CLT FEASIBILITY STUDY

A STUDY OF ALTERNATIVE CONSTRUCTION METHODS IN THE PACIFIC NORTHWEST

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Image front page: Structurlam

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CLT roof panel lifted into place. Image: Structurlam

INTRODUCTION

CROSS LAMINATED TIMBER

This study explores the use of Cross Laminated Timber (CLT) in a 10-story residential building as an alternative building method to concrete and steel construction. The study is not meant to be exhaustive, rather a preliminary investigation to test the economic viability of utilizing this new material to increase density, walkability and sustainable responsiveness in our built environment.

Based on international precedent, CLT is an applicable material for low-rise, as well as mid-rise to high-rise construction and has a lighter environmental footprint than traditional concrete and steel construction systems. Cross-laminated timber is a large format solid wood panel building system originating from central Europe. As a construction system it is similar to precast concrete in which large prefabricated panels are lifted by crane and installed using either a balloon frame or platform frame system. The advantages to using CLT are many, but the main benefits include: shorter construction times, fewer skilled laborers, better tolerances and quality, safer work environment, utilization of regional, sustainable materials, and reduction of carbon footprint of buildings. As a new, unproven material in the Pacific Northwest, this study investigates the cost competitiveness of CLT versus traditional materials for “low high-rise” buildings.

THE STUDY

A NEW OPPORTUNITY?

Common assumptions for the Seattle market dictate that concrete is too expensive for building only slightly above midrise (heights above 75 ft and lower than around 125 ft). For purposes of this study we will refer to these buildings as “low high-rise.” Consequently, lots in certain zones may not get built-out to their maximum zoning height potential. Instead, economical 5-over-2 construction is used and lots leave valuable development potential unrealized. Seattle has a unique amended building code that allows 5 stories of light wood frame construction to be built on top of 2 stories of concrete construction for a 7-story building, commonly referred to as “5-over-2”. While this construction type is economical and has proliferated across the city, it does not offer the potential for vertical expansion to meet the needs of a rapidly growing and evolving city.

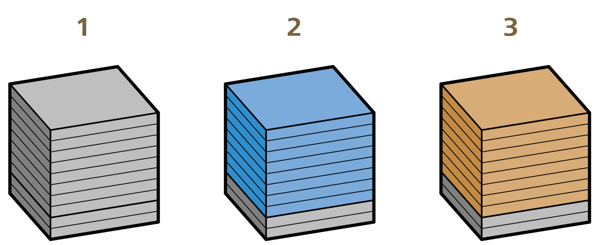
The study takes an existing 7-story student housing project as a base for investigation of several other construction material options. Importantly, each study adds three stories to the existing 7-story base building. The study then compares three alternative 10-story structural options:

:: Concrete
:: Metal (light gauge frame)
:: CLT

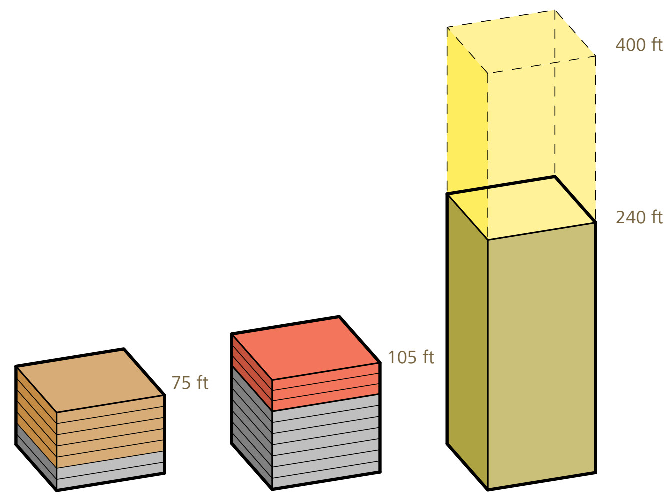
Due to the nature of the existing 5-over-2 building, the first two stories are maintained as concrete in all three schemes and only the upper 8 stories are changed (see Figure 1). All three structural schemes are priced to compare which option is most favorable to the Seattle market.

10-story buildings in Seattle, while not common, would typically be erected as a cast-in-place concrete frame structure with post-tensioned concrete floor decks. As such, a 10-story concrete building was used as the base-line cost model for this study from which the two other structural systems (steel and CLT) were compared.

