

Modularity and prefabrication are of specific interest in high-rise design where labor cost, quality control, repetition, and the economy of scale can lead to significant reductions in floor-by-floor construction



Seattle Mass Timber Tower Exterior Close-up



Mass Timber Tower\_Exterior Corner

cycles and schedules. The tower's modular and prefabricated building components include floor assemblies, beams, columns, powder room and kitchen modules, and a unitized curtain wall. The tower's only "wet" construction is limited to the concrete core and two adjoining shear walls. The innovative design of a lightweight, high-performing, and pre assembled carbon fiber net complements and completes the requirement for structural shear and outrigger design of the tower core.



Seattle Mass Timber Tower Interior



Timber-frame House, Germany Interior



Seattle Mass Timber Tower Interior



Timber-frame House, Germany Interior

### MODULATION, DESIGN AND BASELINE

Standing 420 feet / 128m tall, this 40-story residential mass timber tower features innovative and technologically advanced building components that demonstrate cost-competitive performance in addition to environmental, industrial, and occupant advantages over conventional concrete construction. The tower comprises a total of 650 residential studios, 18 compact and larger studios per floor, at an average size of 460 square feet per studio. Individual private studios are outfitted with state-of-the-art, prefabricated, and hoisted-in-place powder room and kitchen modules. Units could be combined to create one or two bedroom typologies if market demands suggest. A three-story tower podium contains commercial, retail, and residential





Floor Enclosure





amenity functions. Six outward-facing double-height community sky gardens are semi-private and offer expansive views of Mount Rainier and the Seattle Space Needle.

The tower design maximizes the use of per-fabricated building components to the greatest extent. While this report emphasizes the use of mass timber, other prefabricated materials and components trigger additional economic efficiencies such as reduced on-site labor and construction time.

Compared to concrete, mass timber is a lightweight building material and offers significant economic advantages associated with lighter dead loads and foundations. However, a lighter tower structure adversely affects the risk of overturning. To counteract this dynamic and to maximize the tower's structural resistance, the core geometry was conceived for maximum structural performance. The central core and its four outrigger walls form a plan configuration of a square I-beam with a double web. The core and two internal outrigger walls are cast in-situ, using high-strength reinforced concrete. The remaining two outrigger walls are exterior walls comprised of a hexagonal, triple-layered net of carbon fiber strand rods. Carbon fiber strand offers unique advantages over conventional buckling restrained steel brace frames: carbon fiber strand is non-flammable, weighs one-fifth of an equal-sized steel rod, and possesses a seven-fold tensile strength compared to steel.

The floor assembly can be composed in either CLT or NLT: 2-foot x 6-foot NLT with  $\frac{1}{2}$ -inch plywood decking, 1/2-inch sound insulation and a 3-inch topping slab, or alternatively, five-layer CLT with 1/2-inch sound insulation and a 3-inch topping slab. Either floor assembly is laid out on a 16-foot x 28-foot column grid and supported by glued-laminated wood beams. Columns for floors one to 30 are steel wide-flange columns and glued-laminated wood columns are used for floors 31 to 40. The enclosure design features a curtain wall with triple glazing for the majority of the tower. Two enclosure segments are comprised of hexagonal rain screen panels with unitized, inbound enclosure modules and integrated vision glazing, insulation, and waterproofing. Two opaque side walls adjacent to these feature walls are clad with fiber reinforced polymer (FRP) panels. The window-towall ratio (WWR) of the tower enclosure is below 40 percent.

As a baseline for this analysis, the design team used a conventional reinforced concrete tower structure with a 24-foot x 28-foot column spacing. Core and columns are in-situ reinforced concrete; the floor assembly is a thin, flat plate post-tensioned slab of 8-inch thickness. For purposes of this cost analysis, seven full parking levels have been assumed below grade, in addition to four grade-level loading docks.





