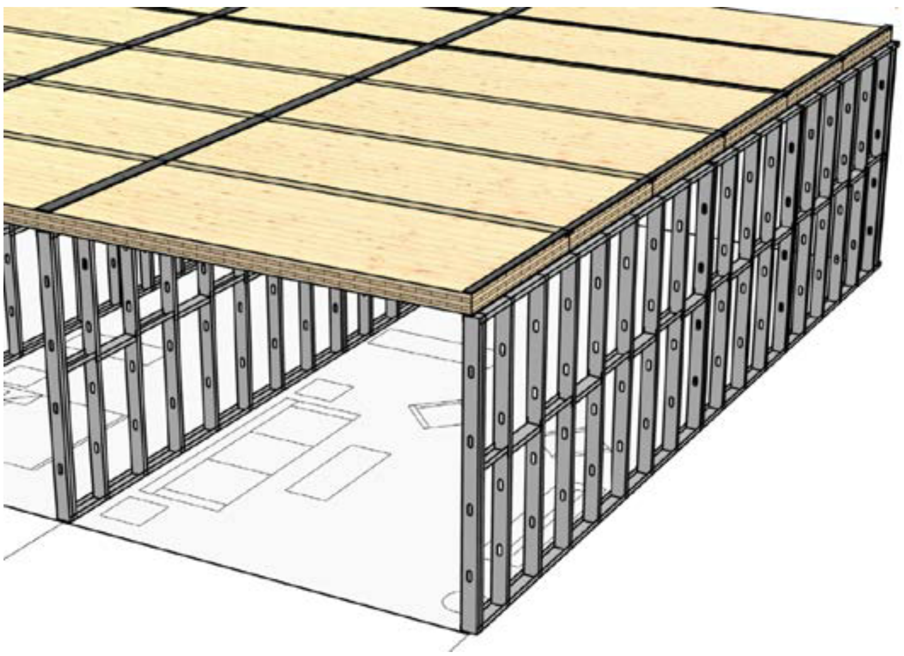

Vienna House Cross-Laminated Timber and Cold-Formed Steel Suitability Assessment

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March 2023

This research is based on the technical case study attached in the Appendix: *Cross-Laminated Timber and Cold-Formed Steel Hybrid System: A New Approach*, November 2021 by Robert Malczyk and Hercend Mpidi Bita of Timber Engineering, Inc.

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Contents

Introduction

Mass timber comprises a growing segment of construction products that uses glue, nails or dowels to layer wood into strong structural panels, posts and beams. It is generally manufactured through off-site production facilities and has strength, fire and seismic properties comparable to steel, but is lighter in weight and less carbon intensive. Cross Laminated Timber (CLT) is one type of mass timber with multiple (often 3,5,7 or 9) layers of kiln-dried dimensional lumber glued at right angles to each other, giving it structural rigidity in both directions. As mass timber becomes a more common component of sustainable construction, interest has grown in using mass timber structural systems for taller buildings. Building codes in many locations around the world now allow taller timber structures. In North America, the 2020 National Building Code of Canada and 2021 International Building Code permit timber structures 12 and 18 storeys respectively for residential, commercial or mixed-use buildings.

Mass timber elements can be used in a number of different hybrid structural configurations to take advantage of the qualities, strengths and costs of different materials. This study investigates the possibility of using a hybrid Cross Laminated Timber (CLT) and Cold Formed Steel (CFS) system for Vienna House, a six-storey multifamily residential building in Vancouver, British Columbia that is currently in development by BC Housing and More Than A Roof Housing Society.

This summary report highlights the features of this hybrid approach and its potential uses. A technical analysis is provided in a separate study conducted by Timber Engineering Inc. in the Appendix.

Figure 1. 5-Ply European Spruce Mass Timber Panel (image courtesy Mass Timber Services Ltd.)

Construction of Mid-Rise Mass Timber Buildings

Mid-rise buildings are not a frequent form when compared to low-rise or high-rise structures in British Columbia. Low rise buildings from single family dwellings up to those of 6-storeys are common. If a building is permitted to be taller than 6 storeys it is more likely a tower. However, as cities seek to densify without towers, buildings in the 7-12 storey range are becoming more attractive and more economical. Those that exist have typically been concrete and steel structures, but recent changes to the B.C. Building Code allow for mass timber buildings up to 12 storeys.

Of the over 760 mass timber projects in Canada, only 31 of those are between 7 and 12 storeys.[1] Of the 334 projects in British Columbia, there are 18 such projects of which 3 are completed, 4 are under construction and 11 are in development. The construction approach to the projects in development varies:

- 2 are CLT floors on steel frame
- 2 are CLT floors on glulam with steel brace frame and concrete core
- 1 is an exterior wood braced frame with CLT shear walls
- 2 are CLT on glulam post and beam structure.
- 1 is CLT on glulam post and beam with a steel brace frame core (complete)

[1] The State of Mass Timber in Canada: https://open.canada.ca/data/en/dataset/9d00aa0a-a825-4804-b29b-1eff4f82a085/resource/079852cd-76db-47d2-b200-0a89c9b29060

Tallwood 1, Langford

2150 Keith Drive, Vancouver

Capstone, Kelowna

Figure 2. Mass Timber projects currently under construction in B.C. (images courtesy naturallywood.com)

Mid-rise mass timber buildings in B.C. are primarily residential (student residences, hotels, market and non-market housing). There are two office buildings and one art gallery. As will be discussed further below, the CFS/CLT hybrid structural system is particularly suitable to residential buildings and offers an affordable alternative to the CLT on glulam post and beam option.

Wood products provide a significantly lower carbon footprint than concrete. Transitioning construction of those buildings from concrete to wood can result in significant emissions reductions. Greenhouse gas emissions from production, transportation, construction, use and disposal of building materials can be reduced by using wood cultivated from sustainably managed, local forests in B.C. By reducing the amount of concrete, a carbon emitter, and increasing the amount of wood, a carbon sink, buildings can contribute to carbon reduction goals.

Notably, a recent study by BC Housing, *The Economics of Encapsulated Mass Timber Construction*, identified that mass timber buildings in this range are economically competitive with steel and concrete structures, both in terms of capital construction costs and lifecycle costs.

Although encapsulated mass timber is allowed up to 12 storeys, there have been challenges with the cost and complexity of construction – particularly with the number of different trades required to sequence work and the time and cost to apply two layers of TypeX drywall to all exposed timber to achieve the required fire rating.

While market and supply chain uncertainty and unfamiliarity may be limiting factors in the uptake of mass timber structures, combining mass timber with cold formed steel can provide an economical option that has more familiar elements. For these mid-rise structures, the hybrid approach has the potential to also offer additional savings.

Advantages of the Hybrid CLT/CFS Approach

CFS is essentially a structural steel stud system that can be pre-assembled into panels. It is a well-known, proven, readily available system with a long track record of use in mid and high-rise buildings. It is non-combustible, durable, yet light weight and easy to install. CFS systems provide an architecturally consistent layout when used in both loadbearing and non-loadbearing walls and have long-term dimensional stability.

Combining CLT and CFS as a hybrid structural approach was recently developed as a cost-effective solution for buildings with 7-12 storeys. Manufacturing prefabricated panels of CFS combines the advantages of speed of prefabrication, limiting waste, and strength of material.

Figure 3. CFS system in platform-type construction (summitdb.com, 2021)

Prefabricated CFS wall panels support CLT floors in a platform style of construction. The CFS wall panels can be spaced to optimize the CLT floor spans and the wide range of available sizes and spacings of the steel studs within the wall panels offers plenty of design flexibility. Technical details are provided in the appendix in a report from the structural engineers at Timber Engineering, Inc., who developed this approach while working at Katerra Technology Canada.

Steel stud construction is the established method of wall construction for 7-12 storey buildings in B.C. due to non-combustibility requirements. Including it in a mass timber project is not out of the ordinary for this building typology. In fact, it is frequently the steel stud subcontractor that also installs the drywall, thereby streamlining processes. Traditionally steel stud construction is site built. However, an increasing number of trades are shifting to panelization to improve productivity and control costs – for both traditional light gauge non-structural partitions as well as the heavy gauge structural systems that would be applicable to the CFS/CLT system. CFS-based envelope panels also offer advantages over traditional site-built systems by reducing the coordination between different trades and the risks of delays and mistakes that this implies. The hybrid CLT/CFS system is planned for the MAC building at Main St. and E. Cordova St. in Vancouver, an 11-floor mixed-use building with social housing, retail and education facilities.

Figure 4. MAC – CLT/CFS in Vancouver (image courtesy MA+HG Architects)

The Vienna House National Housing Demonstration Project

Vienna House is a multi-family residential housing project in Vancouver that provides an opportunity to advance innovations in construction through support from CMHC National Demonstrations Initiative, Natural Resources Canada, Forestry Innovation Investment, the City of Vancouver, and BC Housing. It has a sister project in Vienna named Vancouver House which is also pursuing innovative construction methods. These two projects are sharing ideas and lessons learned and studying how housing is constructed in the others' jurisdiction. This innovative environment allows for exploration of new ideas and approaches such as the use of CLT/CFS for the structure.

Figure 5. Vienna House entrance design (image courtesy PUBLIC Architecture + Communication)

Vienna House is designed with a central courtyard to aid in providing airflow to all units while limiting noise from the adjacent SkyTrain. This design is also intended to aid in building a strong community among the residents through increased capacity to interact when compared with a typical double-loaded corridor style building. It is comprised of studio apartments and 1,2,3 and 4-bedroom units, with 56 of the 123 units targeted to families.

As part of the objectives defined by the client, Vienna House has a low-carbon design striving for Passive House certification. Following BC Housing's Mobilizing Building Adaptation and Resiliency (MBAR) initiative, it used the Integrated Building Adaptation and Mitigation Assessment (IBAMA) framework to define climate risks while optimizing GHG reduction and sustainability goals. It is designed with 2050 climate data in mind, limiting residents' exposure to extreme heat events that have become more frequent. Hot water tanks are located on the roof to provide supply in case of earthquake or drought. Rainwater management systems retain water collected through the permeable paving for landscaping use before allowing it to contribute to the local storm system. Designers are exploring the option for future installation of rooftop photovoltaic systems to reduce the risks of power outages. These are but a few of the innovations explored in this project, which is being documented by BC Housing Research and shared through case studies, a website and social media.

Figure 6. Vienna House courtyard design (image courtesy PUBLIC Architecture + Communication)

The configuration of units within Vienna House provides a form that would work well with the CFS/CLT hybrid structure. CLT floors are exposed on the ceiling and supported by prefabricated exterior wall panels. The structure could be modified to exceed its current six storey design if permitted by local zoning.

Figure 7. Vienna House cross section (image courtesy PUBLIC Architecture + Communication)

The innovative nature of the Vienna House project and the research associated with it allowed for further investigation of the use of the CFS/CLT Hybrid system and access that would likely not be available with another project. While CFS/CLT is anticipated to demonstrate the most cost savings in the 7-12 storey range, Vienna House provided an example to provide a baseline and potentially, information that could be scalable to taller structures.