BELOW | FIGURE 1: THREE MATERIAL OPTIONS STUDIED FOR THE FEASIBILITY STUDY



BELOW | A FEW COMMON SEATTLE BUILDING HEIGHTS CONSIDERED FOR THE STUDY



The site for the existing 7-story student housing project is zoned as MIO-105-MR, meaning that the maximum building height is 105 ft from grade. The 5-over-2 construction type used for the existing building could only reach a maximum height of 75 ft by code, which is the threshold between midrise and high-rise construction. The consequence of building 5-over-2 was 30 feet of buildable height was unrealized.

The team for this study hypothesized that CLT could be an economically favorable option for buildings taller than 75 ft, but shorter than 125 ft. The benefits of finding an economic development solution to this zoning height range (75 ft – 125 ft) are twofold: it provides more potential revenue for developers and will help fill-out the city's desired density targets to promote smart and sustainable growth.

There are many other areas of Seattle zoned (with varying uses) between 85 ft to 125 ft, which is seen as an ideal height for CLT in the Pacific Northwest by the study team. Areas of Seattle that have zoning between 85 ft to 125 ft include: Ballard, Belltown, Capitol Hill, Duwamish, First Hill, International District, Lower Queen Anne, NE 65th, Pioneer Square, SODO, South Lake Union, the University District and others. While not all pockets of these zoning heights are large, as Seattle continues to gain population, as it has over the last decade, we can expect zoning heights over time to increase. Taller structures provide more density and support sustainability and livability goals like those promoted by the City of Seattle's Comprehensive Plan.

CHALLENGES

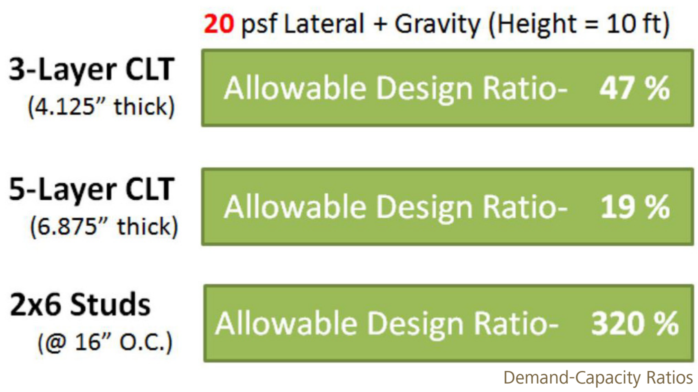
BUILDING CODE

A 10-story building whose structure is built from wood presents several jurisdictional challenges. The City of Seattle Department of Planning and Development (DPD) has started a CLT Advisory Committee to explore the use of CLT and other solid wood/mass wood building systems in taller applications than currently allowed by code (see End Note 1). The Advisory Committee has helped lead to an early introduction of CLT into the City's building code, but issues involving seismic design and combustibility require additional discussion.

According to the International Building Code, of which Seattle uses an appended version, combustible materials are not allowed as load bearing structure in high-rise buildings (taller that 75 ft). While using a wood based building system for low high-rise construction may at first seem questionable, CLT is capable of offering ample fire and life-safety. Like Heavy Timber (HT) construction, CLT panels char in the event of a fire. This protective char layer allows CLT wall and floor panels to be exposed for extended periods of time during a fire without sacrificing structural integrity. Unlike structural steel, CLT needn't be encapsulated with layers of non-combustible material to maintain its strength during a fire. CLT assemblies have been demonstrated to last 2 and 3 hours fully loaded in standard fire-resistance tests, depending on their thickness (American Wood Council, 2012). Encapsulating CLT with layers of gypsum board or other cladding can be used to further improve fire-resistance.

Cross-laminated timber was added to the 2012 Seattle Building Code (SBC) and will be included in the model 2015 International Building Code (IBC). In Seattle, CLT is currently allowed in Type IV and Type V construction (however, Type IV construction is also allowed to varying degrees in Types I, II, and III construction as well). In Type IV construction, CLT can be used as external bearing walls and floors with some