#### **Mass Timber Design Statistics**

- Column spacing: 16-foot x 28-foot
- Columns, floors 1-29: Precast RC or steel
- Columns, floors 30-39: Glued-laminated
- Core and shear walls: In-situ RC
- Exterior braces, gridlines D3-4 and H1-2: Carbon fiber hexagonal net
- Beams: Glued-laminated
- Floor assembly: 2-foot x 6-foot NLT with ½-inch plywood decking, ½-inch sound insulation, 3-inch topping slab; or alternatively: 5-layer CLT, ½-inch sound insulation, 3-inch topping slab

#### **Baseline Design Statistics**

- Column spacing: 24-foot x 28-foot
- Columns: In-situ RC
- Core and shear walls: In-situ RC
- Exterior braces: RC or steel BRB frame
- Floor assembly: Thin flat plate PT slab, 8-inch thick; no topping slab
- Beams: N/A

### TOWER STATISTICS

- Type-1 construction (3hrs for structural components, 2hrs for unit partitions, etc.)
- Full automatic sprinkler system
- Three passenger elevators and one fire service access elevator
- Two stories retail: level 1 (18 feet, 9 ½ inches floorto-floor); level 2 (13 feet, 6 inches floor-to-floor); 24,000 square feet each
- Amenity floor: level 3 (13'-6" floor-to-floor); 10,575 square feet
- 37 stories, 18 residential studios/floor, 9'-8" floor-tofloor, 10,575 square feet each (includes sky gardens)
- Six two-story sky gardens (610 square feet each)
- Prefabricated bathroom and kitchen units
- Unitized curtain wall, triple glazing, with awning window/each unit
- Tower crown, 26 feet
- Tower height: 420 feet

# SYSTEM DESIGN

Diagrams below illustrate building systems that will be further describe in the following sections.

1. Structural System: Central Core with Types of Outrigger Walls



2. Steel Columns and Glued-laminated Beams, 16' o.c.



3. Interior, Non-load-bearing Partition Walls



4. Installation of Prefabricated Powder Room Modules



5. Instalation of Prefabricated Kitchen Modules



6. Next Floor Prep/Install of the Central Core and Outrigger Walls



7. Steel Column Extensions and Mass Timber Floor Modules



8. Next Floor Glued-laminated Beams



9. Interior, Non-load-bearing Partition Walls



10. Modular Framed Enclosure Units



11. Completed Floor Enclosure



CallisonRTKL 21

### FIRE SAFETY

For reasons of life safety and for compliance with firesafety regulations, and in addition to structural wind load resistance requirements, the tower's core walls are proposed in in-situ reinforced concrete. Tower core walls encapsulate all vertical circulation, including a designated fire service access elevator and two pressurized escape staircases. The tower is outfitted with an automatic sprinkler system throughout.

Mass timber products resist fire well due to their makeup, scale and thickness. When exposed to flames, they will develop a protective charring layer at their surface instead of catching fire and burning in a way that is associated with regular timber frame products and construction. Common practice methods refer to the nominal char rate of 1.5 inches to 1.75 inches per hour to extrapolate the required char thickness of the member's fire-rating, which is then added to the structurally required dimension of a respective assembly. Projectspecific performance testing, common in Canada, Japan, Australia, and Europe, provides an alternative compliance method for consideration by local jurisdictions and city officials.

Type-1 construction of towers 420 feet and below requires a fire-resistance rating of 3 hours for all primary structural components; all other building components are subject to 2 hours.



Source: The Journal of American Institute of Architecture Courtesy FPInnovations

### RISK MANAGEMENT AND INSURANCE

Interdisciplinary and goal-oriented development of non-standard property insurance and finance models are critical for the success of MTC in the United States. Code incentives and strategically placed governmental funding and subsidies play a crucial role in kick-starting and boosting the industry. Longer term in-use MTC studies around events such as fire, flood, hurricane, and earthquakes will likely need to be established in terms of algorithmically derived case-by-case contingencies.

Over the last two decades, a risk averse business mentality, conservative building regulations, and lack of innovative technological advocacy in the United States have hindered the development of multi-story MTC projects embraced in other regions of the world, most notably in Canada, Japan, Europe, and Australia. The tallest MTC building in the world and the first that qualifies as a high-rise structure is the 90-foot tall Wood Innovation Design Center in Prince George, British Columbia. In the United States, the U.S. Department of Agriculture (USDA) is funding industries that provide technical support to architects and developers and push other federal departments to adopt new mass timber technologies.