Structural Description for CLT/CFS Hybrid Approach

The CLT/CFS approach is similar to light wood framing in that it uses platform construction, with walls resting on each floor. The system is designed to be structurally strong when built this way up to twelve storeys.

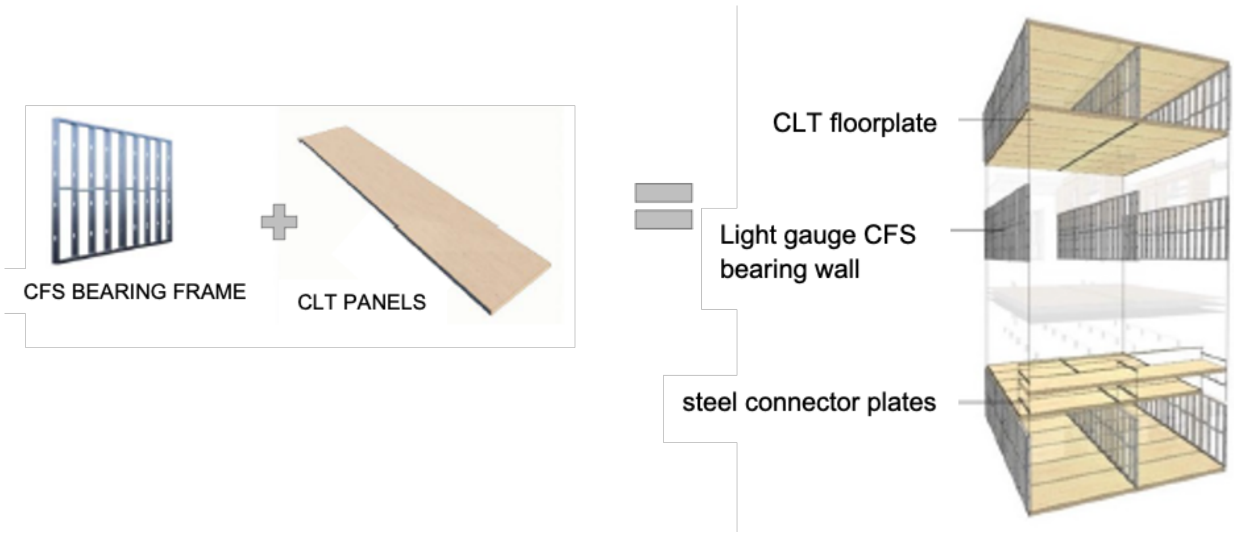

Figure 8. Novel CLT/CFS system (image courtesy Timber Engineering, Inc)

The Gravity Load-Resisting System (GRLS) of the system uses CFS walls typically spaced at 12’ (3.7m) on centre to support double or triple-span continuous CLT floor panels, as shown in Figure 9. This design uses the maximum allowable span of the CLT panels and the allowable sizes and spacings of the steel studs within the CFS walls. The Lateral Load Resisting System (LLRS) may be concrete core or steel braces (Figure 10) for buildings located in high seismic zones, or conventional wood or steel braced frames or concrete or mass timber shear walls for low seismic or wind-governed zones.

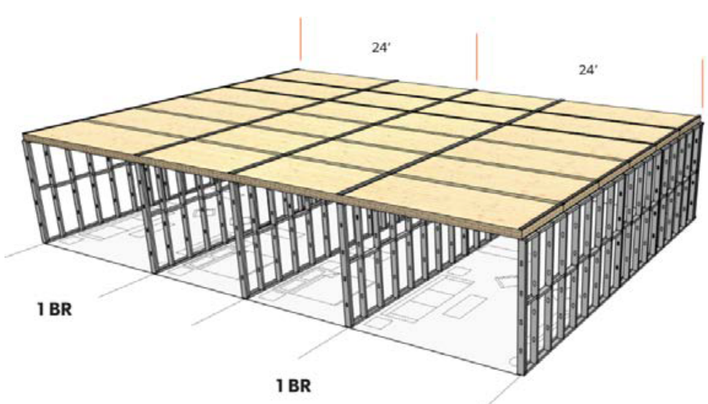

Figure 9. Novel CLT/CFS system GLRS (image courtesy Timber Engineering, Inc.)

Figure 10. GRLS CLT/CFS with LLRS steel braced frame (image courtesy Timber Engineering, Inc)

The direct load paths for gravity loads provide a simple system to transfer forces following the CFS loadbearing walls from one level to the next. This is a cost-effective solution as no transfer elements are required. No extra connections are necessary because the forces are applied as a line load. Savings are also found due to the high strength-to-weight ratio of the CFS loadbearing walls, which reduces seismic structural requirements, connections and foundation requirements.

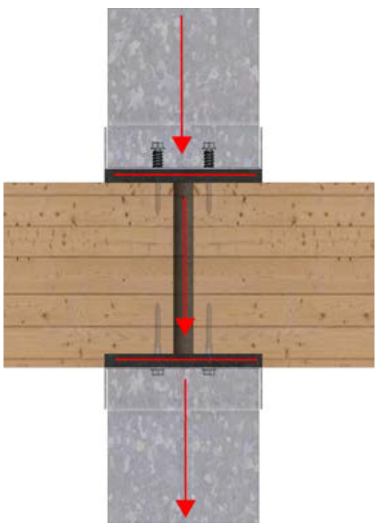

Figure 11. Novel CLT/CFS connection detail (image courtesy Timber Engineering, Inc)

Issues of crushing of the CLT panels and shrinkage for the timber elements can be addressed through the use of steel spacers at each floor (Figure 11). This method is well established in construction, as concrete or hardwood spacers are sometimes used. Steel spacers are a standard product, not anything new.

Technical details are provided in the report attached in the Appendix describing the system including specifics regarding design and loads, fire and acoustic performance, prefabrication, sequencing, and minimizing building movement, shrinkage and compression, and the use of spacers. Results of testing for connections and loads are also provided.

Speed and Simplicity of Construction

One factor that has not been considered in this study is speed of construction. The importance of providing affordable housing as quickly as possibly has given new weight to this consideration, however it is not something that is well known. Assuming that both light wood frame panels or CFS panels were prefabricated offsite at a time parallel to site preparation such that either are available when the site is ready, would assembly be quicker with one method or the other?

Certainly, the approaches require a different combination of trades, with fewer trades being involved with CFS. With a typical light wood frame system it is normal to see rainscreen, framing, air-vapour-moisture (AVM) barrier, insulation and drywall all performed by different contractors. Sometimes an envelope contractor may aggregate some of these activities but there is still the potential for inefficiency. By comparison, for CFS, there would be a single contract for steel stud and drywall (SS&D) installation, and many SS&D contractors will also install insulation. However, more research is needed to quantify the benefits.

Costing Estimates for Vienna House

Costs for the CLT/CFS Hybrid approach will vary with prices for timber and light gauge steel. Given the environment for steel and lumber prices in the summer of 2022 when estimates were being developed for Vienna House, the option to use the CLT/CFS Hybrid method came in $353,400 (5.3%) lower based on a Class D level of costing. Margins are significant enough at that level that fluctuations in material prices may be more significant than this difference. Vienna House is designed as six storeys above the parkade. Further study on a taller building may identify greater savings with increased building height. The cost comparison is set out in Table 1.

Table 1. Comparison of high-level costing of Vienna House panels (courtesy Kindred Construction Ltd.)

		CLT + Prefab Wood Panels	CLT + CFS Hybrid
1.	Supply, fabrication and delivery of CLT Floor/Roof Panels	$2,567,000	$2,567,000
2.	Supply, fabrication and delivery of Prefabricated Wood Walls c/w framing hardware and hold downs (5,500LF)	$2,955,200	$953,800
3.	Supply, fabrication and delivery of CFS Walls c/w plywood sheathing.	-	$1,498,000
4.	Labour, tools and equipment to install CLT Floor/Roof Panels and Prefabricated Wood Walls Panels	$1,158,000	$1,158,000
5.	Misc. allowance for hardware and accessories	-	$150,000
6.	Crane & operator	Excluded	Excluded
Total (exc. taxes)		**$6,680,200**	**$6,326,800**

While the potential savings of the CFS/CLT method are significant, other considerations resulted in the choice to continue the design with prefabricated light wood frame panels and CLT floors instead of the CFS/CLT system. The cost estimates were conducted using an early model in the design process and during a period of greatly fluctuating prices for both lumber and steel. As shown in Figure 12, prices for steel began increasing dramatically in 2020, and prices for lumber have varied considerably, but also increased significantly.

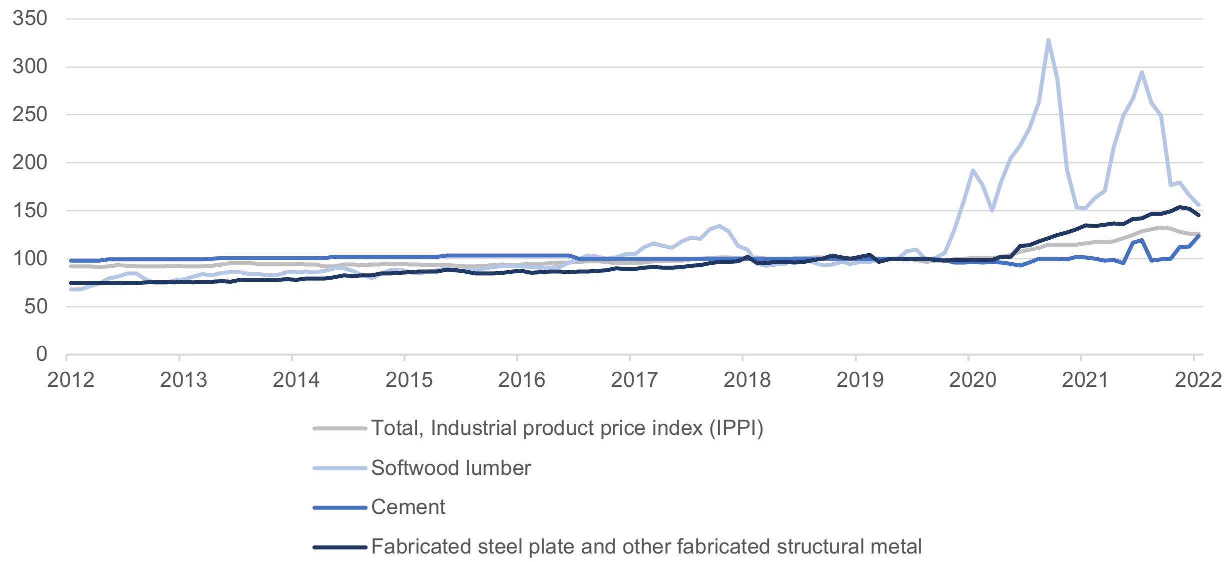

Figure 12. Industrial Product Price Index for softwood lumber, cement and fabricated steel plate and other fabricated structural metal from 2012 to 2022. Index, 202001=100 (Statistics Canada Table: 18-10-0266-01)

This added an element of risk to the project, and the project team felt that switching designs late in the design process would add additional risk that was not warranted. The change in design could also have delayed the schedule, which was undesirable given the urgent need for affordable housing. The team also cited uncertainties with the supply chain and appropriately skilled labour. At the time of preparing this report, prefabricated CFS panels are not currently manufactured in B.C., although there are producers in central Canada (mostly Ontario) that are supplying projects across the country.