BELOW | COMPARISON OF EXTERIOR WALL GRAVITY SUPPORT SYSTEM FOR AN 8-STORY BUILDING



BELOW | FIGURE 2: COMPARISON OF CLT FLOOR SPANS CONSIDERING STRENGTH, DEFLECTION AND VIBRATION

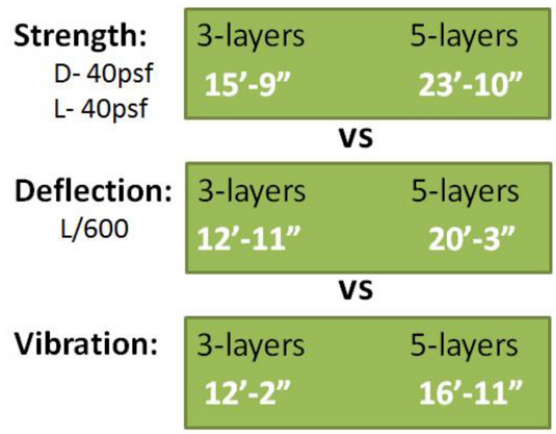


Image: Coughlin Porter Lundeen

limitations (see SBC Sections 602.4.2 and 602.4.6.2), allowing a maximum 6-story / 85 ft height for certain occupancies when sprinkled. The IBC allows a maximum of 4-stories and 70 ft of type VA construction if fully sprinkled (5-stories in SBC if fully sprinkled).

CLT, however, does not fit well into these existing construction classifications – Type IV is a vestige from late 19th century industrial timber construction technology and Type V is for light wood frame buildings. CLT, as a high mass panelized modern method of construction, is neither. Because of the inherent fire-resistiveness and structural capacity of CLT, this construction type is seen by the study team as roughly equivalent to Type 1B construction when properly detailed. Type 1B construction allows buildings to reach 12 stories. While this codification may not be perfect for CLT development, a 10-story CLT structure is imminently achievable with today's technology without sacrificing fire and life-safety standards.

SEISMIC

Cross-laminated timber as a load bearing structural material is used in high rise building construction in multiple countries. There is little doubt regarding CLT's ability to support gravity loads. But what about CLT structures constructed in high seismic zones? The goals for this study include a review of CLT's gravity load-bearing capabilities, but more importantly the investigation of the product's feasibility for use in high-rise lateral force resisting systems.

Cross-laminated timber products, because of the volume of wood, are more expensive than traditional 2x wood framing. Therefore, value engineering of the product to the minimal amount required structurally is an important design constraint, as it is with most structural materials. In many instances, 3-layer panels (which are the thinnest panels available) have adequate capacity to support gravity loads with reasonable resistance to deflection and vibration. However, additional layers are required when charring is relied upon for fire resistance (see page 4 for further discussion of fire strategy). Therefore, in the design for this study 5-layer panels were used at the floors and all load bearing walls. More economical 3-layer CLT is used only in the roof construction.

Figure 2 illustrates span capabilities for common residential loads and shows that vibration is a controlling design criterion for CLT floors. The load bearing CLT wall panels have low demand-capacity ratios in the order of 20% under 8 stories of load.

Unfortunately, a lateral force resisting system with solid panel wood shear walls like CLT is not defined in American Society of Civil Engineers (ASCE) 7 or the IBC. Establishing the required seismic coefficients, such as a Response Modification Coefficient (R) for CLT shear walls, is a laborious and expensive venture that is beyond the scope of this investigation. However, that effort is necessary for practicing structural engineers to eventually design buildings like the one in this study – see Figure 3. In order to proceed with conventional engineering methods, we rationalized that an R of 5 will produce a desirable earthquake response, is a reasonable target coefficient, and seems feasible to achieve with proper detailing of ductile panel connections and hold downs. Admittedly, this is a notable leap of faith and must ultimately be verified through proper testing and research, such as the protocol established in Federal Emergency Management Agency (FEMA) P695. Such efforts are now underway with funding from the federal government.