#### CODE

In 2015, CLT was incorporated in the International Building Code (IBC) and adopted by the City of Seattle. The primary change in the 2015 IBC allows use of crosslaminated timber in exterior walls of Type IV—heavy timber—construction. The American Wood Council is proposing further changes for the 2018 IBC which are currently under development. The proposal would allow two- or three-hour-rated heavy timber to "safely serve in diverse structures." The maximum height for such structures is currently at 100 feet, however, this change proposal does not take into account a componentspecific, targeted use of two-to-three hour mass timber assemblies as part of taller hybrid structures. Publications such as this study are designed to educate city, building, and fire service officials about the potential and feasibility of mass timber tall structures.



### STRUCTURAL DESIGN

To assess differences in building performance, our team conducted a comparison of structural performance for a typical concrete framed structure and a timber floor framed structure. For both buildings, the concrete core is continuous from roof level to base level. Outrigger walls were assumed to run to the third level and sit on columns that extend to base level. In the lower levels, the concrete core is modelled with 15" thick walls to the perimeter of the core and 8" thick walls internally. The outer core wall thickness has been modelled with a reduction from 15" thick to 12" at level 15 and 9" thick at level 30. Concrete strength in the core and shear walls vary from 65MPa at level 10 to 50Mpa at level 20 and 40MPa above. The study adopts the use of concrete for the main core elements to provide robust, economical solutions to many issues within a building of this height. Life safety is of paramount importance, and solid concrete core walls afford the best solution. The thickness of timber core walls can be comparable to concrete for support of gravity loads, but for lateral loading, the timber planks require significant shear connectors across joints to provide the stiffness required. These connectors require careful design to ensure the shear can be transferred

between timber panels without panel failure and that the connection method is buildable. As such, timber core walls have not been developed as part of this project. The baseline solution represents a typical structural solution for a project such as this, with 8" thick slabs for structural and acoustic reasons. When comparing the standard concrete solution to a timber floor with a concrete topping system, there is a 38% reduction in the floor plate mass. Without changing the wall design, this results in a 28% reduction in the total building mass. We modelled the two building options using structural analysis software Etabs 2015 to investigate the building's lateral performance. The analysis model ignores the floor plates as part of the lateral resisting system, relying on the concrete core to provide stiffness. With the reduction in mass, the building fundamental frequency increases by 16%.

In the current design, the 3" topping slab contributes over half of the self-weight load for the floor system. With further study on topping slab reduction, further gains may be made with regard to building performance under lateral loading.



1. Shear Wall Location



2. Carbon Fiber Shear Wall Net and Frame



3. Solid Wall Assembly



4. Completed Wall with Glass Panels and Rain Sceen

### WIND RESISTANCE

The performance of a tall building exposed to wind is a function of the dynamic properties of the building. The taller the building, the lower the frequency becomes and the more significant the dynamic component is in estimating wind loads. A frequency of less than 1.0Hz is the standard for determining if the structure has a significant resonant response. Both base and timber building solutions have a fundamental frequency of less than 0.5Hz.

Keeping the building core and shear wall system the same for both buildings and using timber floors with a reduced floor mass as opposed to concrete floors results in a positive increase in the building's natural frequency. This reduces the resonant response of the building and results in lower design wind forces.

Building mass reduction therefore indicates a notionally stiffer building; however, as the main concrete core structure used to resist the lateral loads is unchanged, lateral drift under static lateral loads also does not change. The increase in frequency is due to the reduced mass, and the benefit--the building's response under wind loads—is important in assessing the building's dynamic performance under both wind and earthquake loads.



View of Etabs Model

### SEISMIC RESISTANCE

Seismic loads are a function of the building mass. Around the globe, there is a wide variety of systems used which idealise the impact of earthquake loads on a system of lateral loads. This is a representation of the inertial loads generated in the building as the ground beneath moves. The building mass is the common element when calculating seismic loads: the loads are directly proportionate to the building mass, so a reduction in mass will result in an equivalent reduction in seismic loads.

A means to dissipate the energy generated through ground movements without compromising the structure or risking collapse is of the utmost importance. This is achieved through reinforcement detailing in concrete structures, which enables ductile behavior under earthquake motion. Energy is dissipated through the cracking of the concrete, while the reinforcement ensures the structural integrity is maintained and concrete confined.