Despite these concerns in applying the CFS/CLT Hybrid system to the Vienna House project, some project team members expressed interest in pursuing this approach on upcoming projects, especially those in the 7-12 storey range, where the cost savings might be more significant.

Appendix

Cross-Laminated Timber and Cold-Formed Steel Hybrid System: A New Approach

November 2021

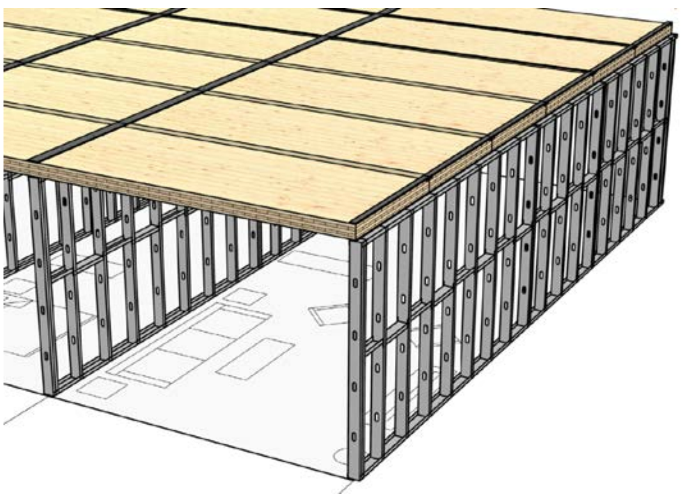

Figure 1-1: CLT/CFS platform-type construction

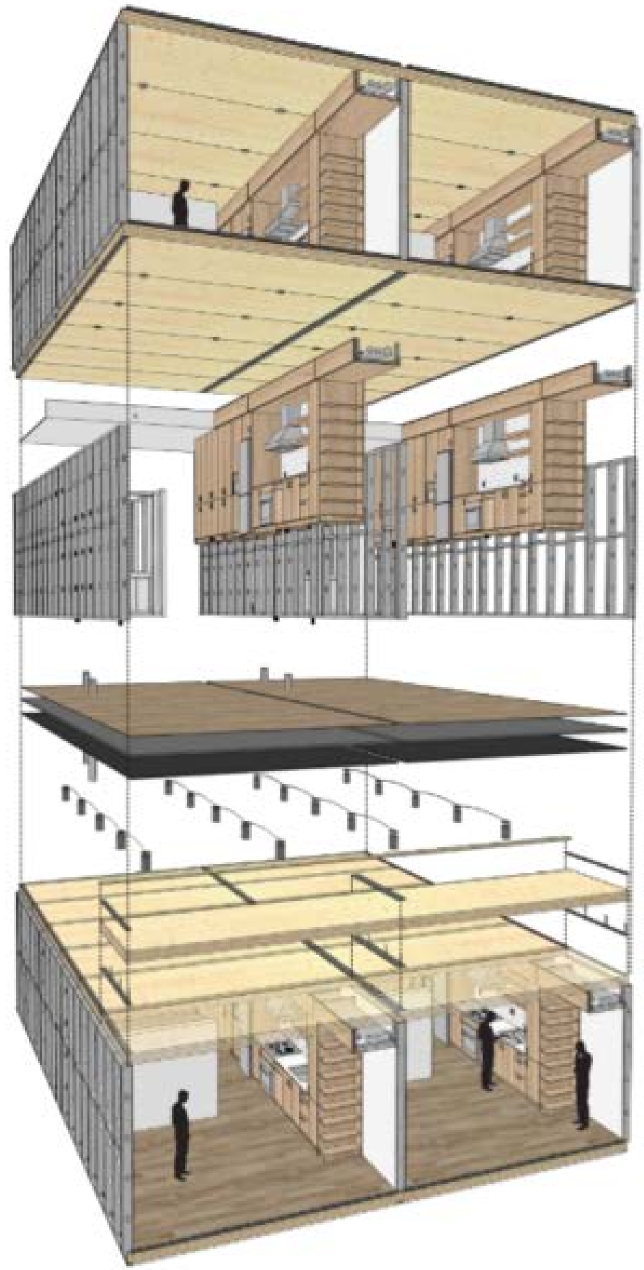

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Table of contents

1 Summary

The report presents structural considerations of the novel cross-laminated timber and cold-formed steel hybrid system, also referred to as the CLT/CFS system. This novel hybrid system uses CLT floor panels and CFS walls in a platform-type construction to carry all gravity loads, whereas the lateral loads are carried by conventional systems, typically concrete cores or steel braced frames. The CLT/CFS system is a new cost-effective and structurally efficient system that helps meet the demand for taller mass timber buildings.

The first section of the report introduces timber as a material and the new trends towards mass timber construction. The second section describes typical and conventional structural systems for hybrid mass timber buildings. The third section explains the combinations of CLT and CFS as structural components to make up the CLT/CFS system, including structural system optimisations and a typical building example. The fourth section outlines the main advantages of the system; and the fifth section presents the key structural considerations of the new CLT/CFS system by means of a worked example.

2 Trends Towards Mass Timber Construction

The growing emphasis on sustainable construction and resource-efficiency, while mitigating the increasing housing demand and capitalise on dwindling land availability in urban centres, renewed the interest in using wood as a structural material. The use of wood is among the preferred approaches to reduce greenhouse gas emission by enabling construction of zero-carbon or carbon negative buildings (Ramage et al., 2017). BC is targeting zero carbon for all new buildings by 2030.

Figure 2-1: Brock Commons Tallwood House – Photo Credit Brudder, courtesy naturally:wood.com

For the past decade, the introduction of innovative structural connections, components, and systems for mass timber constructions provided the opportunity to extend wood-based systems to high-rise constructions including in earthquake-prone regions (Tannert et al., 2018). The advances in mass timber construction are also reflected by the recent code changes in North America, i.e., encapsulated mass timber solutions in the 2020 National Building Code of Canada (NBCC) for buildings up to 12 storeys (NBCC, 2020) and in the 2021 International Building Code (IBC) for buildings up to 18 storeys (IBC, 2021).

Mass timber construction is no longer dominated by low-rise construction, but it includes large, tall residential, office, commercial mixed-use buildings, and buildings in the high importance category (Tannert et al., 2018). The 18-storey Brock Commons Tallwood House, the world's tallest hybrid mass timber building at its completion (Figure 2-1), is a prominent example.

Hybrid structural systems expand opportunities to build tall buildings with mass timber. This report presents a novel hybrid system composed of cross-laminated timber floors and cold-formed steel walls, also referred to as CLT/CFS system, as a cost-effective structural solution for 7-12 storey buildings.

3 Conventional Hybrid Mass Timber Building Systems

Hybrid mass timber buildings integrate mass timber components with structural elements made of other materials to form a structural system that makes use of each material's strength while overcoming their individual weaknesses (Pan et al, 2021). Hybrid structural systems achieve a match between architectural forms, structural functions, and building physics functionalities. This solution optimises the application of the individual structural material, e.g., mass timber, concrete, steel, and masonry. It offers reduced construction schedules through prefabrication and may achieve overall project cost savings. While hybridisation can be at component level, such as timber-concrete composite floors, the focus of this report is on the building-system level.

3.1 Lateral Load-Resisting System (LLRS)

The lateral load-resisting system (LLRS) of hybrid mass timber buildings are typically non-wood based. The choice of material is dictated by not only the lateral demands on the LLRS, but also on the overall constructability and cost. Herein, the most common options for LLRS in multi-storey buildings taller than six storeys are concrete shearwalls or cores and steel braced frames, as shown in Figure 3-1 left and right, respectively. For tall buildings, concrete and steel braced frames are also the preferred LLRS in high-seismic zones, whereas others LLRS are mostly used in low seismic, or wind governed zones given their limited ductility and energy dissipation capabilities.


Figure 3-1: LLRS with concrete core – photo credit Hercend Mpidi Bita (left); and with steel braces – Photo credit Omer Mohammed (right)

3.2 Gravity Load-Resisting System (GLRS)

The gravity load resisting systems (GLRS) for mass timber hybrid buildings are typically wood-based: i) post and beam with floor system, see Figure 3-2-top, ii) flat-slab or point-supported system, see Figure 3-2-middle, and iii) loadbearing wall and floor system, see Figure 3-2-bottom.

Figure 3-2: Typical GLRS: Post and beam system (top); point-supported system (middle); and load bearing wall system (bottom) – Photo credit Hercend Mpidi Bita

The post and beam system may be composed of glulam posts and beams, glulam posts and steel beams, or steel beams and glulam posts. This system is popular for residential and office buildings with a structural grid system that has the main span from 15' to 30' (4.5m-9.0m), i.e., span of the beams, and the secondary span from 10'-25' (3.1m-7.6m), i.e., span of the CLT panels on top of the beams. Secondary beams or purlins between the main beams or girders are often utilised to reduce the span of the CLT panels, resulting in thinner CLT sections.

The flat-slab system is typically composed of CLT floor panels simply supported on columns. No beams are required as the CLT panels sits directly on the columns. Consequently, the main column spacing is limited to the maximum span of the CLT panels, typically from 20'-25' (6.1m-7.6m) depending on the thickness. In this system, the column spacing in the perpendicular direction is limited by the maximum width of CLT panels, which is between 10'-12' (3.1m-3.7m) depending on the CLT manufacturer. Consequently, point-supported systems are typically used for residential building that can accommodate loadbearing elements at a maximum 12' (3.7m) spacing. Novel connection systems and technologies, such as spider or pillar connections (Rothoblass, 2021) and Timber Structures 3.0 (TS3, 2021), can be utilised to extend this spacing limit up to 25' (7.6m).

The loadbearing wall and floor system is dominated by mass timber floor systems on light-wood framing walls or mass timber walls. For this system, walls may run in both directions to support the floor and creates a redundant system, with limited open space and flexibility for future office layout changes or updates. The location of the walls is governed by the maximum span of the CLT panels unless additional supporting beams are considered.

4 CLT/CFS System

4.1 Cold-Formed Steel (CFS)

Cold-Formed Steel (CFS) systems are composed of floor or wall components. The CFS panels are repetitive steel studs, typically spaced at 24” (610mm) on centre, with steel tracks on top and bottom, as shown in Figure 4-1-left. When forming a system of floors and walls, the latter are typically placed on a 12’-20’ (3.7m-6.1m) grid spacing. Figure 4-1-right illustrates typical connection detail for CFS system with CFS wall and floor used in platform-type construction, where the walls span a single storey with floors directly placed on top to act as a platform for the next wall above.