BELOW | FIGURE 3: DIGITAL STUDY ANALYSIS MODEL

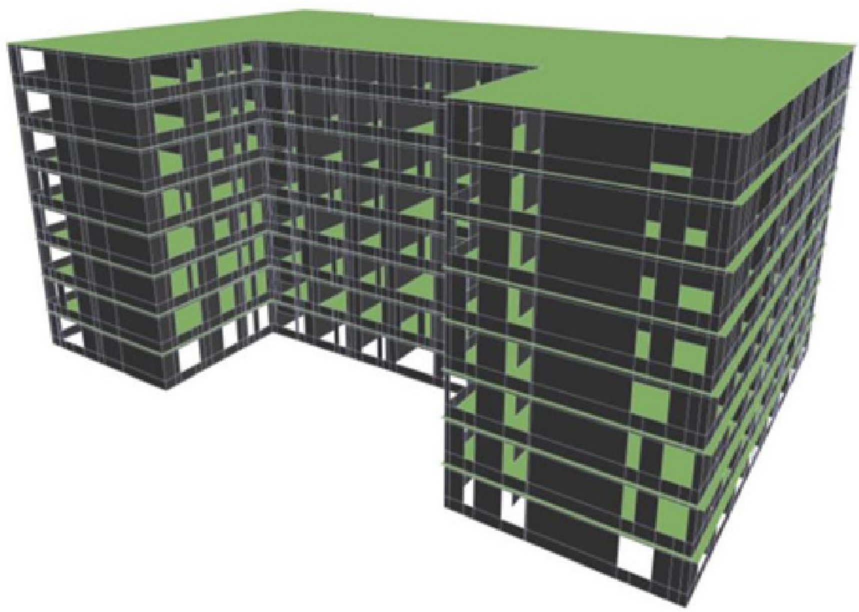


Image: Coughlin Porter Lundeen

The trial R value and other assumptions were used to analyze the CLT shear walls, which consisted of the 5-layer load bearing walls and 3-layer panels at wall locations with no fire resistant requirements. We reviewed three primary failure modes: horizontal shear stresses, compressive or tensile stresses from overturning, and torsional stresses developed by load transfer between laminations. The results illustrated how capable a structural product CLT can be, even after value engineering much of the CLT walls out of the building. For example, the controlling failure mode in the highest stressed 3-layer panel had a demand-capacity ratio (DCR) of 60%. The DCR for the highest stressed 5-layer panel is roughly 30%, and DCR's for horizontal diaphragm shears are similar. Despite our aggressive assumptions for deriving seismic base shear, we can conclude that lateral force resisting systems in 8 to 10 story high rise buildings can be constructed using CLT products. Future development in the U.S. should include investigations in ductile connections leading to codification of CLT shear wall systems.

While engineering CLT buildings for seismic zones is still developing, shake table tests have been conducted on full-scale solid wood cross-laminated timber buildings at 3-story and 7-story heights with favorable results. Of considerable interest is the 7-story CLT structure tested by the Italian SOPHIE project at the world's largest shake table in Kobe, Japan. The CLT structure survived without needing significant repairs and the structure was not permanently deformed. In fact, the CLT panels were shipped back to Italy and reused in another structure (Quenneville et al. 2007).

FIRE

Type IB construction requires all interior and exterior load bearing walls to achieve a 2-hour fire rating. For the proposed CLT study option, all load bearing walls are constructed from 5-layer CLT. By cladding each side of the CLT wall with one layer of gypsum board, the assembly is assumed to meet a 2-hour fire rating based on assumptions from full-scale fire tests. The floors are also constructed from 5-layer CLT panels with a gypsum topping and dropped gypsum wall board ceiling below and assumed to meet a 2-hour fire rating based on full-scale fire tests (Osborne et al. 2012). Required walls and floors are also furred-out and filled with acoustic insulation to meet sound transmission requirements. Although CLT panels meet Class B flame spread index for an interior finish material (depending on the wood species used at exterior layers), encapsulation with gypsum wallboard provides an additional level of safety.

For Type IB buildings, non-bearing walls are not required to be fire rated. Because the majority of exterior wall area in the test building was not required to take vertical loads, most of the exterior envelope is constructed from light gauge, non-load bearing, non-combustible steel framing with traditional sheathing and gypsum board interior finish rather than with CLT. The study also assumes a fully sprinkled building and a short fire response time based on the building's location only 4 minutes away (by car) from the nearest fire station. It is believed that with the combination of fire resistance of CLT, the protective gypsum board cladding and sprinkler system, the proposed design meets the technical requirements of a IB structure.

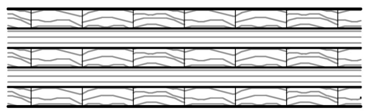
BELOW | FULL SCALE CLT WALL ASSEMBLY FIRE TEST