Testing has been carried out on a seven-story CLT building by IVALSA (Trees and Timber Research Institute of Italy) in Japan (reference Ceccotti, A. [2010] Cross Laminated Timber Introduction to Seismic Performance, Trees and Timber Institute IVALSA-CNR National Research Council, Italy). The building was placed on a shake table and demonstrated ductile behavior and good energy dissipations. The most influential factor in the performance was the nature of the mechanical connections used.

A detailed assessment of mechanical connections for timber floor systems has not yet been carried out, though testing indicates that ductility can be achieved. This, combined with a concrete core wall system, is designed to carry lateral loading.

### DESIGN FOR SUSTAINABILITY AND HEALTH

The use of wood and timber technologies in architecture and design is not only popular with users and tenants but has also received recent endorsement from the scientific community which asserts a direct correlation between exposure to wood surfaces and the health benefits. In recent studies, the positive physiological and psychological effects of exposure to wood and wood surfaces (both visual and tactile) have been scientifically tested and documented in reports of neuroscience and behavioral psychology.

http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3660240/

# PACIFIC NORTHWEST MANUFACTURING

D.R. Johnson became the first U.S. company to be certified for manufacture of CLT for structural use in the fall of 2015. Following a visit to CLT manufacturing facilities and projects in Austria and Germany and with the help of existing capital and other funds—including a \$50,000 Oregon Best grant—the company added the necessary equipment to their laminating production line. With APA/ANSI certification by the American Plywood Association/American National Standards Association guidelines, D.R. Johnson currently produces CLT panel in sizes up to 10 x 24 feet in three, five, and seven layers, primarily in Douglas fir or Alaskan yellow cedar. According to a June 2015 news article in Seattle Business Magazine, Washington State University received a \$250,000 grant from the U.S. Department of Agriculture for a joint effort with the private sector that it hopes will improve the functioning of an entire intrastate CLT supply chain.



#### MODULAR PREFABRICATED, FACTORY-BUILT COMPONENTS

Substantial schedule reductions can be achieved by seamlessly integrating the installation of modular powder rooms and kitchens into the construction process and timetable. In construction, time is invaluable and cost benefits associated with pre-fabrication increase exponentially based on module quantities, floor repetitions, and the overall scale of tall buildings. Additionally, labor cost savings due to off-site factory assembly lead to a significant source of cost savings, particularly given the current labor-supply shortages in Seattle. Prefabricated, factory built powder room and kitchen modules are adaptable building components engineered to meet design criteria. The adaptable module design fully integrates with the tower's architectural, structural, and MEP criteria. Structural gauge metal framing gives strength and stability to the modules. Wall and ceiling panels are completely welded to create units that are extremely resilient and durable, allowing easy transportation, staging, and job site handling.





Prefabricated Powder Rooms and Kitchens\*

Prefabricated Bathroom Module Photo: Modulbad



\*) PowderRroom Walls Are Shown Transparent for Drawing Clarity

### CONSTRUCTION TECHNOLOGY, PROCUREMENT AND LABOR POOL

#### Hoisting

The construction of tall buildings in mass timber technology relies heavily on the tower crane for all hoisting needs since all mass timber components are prefabricated. Modularized, factory-built, and sitedelivered kitchen and powder room pods will put additional strain on the tower crane schedule. Careful assessment should be made relative to "hook time" requirements and availability. Depending on the site logistics and the schedule for construction, an additional crane could be considered for a more efficient construction process.

CLT and NLT floor panels are typically set one at a time using a tower crane or some other lifting device. While more conventional construction such as steel erection uses a "Christmas tree" method (several steel beams are hoisted simultaneously and placed in the same pick), mass timber floor panels will allow the overall completion of the floor assembly in a more efficient manner. Depending on size, most timber columns can be lifted into place with a two-person crew once the columns have been landed on the destination deck. This is advantageous over other structural systems because it does not rely on the use of cranes other than hoisting the materials onto to the level they will be installed.

A comprehensive erection plan linked with fabrication, delivery, and manpower schedules is a prerequisite for smooth on-site operations and successful installation.