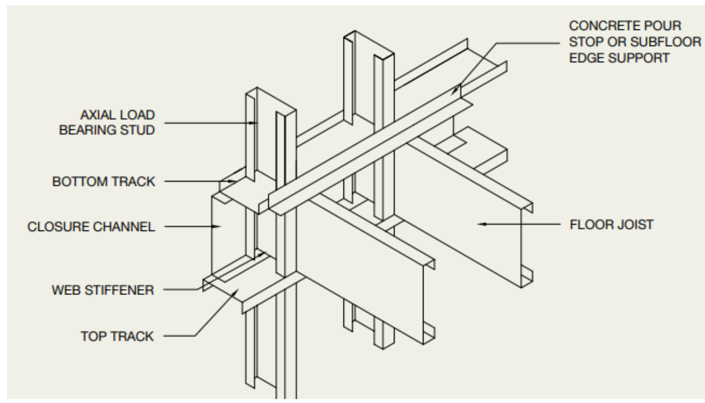


Figure 4-1: CFS system in platform-type construction (left) (summitdb.com, 2021) and schematic detail for platform-type construction (right) (Cssbi, 2002)

The idea of using CFS system with floor and wall panels has existed since the late 19th century and was adopted in the US building code after the first design guidelines in 1946 (Madsen et al, 2016). Because CFS panels are composed of several thin pieces that are both lightweight and easy to handle, their application in building was facilitated by ‘panelisation’ where the individual panels or framings were assembled with all components and shipped to site ready for installation. Over the past years, CFS framing has been successfully used in different construction applications from non-structural partitions, ceiling and external cladding to loadbearing walls and floors parts of the GLRS and/or LLRS.

Compared to other conventional concrete and steel systems, the following are the key advantages of CFS systems (Madsen et al, 2016) :

- Structurally, CFS systems are lightweight which result in buildings with lower seismic weights and savings in foundations.
- CFS panels are non-combustible and can achieve the required fire rating with an addition of layer(s) of gypsum boards.
- Architecturally, CFS systems offer a uniform wall layout in plan with almost no visual difference between non-loadbearing and loadbearing walls.
- CFS walls do not require fire stops, sheathing, house wrap, gypsum wallboard or separate steps for insulation and continuous insulation.
- CFS system is an established construction type, with durable and sustainable structural components that are repetitive, easy to handle, and easy to install given their construction tolerance.
- CFS panels are prefabricated structural components, which include all wall and floor components as well as openings.
- For long-term performance, CFS systems are dimensionally stable, with no significant long-term deformations.

4.2 CLT/CFS as Hybrid Mass Timber System

A first-of-its-kind hybrid mass timber structural system with cold-formed steel (CFS) walls and cross-laminated timber (CLT) floors, also referred to as a CLT/CFS system, was developed by structural engineers with Timber Engineering Inc. during their time at Katerra Technology Canada. The CLT/CFS system was found to be a cost-effective and structural efficient solution for buildings with 7 to 12 storeys. Figure 4-2 illustrates schematically the CLT/CFS system assembly. The floor system is composed of CLT panels directly supported on CFS walls. This system is a platform-type construction, where the floor panels are sandwiched between two consecutive single storey walls as they act as a platform for the next immediate storey.

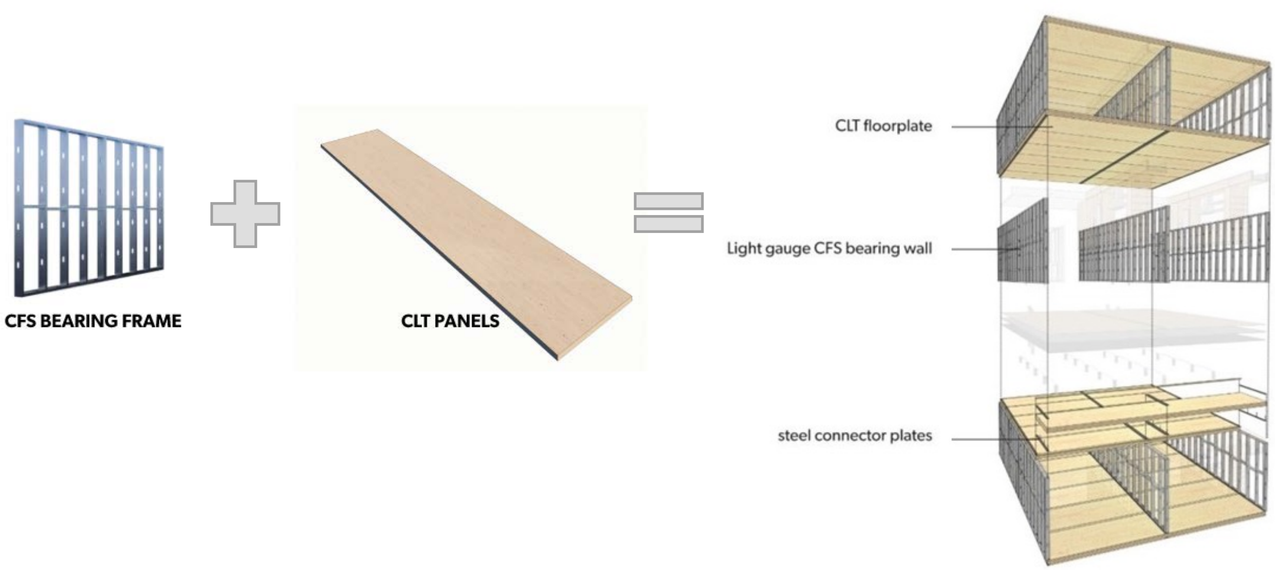


Figure 4-2: Novel CLT/CFS system

To maximise the structural performance for both CLT floor panels and CFS walls, the GLRS of the novel CLT/CFS system uses CFS walls typically spaced at 12’ (3.7m) on centre to support double or triple-span continuous CLT floor panels, as shown in Figure 4-3-top. The design is not only governed by the maximum allowable span of the CLT panels in terms of serviceability limit states and fire performances, but also by the allowable sizes and spacings of the steel studs within the CFS walls. Just like conventional 7-12 storey hybrid mass timber buildings, cost-effective LLRS of the novel CLT/CFS may be concrete core or steel braces (as shown in Figure 4-3-bottom), for buildings located in high seismic zones, or conventional wood or steel braced frames or concrete or mass timber shear walls for low seismic or wind-governed zones.

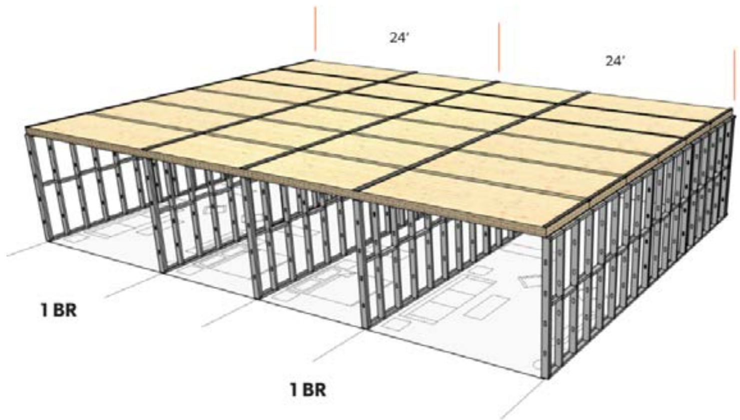
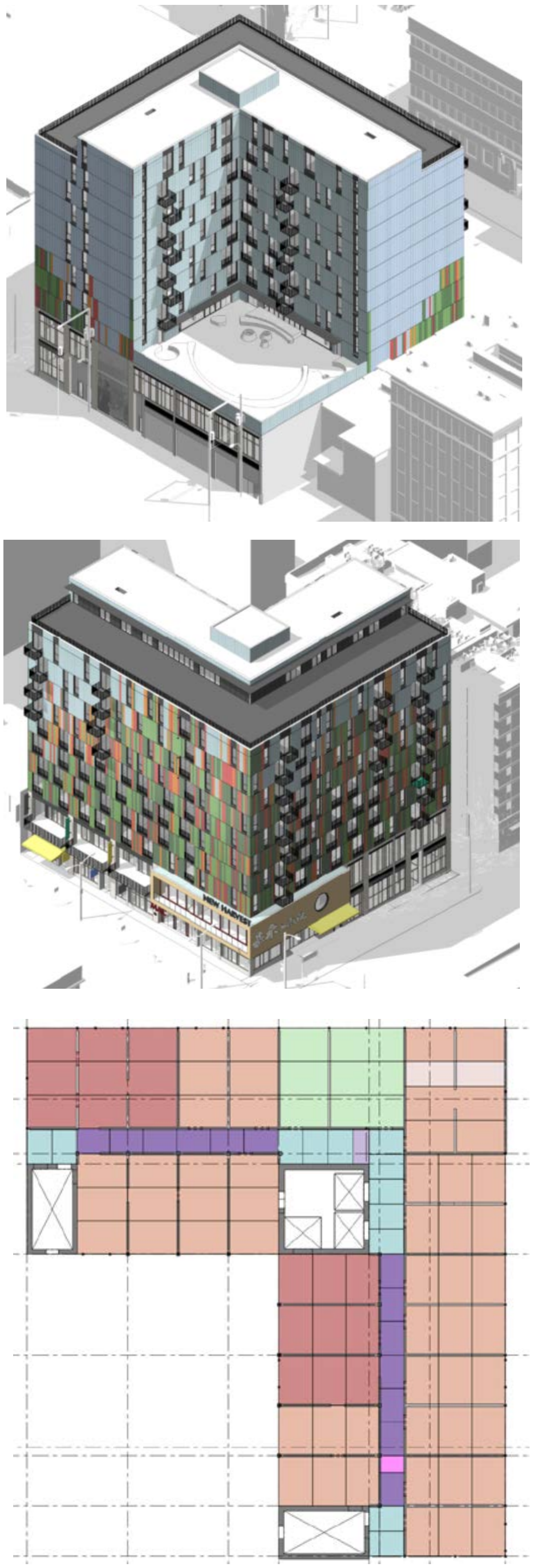


Figure 4-3: Novel CLT/CFS: GLRS (top); and LLRS steel braced frame and GLRS CLT/CFS (bottom)

4.3 Example Building



The MAC building shown in Figure 4-4, currently under design, will be located in Vancouver, British Columbia, Canada. The architects on the project are Marianne Amodio and Harley Grusko Architects Inc. and EskewDumezRipple. The new 11-storey hybrid mass timber building will be approximately 120’ (36.5m) tall and contain approximately 15,855sf (1,473m^2) of developed area. The building will be mixed-used occupancy type, consisting of nine (9) storeys residential use, over two (2) storeys mixed-used commercial, office and residential use, over one (1) level underground parking and storage. The building will have an L-shape at residential levels and will be mostly rectangular below the podium level, i.e., transition slab from mass timber residential to concrete mixed-used located at Level 03.

The novel CLT/CFS system is seen as the ideal structural system for the GLRS of the 9-storey residential building given the planned structural layouts and elevations. The loadbearing CFS walls will be placed at 12’ (3.7m) on centre maximising the structural performance of both CLT floor panels and CFS walls with respect to the thickness of the mass timber panels required for up to 2h fire rating, and size and spacing of the CFS wall studs. As platform-type construction, the CFS walls line up from the roof to the concrete transfer slab at Level-03. Figure 4-4-bottom shows the CLT panel layout with minimum double-span continuous CLT panels running on top of the single-storey CFS walls.