Fire testing CLT wall assembly. Image: FPInnovations

BELOW | FIRE RATED ASSEMBLY ASSUMPTIONS BASED ON FULL-SCALE FIRE TESTS*

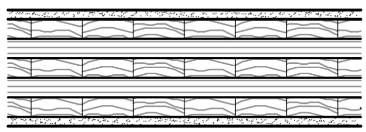
WALL ASSEMBLY

FIRE-TESTED WALL ASSEMBLY*



5ply CLT unprotected = 113 min

PROPOSED MODIFICATION TO FIRE-TESTED WALL ASSEMBLY

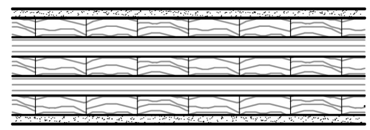


5ply CLT + 1 layer 5/8" gyp = 143 min estimated

* See End Note 4

FLOOR ASSEMBLY

FIRE-TESTED FLOOR ASSEMBLY*



5ply CLT + 1 layer 5/8" gyp = 124 min

CONSTRUCTION COST ANALYSIS

BASIC ESTIMATING ASSUMPTIONS

As noted earlier, the assumptions for estimating the three models is based upon a recently completed existing facility which includes a substantial two level concrete podium on which five wood framed floors were constructed. The specific use of the building and any design cost premiums that would follow remain consistently applied to each cost model estimate. Therefore the true cost differences for each structural component model would include only those items specific to each model's material use requirements. Additionally, the added costs for life safety "high rise" elements due to exceeding the height threshold of 75 ft have been applied equally to all options studied.

It should also be noted that the team assumed only minor variations in the design of the 2-story concrete podium structure would be required for the three different structural model applications, so the cost for this area of the building is consistent in each estimate compared. The study keeps primary details of the exterior enclosure the same for each option as to compare "apples to apples." All 3 options include the same exterior enclosure components, such as sheathing, weather resistant barrier, insulation, external cladding and backup system. All interior partitions are assumed to be metal stud with gypsum wall board except where load bearing CLT walls occur. HVAC equipment is the same in all cost models.

CONCRETE BUILDING ASSUMPTIONS

The Concrete Frame option assumes a fairly typical concrete column spacing and shear wall layout with a 7 inch post tension concrete floor assembly and 5 inch post tension roof assembly. This option offers a more flexible partition wall layout due to its independence from unit stacking requirements.

STRUCTURAL METAL STUD FRAMING

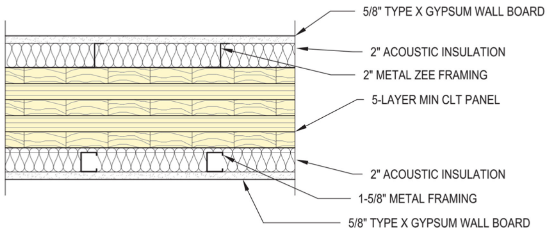
The metal stud option includes cost assumptions that were derived from a current project cost estimate in a building with similar use. This was done not only to identify component type and size but also to maintain current market price information in the study. This design includes metal stud bearing walls integrated with concrete shear walls with floor and roof construction consisting of two inch Versalock Deck material allowing for a three inch concrete fill. This approach also concedes that the design maintain a consistent stacking of unit bearing walls in order to minimize any transfer loads which would require more complicated and costly framing. 2-hour fire rated exterior walls require 3 layers of Type X gypsum board cladding and 2-hour rated floor and roof assemblies require 2 layers of Type X gypsum wall board suspended on the underside of structure.

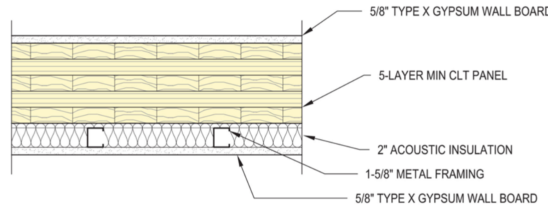
CLT COST ANALYSIS

The approach taken by the team initially was to use CLT panels of various sizes and thickness for all walls noted in the original building design. Bearing walls would receive 5-layer panels while non-load bearing walls would utilize a lighter and more economical 3-layer panel. This approach was quickly dismissed for three reasons. First, where the benefit of CLT panels for their intrinsic load bearing capacity is not required, why pay a premium for this heavier construction element over a conventionally framed infill wall? Second, the conventional infill framing allows easier installations of mechanical, plumbing and electrical rough-in components. Finally, fewer CLT panels to erect during the structural framing phase of construction saves critical path construction time. See Figure 4 for proposed CLT wall and floor assemblies used in the study.