#### **Tower Crane and Manlift Tie-Ins**

Temporary equipment must be connected directly back to a concrete core, not the timber frame. The braces must therefore be placed to minimize or avoid conflicts with the MTC frame and allow them to be placed independent of each other.



#### **Construction Technology**

Full-height steel knife plates are recommended for connections between framing members, ensuring better quality control and easier installation of MTC Components.

#### Material Procurement

Manufacturers for consideration:

- Vaagen Brothers Lumber, Colville, Washington, USA
- D.R. Johnson Lumber, Riddle, Oregon, USA
- Structurlam, Penticton, BC, Canada

Different manufacturers will produce laminated products in wood species that are native to the location of the manufacturing facilities. Therefore these different wood species must be carefully reviewed for performance, strength, and appearance.

The use of local manufacturers such as those in Washington State is advantageous for several reasons. Delivery times between manufacturing facilities and jobsite can be reduced and often minimized, thus increasing the opportunity for time and cost-effective procurement. Using local materials is also a sustainable practice.

#### **Construction Labor Assessment**

Currently in the USA, the availability of skilled construction labor is limited. By focusing on prefabrication of building components used in MTC systems, and modularization of kitchen and powder room pods, the need for large on-site labor crews can be reduced significantly. With proper training, these smaller crew sizes can be just as productive as larger crews found in more conventional construction projects.



Photo: KLH Massivholz

#### CONSTRUCTION SCHEDULE COMPARISON AND EFFICIENCIES

For a conventional residential tower project (posttensioned concrete slabs), the construction cycle is typically planned on a production cycle of one week per floor for the structural work.

MTC buildings offer opportunities to prefabricate many of the structural elements (e.g. wall panels, floor assemblies, beams and columns). This has the potential to improve the construction schedule if it is properly planned out, detailed, and engineered. Some considerations that must be addressed are below.

- Thermal movement of timber can become greater than steel, so it must be accommodated in the design and details.
- Expansion and contraction due to moisture swelling of the wood must also be accommodated in the design and during construction. Expansion joints must be properly engineered and installed in the correct locations.
- Steel connections between MTC elements are required by some jurisdictions to have a fire protection coating on the exposed portions to maintain the overall fire-resistance rating of the floor or wall assembly. In most cases intumescent paint can be used, but this requires the application of multiple coats and is a time consuming process. During the application process the adjacent MTC components must be masked off to prevent overspray and maintain the desired aesthetics of the exposed wood surfaces. Having these components built in a factory setting or off-site conditions also produces the added benefit of an increased level of quality control and quality assurance.

On a conservative basis there is a distinct possibility of a nine week reduction in construction schedule for this case study.

#### COST ANALYSIS

#### Introduction

To support the comparison of the concrete framed versus timber framed high rise development study, an opinion of probable construction cost was developed for each scenario based on the conceptual design. The cost study was based on a comparison of the expected hard construction costs for the two scenarios, and baselined for a project in Seattle priced in August 2016 dollars. Hard construction cost dollars are defined as the forecast amounts that would be paid to contractors to provide all labor, materials, equipment, supervision, and project management to construct the project and that would be the subject of a contractor bid for the work. The cost study did not contemplate differences in the project soft costs between schemes particularly in terms of design fees, nor did it consider any potential difference in rental rates that might be more favorable for one scheme over the other.

#### **Summary Findings**

The estimated construction costs for the base concrete framed scheme is slightly under \$300/SF, which is consistent with current market pricing and is comparable with similar upcoming residential schemes in the Seattle area when normalized for program mix, size and height. CLT construction costs are much more weighted in material and pre-fabrication costs rather than labor. It must be understood that current cost structures for conventional concrete framed structures in the Seattle market in particular and the Pacific Northwest in general are somewhat inflated from the norm due to intense construction activity and may not be a true indicator of the national market.

From an extensive cost analysis for the CLT option undertaken by Arcadis, it is our conclusion that the timber frame scenario in the currently active market is approximately 4% more expensive than the concrete framed option. The construction cost using timber is partially offset by savings accrued from schedule reduction which was conservatively estimated at about nine weeks. This schedule reduction has a clear advantage in time to market and therefore revenue cash flow, but that assumes that the pre-construction schedule, including items such as design and City reviews and approval, is neutral between the two schemes.