The LLRS is composed of three (3) concrete cores that also serve as elevators and stairs. All three cores will run uninterrupted from roof to foundations. Lateral forces due to wind and seismic events will be carried by CLT floor and roof diaphragms at the residential levels (Level 04 to roof), and concrete slabs from Level 03 below, before being transferred to the cores and subsequently the foundations. The elevation and floor plan in Figure 4-4 show a simple and repetitive structural system. This will ultimately result in clear and simple load-paths for both gravity and lateral loads.

Figure 4-4: MAC Building: Isometric SW view (top) and NE view (middle); and typical floor plan with panel CLT layouts (bottom)

5 Advantages of the CLT/CFS Hybrid Mass Timber System

5.1 Structural Performance

The main structural advantage of the CLT/CFS system in 7-12 storey buildings is its simplicity. The structural efficiency of the system enables clear, simple, and direct load paths for gravity loads where the forces are transferred from the top or roof level to the lowest levels or foundation through lined-up loadbearing CFS walls. The CFS walls in plan can either be straight or follow the architectural layout, provided they are stacked up at all levels. These direct load-path provide a cost-effective solution as no transfer elements are required.

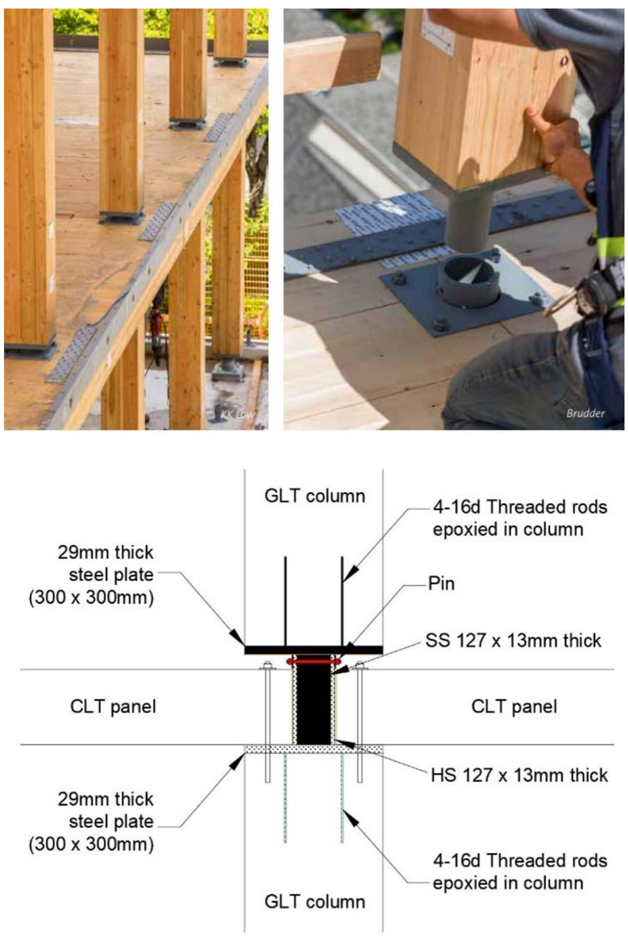


Figure 5-1: Brock Commons Tallwood House: Column-to-column connection: Photos (Top) (naturally:wood, 2017); and schematic representation of the connection components (bottom) (Mpidi Bita and Tannert, 2018)

The novel CLT/CFS system typically use 12' (3.7m) spacing between the CFS walls. In other words, this layout is cost-effective for residential buildings with micro-units, as shown in Figure 4-4-bottom for the MAC building in Vancouver. The CLT/CFS system has a significant structural advantage over other mass timber structural systems that could be proposed for this application, such as the point-supported system (Figure 3-2-middle). In a point-supported system with columns supporting the CLT panels at minimum every corner, column-to-column connections such as shown in Figure 5-1-top would be required not only to provide sufficient bearing for the CLT panels but also to allow the direct load transfer from the column above to the column below. Figure 5-1-top shows the schematic representation of the column-to-column connections, which add up to the overall connection costs and ultimately the project costs, compared to the CLT/CFS system where the loads are applied as a line load. Alternative connections, such as spider or pillar connections (Rothoblass, 2021), would not be cheaper. The advantage of the CLT/CFS system is that such expensive connection details would not be required given that the forces are applied as a line load.

Another structural advantage of the novel CLT/CFS system is the high strength-to-weight ratio of the CFS loadbearing walls. As mentioned in section 3.1, CFS walls are lightweight which result in buildings with low seismic weight and foundation loads. This results in savings on seismic structural requirements for the LLRS, including the connections, as well as a cost saving for foundations.

5.2 Fire and Acoustic Performances

Since CFS wall panels would meet the code requirements for non-combustible construction, the overall area of exposed combustible structural components is reduced in the CLT/CFS system. Design guidelines for CFS system (SFA, 2013; CSSBI, 2002) demonstrate the fire rating performance of CFS systems. Depending on the layers of gypsum board on both faces, CFS loadbearing walls can achieve a fire resistance rating (FRR) of up to three (3) hours. Figure 5-2 shows a typical wall assembly for a 2-hour FRR achieved with two layers of gypsum boards, e.g., 5/8” (15.9mm) Type X gypsum board, on each side of the panel. For CLT panels, the fire performance can be quantified as per CSA-O86 (CSA, 2014) or alternatively based on the CLT manufacturer’s fire tests.

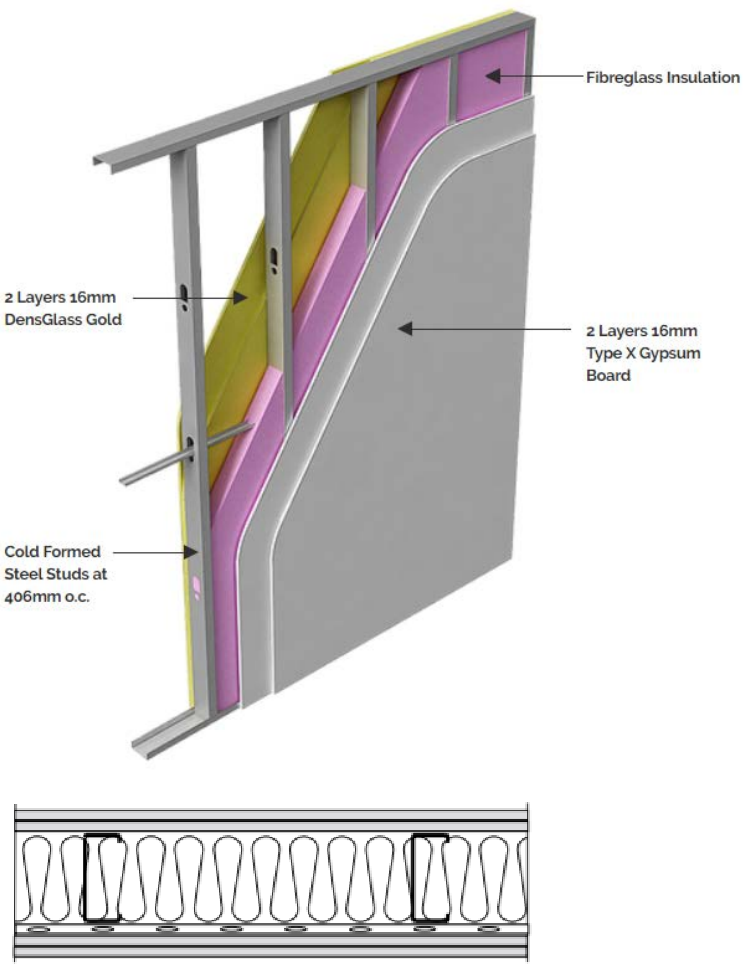


Figure 5-2: CFS loadbearing wall assembly (SFA, 2013; CSSBI, 2002)

The building code (NBCC, 2015) requires that separations between dwelling units be designed for a sound transmission class (STC) rating of 50, typically. Design guidelines for CFS (SFA, 2013; CSSBI, 2002) demonstrate that such rating can be achieved with CFS systems. The CFS loadbearing wall assembly shown in Figure 5-2, with three 3 5/8” (90mm) thick fiber glass insulation, can achieve an STA of 50. For the CLT floor panels, a floor build-up that uses 2” (50mm) concrete/gypcrete topping on 1” (25mm) insulation on CLT floor panel may be considered to meet acoustic requirements.

5.3 Prefabrication

For the past decade, the building construction industry has been shifting toward full prefabrication as a solution for a smarter, faster, and safer project delivery, compared to conventional on-site construction or assembly. Just like CLT panels, CFS construction is also panelised, and mass produced. The novel CLT/CFS system is therefore composed of structural components that are repetitive, lightweight, easy to handle, that can be panelised off-site and brought to site as shown in Figure 5-3-top and bottom for CLT floor panel and CFS wall, respectively. Both CLT and CFS panels are produced in controlled manufacturing environments; they can be prefabricated with exceptional precision to minimise on-site waste and achieve superior coordination to improve erection time and minimise on-site defects and fixings. While holes and cuts can easily be made in CLT panels, CFS walls are manufactured with regularly spaced holes within the studs that can accommodate electrical and plumbing lines (Figure 5-3-bottom). This would ultimately speed up MEP installation in the building.

Both CLT and CFS panels allow choice in surface finishes to achieve the desired aesthetics for project. The complete CFS wall assembly with insulation, gypsum board and all surface finishes, as shown in Figure 5-2, can therefore be prefabricated and brought to site for faster installation. This brings considerable cost reductions compared to other structural mass timber systems, such as a point-supported system, where the columns at the wall line between the units needs to be covered with non-loadbearing walls, to meet both fire and acoustic performances. In addition, the CLT/CFS system with a typical spacing between CFS walls, e.g., 12’ (3.7m) as for the MAC building in Figure 4-4-bottom, would result in less waste because CLT master panels are typically produced at 36’, 42’, 48’, 54’ and 60’ (11m,12.8m, 14.6m, 16.5m, 18.3m).