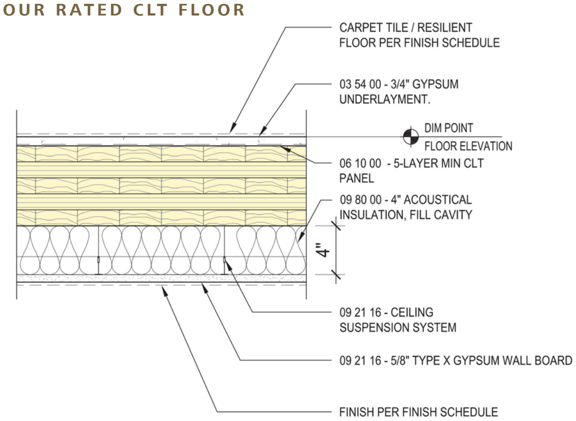
BELOW | FIGURE 4: PROPOSED CLT WALL, ROOF AND FLOOR ASSEMBLIES

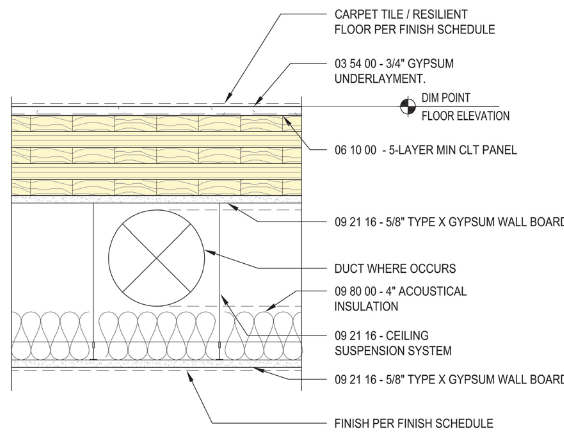
PROPOSED 2-HOUR RATED CLT INTERIOR WALL ASSEMBLIES*



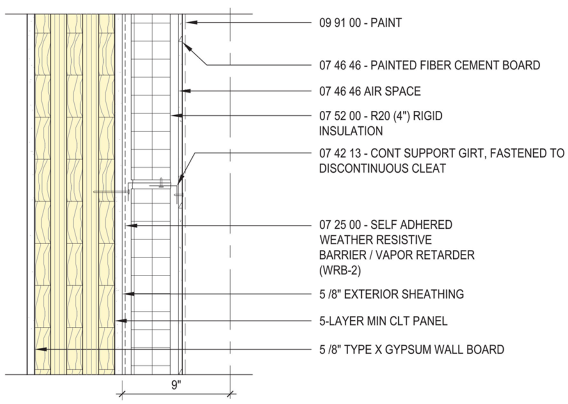


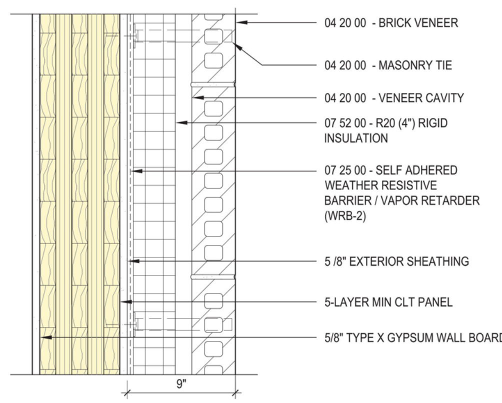
PROPOSED 2-HOUR RATED CLT FLOOR ASSEMBLIES*



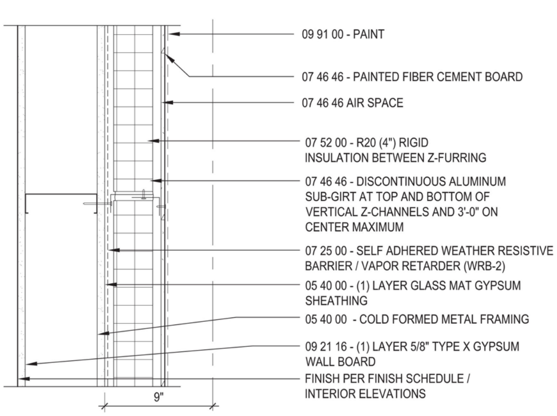


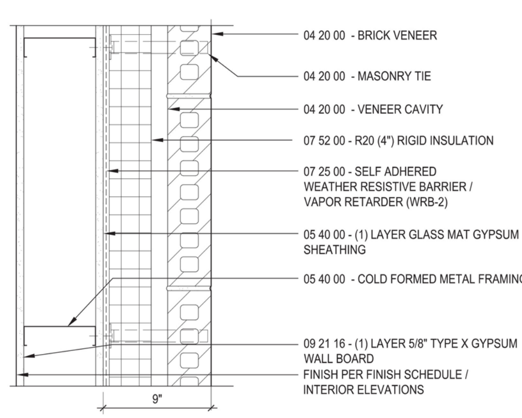
PROPOSED 2-HOUR RATED CLT EXTERIOR WALL ASSEMBLIES*