It must also be observed that empirical data of mass timber construction in mid-rise buildings is currently a work-in-progress and not a truly reliable benchmark for taller structures. CallisonRTKL would be pleased to share the cost analysis for those interested in scrutinizing the numbers. Ultimately cost comparison on one-of projects is always a contentious issue in a fledgling industry. It has never been the intent of the project team to tout this technology for its cost competitiveness in the current market, only to clearly report its findings. The pursuit has always been driven to explore longer term sustainable and urban growth solutions. Analogies to the cell phone and more recently to the electric car are appropriate as with advances in technology, critical mass of built projects and familiarity with construction techniques, price competitiveness will hopefully become a non-issue.

#### MARKET OUTLOOK

Mass timber construction (MTC) is rapidly growing in popularity and stands a good chance of reducing the market share of steel and concrete as default building materials. While steel and concrete will continue to find unmatched applications, there are plenty of uses where MTC may be the better fit due to its compelling environmental benefits, reduced construction schedules, comparatively lightweight character, and widespread user appeal. As with any design pursuit that leans on new and innovative processes, vision and strategy are key. The challenges are many, including establishing a local mass timber manufacturing plant and supply chain and assembling engineering expertise. Mental shifts and strategic adaptations are necessary to develop approvable financing, insurance, marketing, and sales models, in addition to adapting existing building codes.

Lend Lease developed the MTC Forte tower in Melbourne, Australia and reported a 30% reduction in construction time, reduced site transportation, noise pollution, and waste, and increased safety and construction accuracies. An important consideration regarding the Forte tower was the decision to develop an independent supply chain. For that particular project, Land Lease was the developer, builder, and contractor—effectively, they were their own client. This enabled a significant risk mitigation strategy compared to employing an independent supply chain consisting of disparate organizations working in unison to deliver a project. This provided Land Lease maximum control over scheduling and program timelines, allowing them ultimate control over the entire construction process.

MTC is future-proof, works in favor of the environment and, if integrated strategically, can lead to significant reductions relative to construction time and cost.

#### CONCLUSIONS

The following key observations and conclusions summarize the findings of this report.

The use of CLT in taller buildings is certainly achievable from a structural point of view. To achieve the heights sought after in this study, the structure in all probability will be of a hybrid nature. This hybrid and composite structural format (steel columns at lower floors, concrete core, and shear walls) takes much of the onus of lateral resistance and life-safety considerations away from regulatory approval considerations. Tighter construction schedules are a distinct possibility and advantage of this typology; speed to delivery will have a positive impact on financial proformas. Pre-fabrication of some of the interior components will also have a positive influence on trades and construction schedules.

Conservative cost analysis brings this typology currently approximately 4% above conventional concrete framed construction. Construction schedules could benefit by this technology for up to 2 months compared to conventional concrete framing. Also, current conditions of labor shortage and inflation are unrealistic determinants for a true cost comparison. From an urban planning perspective, higher densities in projects of this type will certainly have beneficial effects on affordability, especially when one bedroom monthly rentals in this city currently approach \$2,500. Flexibility in the layout of units and combination of smaller units into medium sized ones could allow for a better mix of urban living.

The preceding documentation is hopefully a precursor to a more exhaustive study of this typology within the contexts of structural possibilities as well as sustainability, resiliency, density, and affordability. Several research papers from industry organizations, design firms, and think tanks are simultaneously exploring the practical limits of building tall with mass timber. Each study has a specific angle it chooses to focus on (structural implications, code compliance, cost ramifications, etc.) The study undertaken by CallisonRTKL and its partners was initially meant to explore only the structural implications of mass timber in tall buildings of up to 40 floors, but as the process evolved, we felt that it was appropriate to touch on the peripheral issues of regulatory approval, cost competitiveness, and practicality in today's sizzling economy and building boom, especially in Seattle. To that extent it is difficult to come to definitive conclusions as this is a continually evolving process and empirical or comparable data is still hard to come by or agree upon. It is hoped that this initiative by Arcadis / CallisonRTKL and its collaborators will open up the topic to a larger group of supporters as well as skeptics. More rigorous discussions (both pro and con) will ultimately inform the local, regional and global stakeholders.





Seattle Mass Timber Tower

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Thank you.

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