Figure 5-3: Panelisation of CLT/CFS structural components: CLT floor panel (top) – Photo Credit Katerra; and CFS wall (Walltechinc, 2021)

5.4 Construction Sequence

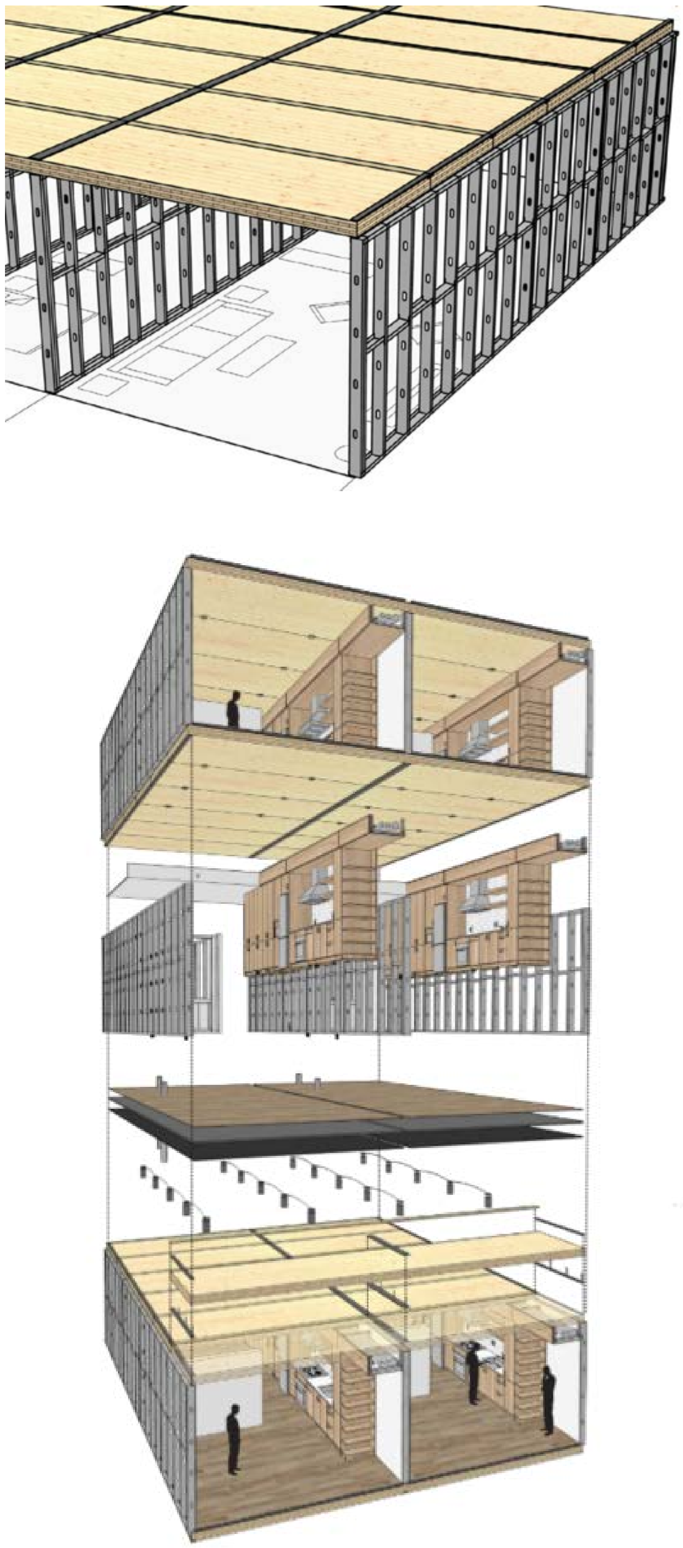


Figure 5-4: CLT/CFS platform-type construction

As mentioned in section 4.1, CFS systems are typically constructed in a platform-type construction, where the floor panels act as a platform for the next level, as the walls only span between two consecutive floor levels. Platform-type construction is also well implemented in mass timber construction where buildings such as the Redstone Arsenal Hotel (WoodWorks, 2016) and Origine (Nordic Structures, 2018) are prominent North American examples.

The novel CLT/CFS system follows the same construction type, with all continuous CLT panels directly placed on top the CFS loadbearing walls, as shown in Figure 5-4, to allow for the installation of the level above. This is a repetitive construction sequence from the bottom to the top floor/roof level. Since the CLT/CFS is a GLRS only, the LLRS components such as concrete cores or steel braces are typically constructed or installed either before or together at the same time as the CLT/CFS. Single storey CFS walls eliminate the requirements for large temporary braces during construction. This repetitive construction type enables a faster installation time as the same tools and installation approaches are used for all levels, reducing the need for special requirements at specific levels.

6 Structural Design of CLT/CFS GLRS

The calculations and design procedures presented in this section are for preliminary sizes and should not be interpreted as a unique solution for CLT/CFS system. A detailed analysis and design of the whole system should be performed and/or checked by a Licensed Professional engineer.

6.1 Applied Gravity Loads

This section presents preliminary analysis and design thoughts for CLT/CFS systems. The presented calculations apply to the 11-storey MAC building, previously described in section 3.3. Nonetheless, focus is only given to the CLT/CFS system as the GLRS of the top nine storeys above the concrete podium (Level 03). Figure 6-1 and Figure 6-2 show the building plan at the typical residential level with CLT/CFS system as GLRS above the concrete podium, and the overall building section, respectively. For the purpose of this report, the considered applied gravity loads are given in Table , i.e., the superimposed dead loads (SID), live loads (LL), and snow loads (SL), are for the ultimate limit state design loads on the CLT floor panels, CFS walls, and the connections between the structural members. The general designs are based on NBCC-2015, which refer to the CSA-O86 (CSA, 2019) and the AISI S100-16 (ANSI, 2016) for the design of CLT and CFS members, respectively.

Table 6-1: Applied gravity loads

Location	Type	LL (kPa)	SID (kPa)	SL (kPa)
Typical floors	Residential	1.9	2.4	-
Roof	Roof level	1.0	1.0	-
	Snow loads	-	-	1.82