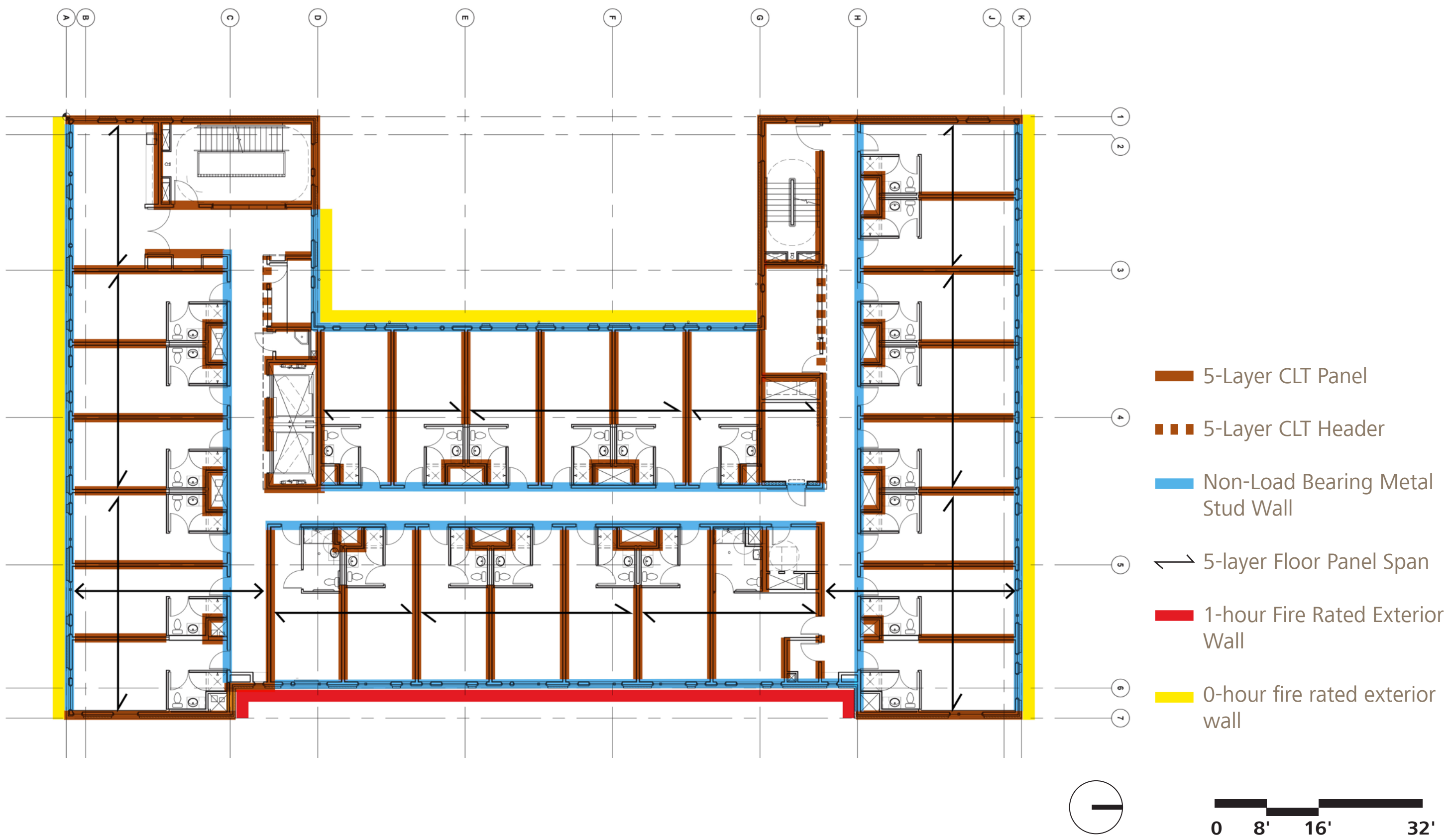
PROPOSED 1-HOUR RATED METAL STUD WALL ASSEMBLIES





* Assemblies here are proposed based on fire testing results in accordance with ASTM E119 standard and additional layers of protective gypsum board cladding.

BELOW | TYPICAL RESIDENTIAL LEVEL FRAMING PLAN



Once the team focused on utilizing the CLT approach only for the required bearing and shear components the complexity and cost lowered to a more favorable level. The overall construction schedule also improved by several months, due to the speed of erecting the prefabricated panels vs. the slower process of cast in place concrete or the metal stud option which still relies on significant concrete shear walls. The cost benefit of reduced general conditions expenses has been realized within the construction estimate for this approach.