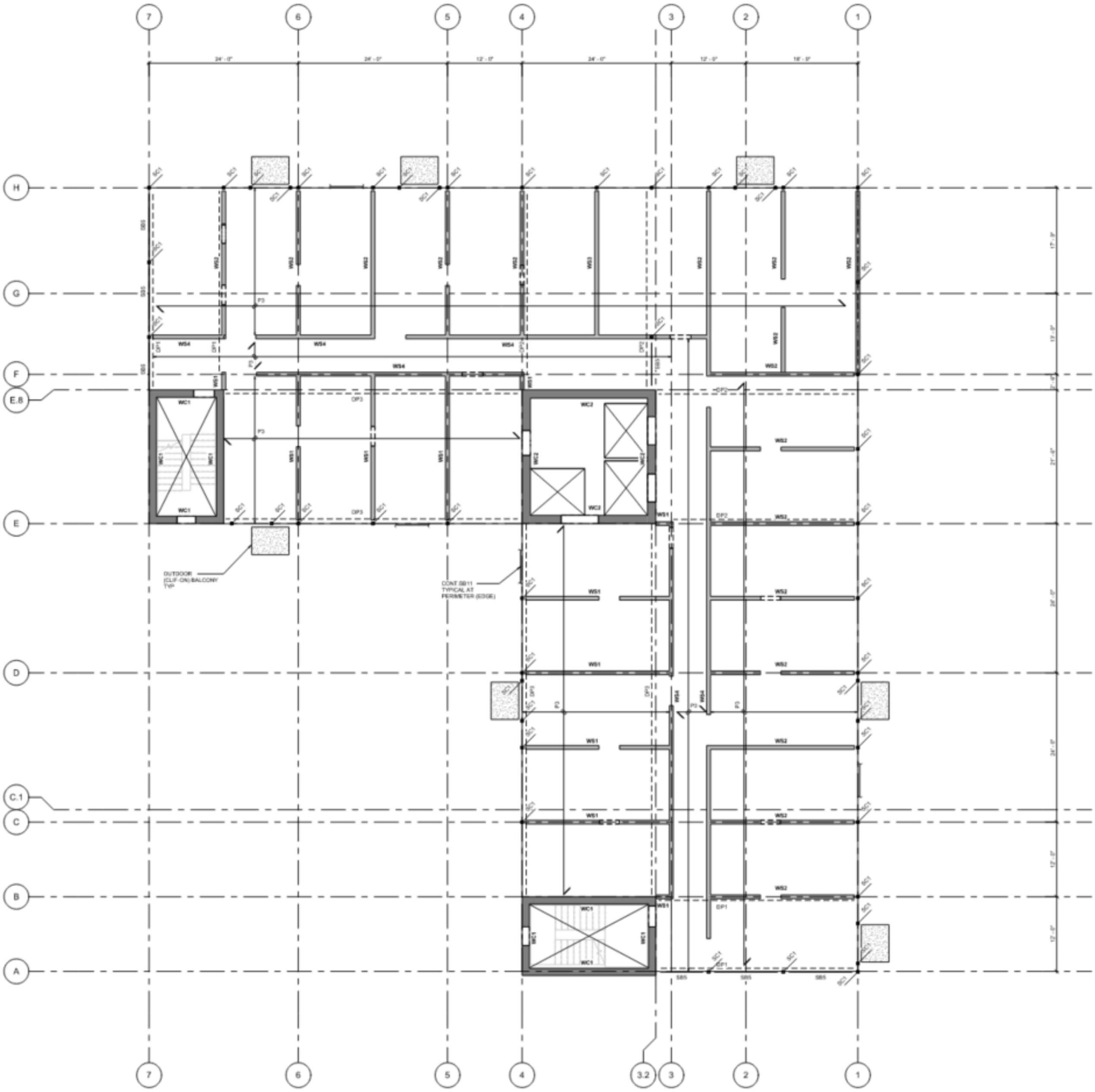


Figure 6-1: Typical floor plan for 11-storey MAC building, Vancouver, Canada

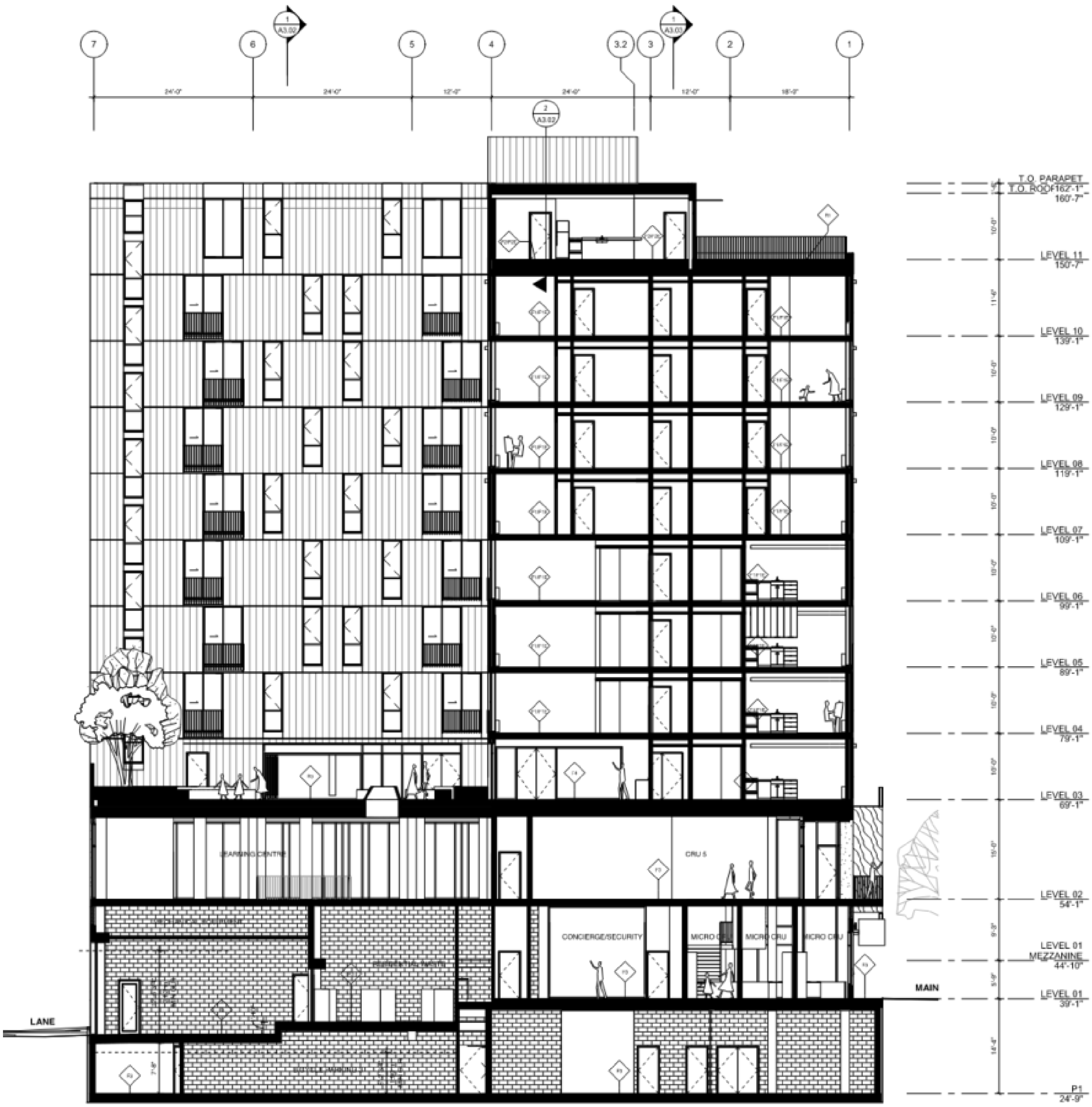


Figure 6-2: Section for 11-storey MAC building, Vancouver, Canada

6.2 CLT Floor Panel Design

The CLT panels are designed as per the CSA-O86 (CSA, 2019), using Woodworks Sizer software (Woodworks, 2020). The CLT panels are 5ply 6 7/8" (175mm), V2-grade per PRG-320, continuous minimum double-span, with supports at 12' (3.7m) on centre. 12.7mm thick Type X gypsum board may be required to achieve 2h FRR under the given loads and CLT span. Alternatively, better stress grade or thicker CLT panels may be proposed for 2h FRR.

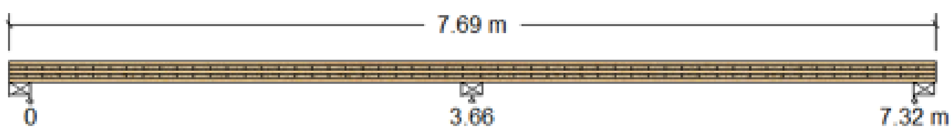
Design Check Calculation Sheet

WoodWorks Sizer 2020 (Update 2)

Loads:

Load	Type	Distribution	Pattern	Location [m] Start	End	Magnitude Start	End	Unit
DL	Dead	Full Area	No			2.40(1.00m)		kN/m2
LL	Live	Full Area	Yes			1.90(1.00m)		kN/m2
Self-weight	Dead	Full UDL	No			0.72		kN/m

Maximum Reactions (kN), Bearing Resistances (kN) and Bearing Lengths (mm) :



CLT Floor Panel, S-P-F, V2, 5 Layers 175 mm (1000 mm width)

Supports: All - Timber Beam, No.2

Total length: 7.689 m; Clear span: 3.6, 3.6 m; Volume = 1.346 m^3 / m; Panel orientation: Longitudinal axis

Exposed to fire on one b-face; Req'd duration: 2 hrs; Protection: 12.7 mm Type X gypsum board

This section PASSES the design code check.

Force vs. Resistance and Deflection using CSA O86-19:

Criterion	Analysis Value	Design Value	Unit	Analysis/Design
Shear	Vf @d = 13.46	Vr,f = 46.84	kN	Vf/Vr,f = 0.29
Moment(+)	Mf = 7.46	Mr,f = 35.15	kN-m	Mf/Mr,f = 0.21
Moment(-)	Mf = 10.74	Mr,f = 32.80	kN-m	Mf/Mr,f = 0.33
Perm. Defl'n	1.3 = < L/999	15.3 = L/240	mm	0.09
Live Defl'n	1.2 = < L/999	10.2 = L/360	mm	0.11
Total Defl'n	2.5 = < L/999	15.3 = L/240	mm	0.16
Vibration	Lmax = 3.660	Lv = 6.170	m	Lmax/Lv = 0.59
Fire				
Shear	Vf @d = 10.47	Vr,f = 48.30	kN	Vf/Vr,f = 0.22
Moment(+)	Mf = 5.48	Mr,f = 13.70	kN-m	Mf/Mr,f = 0.40
Moment(-)	Mf = 7.99	Mr,f = 13.70	kN-m	Mf/Mr,f = 0.58

6.3 CFS Wall Panel Design

The CFS walls are designed as per the AISI S100-16 (ANSI, 2016), using CFS Designer by Simpson Strong-Tie (Simpson Strong-Tie, 2020). Table 6 gives the applied loads, i.e., SL, DL, and LL, on top of the CFS wall studs, as well as the sizes and spacings of the studs for every levels. It is worth noting that the calculations, performed using the loads given in Table , conservatively accounted for the continuity of the CLT floor panels on top of the CFS walls at every level by multiplying the tributary widths of the wall by 1.25. The height of all studs was assumed as 10’ (3.1m), and the yield strength of the studs are taken as 50ksi (340MPa). For local stability, all studs were assumed to be braced at mid-point.

Table 6-2: Sizes and spacing of CFS wall studs per level

Level	SL kN/m	DL kN/m	LL kN/m	Studs [-]	Spacings (mm)
Roof	8.32	8.18	4.57	600S137-54	600
Level 11	8.32	24.73	13.26	600S162-97	600
Level 10	8.32	41.29	21.95	600S200-97	600
Level 09	8.32	57.84	30.63	600S200-97	400
Level 08	8.32	74.39	39.32	600S200-97	400
Level 07	8.32	90.94	48.01	600S250-97	400
Level 06	8.32	107.49	56.69	600S350-97	400
Level 05	8.32	124.04	65.38	600S162-97 (B2B)	400
Level 04	8.32	140.59	74.07	600S162-97 (B2B)	400

All stud sizes are given in a format “depth of the web” – “Style of the member” -” flange width” – “thickness in Mil (1/1000 of an inch)”, e.g., 600S200-97 are 6” deep studs with 2” wide flange and 97mils thickness. Based on Table 6, all CFS walls were 6” (152mm) wide corresponding to the depth of the studs. From Table 6, all studs were single C-section as shown in Figure 6-3-left. The design shows that the sizes of the CFS studs increase lower down in the building, i.e., the sizes increase as the loads increase. Furthermore, to keep the sizes of the studs reasonable and practical, the spacing between them also varies. Based on the provided spacing, single studs can be used until Level 06. From Level 05 and Level 04, double back-to-back (B2B) C-section studs, as shown in Figure 6-3-right, are preferred as spacing smaller than 400mm becomes unpractical for the application and concept of the CLT/CFS system as explained later in section 7.

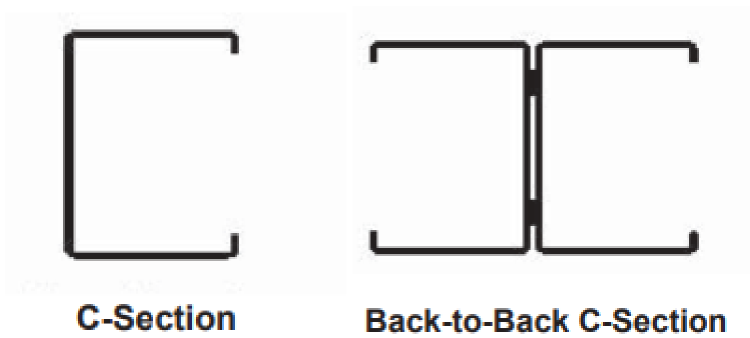


Figure 6-3: Section of CFS studs; C-Section (left);
and back-to-back C-section (right) (NAHB, 2003)

6.4 Building Vertical Movements

Possible vertical building movements, e.g., shrinkage, elastic, and creep deformations of the CLT floor panels, are major design considerations for buildings in platform-type construction. In this construction type, at every level, the floors are sandwiched between the consecutive walls above and below. Without additional detailing considerations, shrinkage, elastic, and creep deformations would cumulate for all levels resulting to not only in additional stresses on the structural components and connections, but also create serviceability limit state issues with excessive deformations that may cause problems to nonloadbearing components. In addition, wood materials are subjected to compression perpendicular (Compression Perp.) to the grain. When added to the elastic and creep deformation, the loaded CFS studs can punch through the bottom track of the wall which in return might result in unevenly distributed loads on CFS studs within a wall.

Previous projects and research on CFS systems, as mentioned in section 4.1, demonstrated that this system is dimensionally stable with no significant deformations over time. In other words, CFS walls would undergo negligible creep and elastic deformations, and they would not lead to significant shrinkage issues due to change in moisture content like wood. Therefore, major vertical building movements would result from the CLT floor panels. The following calculations illustrates how the vertical building movements of CLT panels could be estimated.

6.4.1 Check for Compression Perp.

The following calculations shows how the demand to capacity ratio (DCR) for the compression perpendicular to the grain of the CLT floors at Level 04, worst-case loads, would be estimated. The obtained DCR=50% shows that the panels were okay with respected to the applied loads from the individual studs.

$DL_{04} := 124.04 \frac{kN}{m} = 8.5 \frac{kip}{ft}$ Applied dead loads @ Floor Level 04

$LL_{L04} := 65.38 \frac{kN}{m} = 4.48 \frac{kip}{ft}$ Applied live loads @ Floor Level 04

$SL_{L04} := 65.38 \frac{kN}{m} = 4.48 \frac{kip}{ft}$ Applied snow loads @ Floor Level 04

$Spacing := 400\ mm = 16\ in$ Spacing between studs @ Wall Level 05

$\ell_{bearing} := 6\ in = 152.4\ mm$ Width of the CFS Studs

$A_b := \ell_{bearing} \cdot Spacing = 0.06\ m^2$ Bearing area of the studs @ Level 05

$P_{SD} := \left(1.25 \cdot DL_{04} + 1.5 \cdot LL_{L04} + 1.0 \cdot SL_{L04}\right) \cdot Spacing = 127.4\ kN$ Applied design loads @ studs @ wall Level 05

$f_{cp} := 5.3\ \text{MPa} = 768.7\ \text{psi}$

Compression perpendicular to the grain for CLT floor panel per CSA-O86

$k_i := 1.0$

CSA O86 modification factors

$K_{Zcp} := 1.0$

CSA O86 size factor for bearing

$K_B := 1.0$

CSA O86 length of bearing factor

$Q_r := 0.8 \cdot \left(f_{cp} \cdot k_i\right) \cdot \left(A_b\right) \cdot K_B \cdot K_{Zcp} = 258.47\ \text{kN}$

Compression perpendicular to grain - bearing resistance

$DCR_{c90} := \dfrac{P_{SD}}{Q_r} = 50\ \%$

Demand to capacity ratio for compression perpendicular to the grain of the CLT floor panel

6.4.2 Check for Elastic and Creep Deformations

The following calculations shows how the elastic and creep deformations on the CLT floor panels could be estimated. This is done for Level 04 only, considering it as the worst-case scenario.