Consultation with CLT suppliers provided us with productivity rates that have been used in other regions. Factoring in connection details for moment frame steel connectors and likely inclement weather conditions, a conservative installation production rate was used to assure ourselves that a composite crew of operators, riggers and carpenters would achieve production much like the crews that install precast concrete panels. We believe with further development of the process and required details; a significant savings in this area is possible.

Because of the extensive prefabrication of the material, CLT could likely use a less skilled workforce, a potential cost saving factor. Temporary weather protection of CLT elements, in addition to sequencing deliveries and storage (if necessary) of the material must also be considered. Projects where the design utilizes exposed CLT components in the finish expression of the building are likely to encounter higher costs for temporary protection.

As previously noted, the requirements for fire rated assemblies demand furred out walls and ceiling assemblies. With these layers of gypsum wall board and the addition of treatments such as acoustical insulation and gypcrete, the required fire and STC ratings can be achieved. These furred areas also provide a chase for running fire protection branch piping, plumbing, electrical and air vent ducting.

The cost drivers for CLT construction are material cost, erection timeframe and site location. Increased familiarity with CLT construction/erection methods and further development of the product supply chain could significantly reduce the costs of CLT construction compared to other construction types.

OTHER ASSUMPTIONS

:: Gross Building Area: 134,950 gsf

:: Total project Housing Area: 120,300 gsf

:: Total number of housing units: 223 (435 beds)

:: Total Rentable SF as Percent of GSF: 53.6%

CONCLUSION

COST SAVINGS

The results of the study are promising. As compared to the base 10-story concrete building, the CLT option offered an estimated 4% cost saving. The metal stud option offered a 2% cost saving compared to the concrete base building. While the estimated 4% saving is not large, it does indicate that CLT is cost competitive and could be even more competitive in the future.

Although there seems to be growing excitement surrounding the use of CLT, it has yet to reach the manufacturing sector. To date, only one viable manufacturer is available to supply panels required for the building model and in close enough proximity for practical shipping to a site in the Pacific Northwest. There would appear to be enough sustainable resources to feed the potential market, but other manufacturers of engineered wood products have not seen enough demand to warrant the capital expense of retooling. With the increased industry interest, we would expect this to change. With the addition of competition and higher production rates the savings could be higher.

Furthermore, because there is little local experience with this construction system, CLT construction is estimated at a cost premium until competency and familiarity is established. Construction time will also likely be reduced once the system is better known. This study has accounted for these "unknown" factors of using a new building system. The 4% cost savings is a conservative estimate because of these unknowns.

CLT represents a different paradigm in project delivery in that the material cost far outweighs labor costs. It should also be noted that the building design in this study was not optimized for CLT panel sizes or designed to take advantage of the benefits of large format panel construction. The design was simply translated from existing light wood frame to CLT construction. As such, the percent savings could be even greater if the building design were to follow the rigor of efficient CLT modular construction.

Finally, the study only investigated more or less "pure" material choices. Optimizing the building design through use of hybrid structural materials could lead to further cost savings and better opportunities for code approval.

To date, many CLT buildings around the world exceed current Seattle Building Code heights, including 7, 8, 9 and 10 story CLT buildings. In Prince George, a city in British Columbia, Canada, a 7-story, nearly 100 ft tall CLT building that meets similar fire and seismic requirements as in Seattle has been constructed. Buildings like these illustrate the potential of using CLT and providing a real alternative to steel and concrete that will help promote carbon neutral growth. CLT and other large format engineered timber products represent the only green alternative to carbon intensive steel and concrete construction. We hope this study helps lead to further research and development. Issues related to building code, seismic response, supply and experience all must be expanded. With recent developments, wood offers the first new structural systems for tall buildings in over 100 years; an exciting time for architects, engineers, contractors, developers and city officials to re-envision how we build for a sustainable future.

End Notes

1. Seattle CLT Advisory Committee web site: <http://seattle.gov/dpd/codesrules/changestocode/crosslaminatedtimber/getinvolved/default.htm>

2. Cross Laminated Timber (CLT) Gains Code Approval, 2012. Available from: <http://www.awc.org/NewsReleases/2012/newsreleases2012.php>. [23 December 2013]

3. Quenneville, Dr. Pierre; Morris, Hugh Morris, 2007. "Japan Kobe Earthquake Shake Table Simulation - The Earthquake Performance of Multi-storey", NZ Timber Design Journal: Volume 15, Issue 4.

4. Osborne, Lindsay; Dagenais, Christian; Benichou, Noureddine, 2012. "Preliminary CLT Fire Testing Report", FPInnovations, Project No. 301006155.

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