$t_{CLT} := 175\ \text{mm}$ Thickness of CLT panel

$b := Spacing = 400\ \text{mm}$ Spacing between the studs

$K_{creep} := 2.0$ Creep coefficient

$E_{eff.f} := 9000\ \text{MPa} = 1.31 \cdot 10^{6}\ \text{psi}$ Assume the minimum E-modulus for the CLT floor (Conservative)

$DL := DL_{04} \cdot b = 11.15\ \text{kip}$ Applied dead loads

$LL := LL_{L04} \cdot b = 5.88\ \text{kip}$ Applied live loads

$$\sigma_{y.f} := \left(\left(\frac{DL}{t_{CLT} \cdot b}\right) \cdot K_{creep}\right) + \left(\frac{LL}{t_{CLT} \cdot b}\right) = 1.79\ \text{MPa}$$

Applied long-trerm stresses

$$\Delta L_{f.creep} := \frac{\sigma_{y.f} \cdot t_{CLT}}{E_{eff.f}} = 0.03\ \text{mm}$$

Total elastic/creep deformations

6.4.3 Check for Shrinkage Deformations

Depending on the moisture content (MC) wood members undergo dimensional changes, i.e., swelling or shrinking when MC goes up or down, respectively. With time, the MC of wood comes to an equilibrium with the relative humidity of the air surrounding it, also known as equilibrium moisture content (EMC). When delivered to site, the MC of CLT panels can go up to 19%, depending on the manufacturer and regions where the project will be built. There may also be a difference in MC depending on season. However, when in service for a few years after the construction is completed, the EMC might go down to 6%-8% (CWC, 2011). In addition, the shrinkage percentage (%) depends on the wood species and the considered direction with respect to the grain of the wood member, e.g., higher shrinkage is observed in the tangential direction (Figure 6-4). The example project is in Vancouver dominated by a wet climate, and the delivered moisture content for this example was assumed to 19%, upper limit, whereas the EMC is taken as 8%. This resulted in about 6mm (1/4”) shrinkage for the CLT panel, at every floor level, per the calculations presented below.

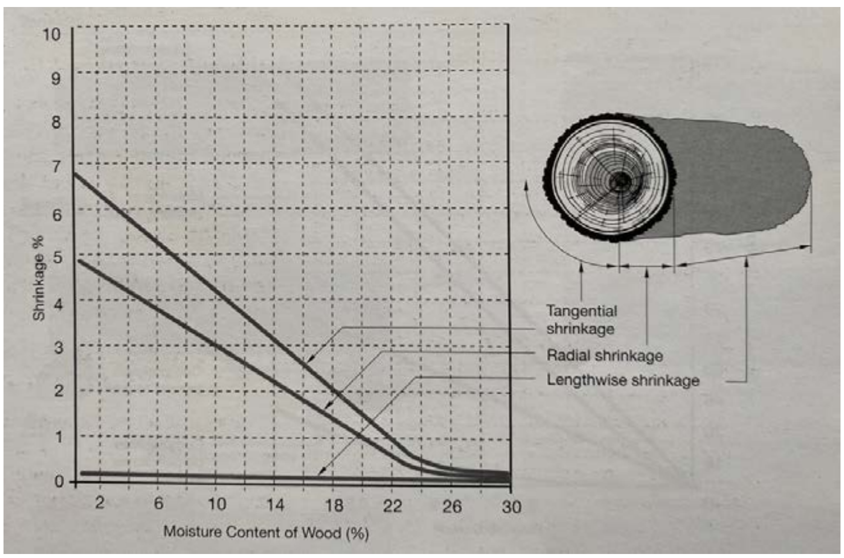


Figure 6-4: Graph giving shrinkage % based on MC of wood and considered direction with respect to the wood grain (CWC, 2015)

SHRINKAGE DEFORMATION

$MC_{actual} := 19$ Initial (delivered) Moisture content for CLT

$MC_{service} := 8$ Service Moisture content

$MC := MC_{actual} - MC_{service} = 11$

Shrinkage of floor

$c_{coeff.actual.floor} := 2.5$

Shrinkage % assuming Tangential

SEE Figure 5.5 (INTRODUCTION TO WOOD DESIGN)

$c_{coeff.service.floor} := 5.8$

ALSO SEE TABLE 5.2 (INTRODUCTION TO WOOD DESIGN)

FOR S-P-F

$c_{coeff.floor} := c_{coeff.service.floor} - c_{coeff.actual.floor} = 3.3$

$$\Delta L_{Shrinkage.floor} := \left(t_{CLT} \cdot MC \cdot \frac{c_{coeff.floor}}{1000} \right) = 6.4\ mm$$

$\Delta L_{Shrinkage.floor} = 0.25\ in$ Total shrinkage deformation

7 CLT/CFS Connection Detail

7.1 Structural Issue due to Vertical Movement

The calculations presented in section 6.4 demonstrated that the main issue contributing to vertical moments of CLT/CFS system in platform-type construction is the CLT panel shrinkage. At every level, shrinkage of the panel was estimated to 6mm (1/4”). It is worth noting that this is a differential shrinkage. In other words, the shrinkage movement is not a uniform, i.e., depending on season and location of the individual CLT panel, the EMC might be higher in some locations then others resulting to different shrinkage (%). For example, CLT panels placed at the perimeter of the building might have smaller shrinkage (%) then the inner CLT panels placed far away from the perimeter where the EMC can go all the way to the assumed 8% EMC.

The calculated shrinkage (%) was done for a single level only. If not dealt through appropriate detailing, the shrinkage movements would cumulate to all levels. For the considered 9-storey building, the total cumulated shrinkage would be 9 floors times 6mm = 54mm (2 ¼”), which would result to significant additional stresses on structural members and considerable damage to nonloadbearing elements if not addressed accordingly.

Therefore, the cost-effective solution would be to limit all vertical movements per floors and prevent accumulation at all levels. Section 6.2 shows existing details for mass timber buildings dealing with shrinkage and the other vertical movements for a building in platform-type construction. For the CLT/CFS system, section 6.3 shows possible details that address shrinkage issues as well as their pros and cons. Section 6.4 presents the ultimate and cost-effective solution as a novel connection detail for CLT/CFS systems, also proposed for the MAC building.

7.2 Existing Structural Details for Platform-type Construction

Multi-storey mass timber buildings in Europe with loadbearing CLT walls directly resting on CLT floors in platform-type construction have addressed the differential shrinkage, as well as the overall elastic, and creep deformations, by interrupting the CLT walls at every level. For the Newington Butts building in London, as shown in Figure 7-1-top, castellated wall solution was the preferred connection detail to limit all vertical movements per floor. The CLT wall and floor panels are cut in teeth, like finger joint, to allow the wall panels above to directly rest on the wall panels below without disturbing the CLT floor panels in between. In other words, this detail with elongation of the walls above and below the floor level provides direct load transfer between the walls, while CLT floor panel differential shrinkage could be contained within the floor level. Herein, issues related to possible compression perpendicular to the grain, as well as creep, and elastic deformations of the floors also became negligeable.

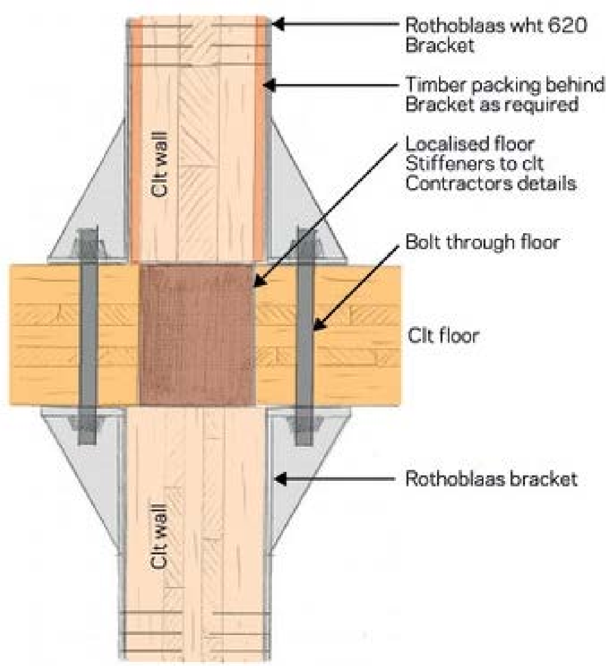


Figure 7-1: Castellated wall solution at Newington Butts, London, UK (StoraEnso, 2021) (Top); Concrete spacer at Dalston Lane, London, UK (Pearson, 2016) (Bottom)

Figure 7-1-bottom shows an alternative detail to the castellated walls, used for the Dalston Lane Building, in London. Concrete spacers were introduced within the CLT floor panels to act as a non-shrinkable material or a dimensional stable material where the loads from the wall above can be directly transferred to the wall below. This detail means that the concrete studs within the floor panels would act like short columns at every level to carry the loads from the CLT wall above to the CLT wall below, while the CLT floor panels in between can take all vertical differential shrinkage movements without restraints. As for the previous detail, compression perpendicular to the grain, creep, and elastic deformations of the floors also became negligeable.

7.3 Alternative Structural Details for CFS/CLT System

For the CLT/CFS system, the proposed Option 1 used self-tapping screws (STSs) as a reinforcement to transfer the load from the CFS wall above and below the CLT floors at every level. Figure 7-2 shows the detail as 150mm × 75mm × 6mm-12mm thick (6” × 3” × 1/4”-1/2”) steel plates, complete with 8Φ × 100 (5/16” Φ × 4”) STSs top and bottom of the CLT floor panel. The steel plates were added to prevent possible punching of the CFS studs on the CLT floors, as discussed in section 5.4, whereas the STSs were used as a reinforcement of the CLT panel at the location of the steel studs to enable direct load transfer between the consecutive CFS studs above and below the CLT floor panels. The steel plate could be either continuous, as shown in Figure 7-2-left, or discrete, only at the location of the studs, as shown in Figure 7-2-right.

The main advantage of this detail was its simplicity with respect to both for design and installation, where the steel plates might be pre-installed in the factory along with the CLT panels. On-site assembly and installation of the CLT/CFS system would be as for typical platform-type construction. Structurally, the thickness of the plate could be designed based on possible tolerances and alignment between the CFS studs at every level. The STSs would be designed as typical reinforcement perpendicular to the grain of the CLT panel, depending on the applied loads. Nevertheless, the main disadvantage was that the STSs only reinforce localised zones. Therefore, the main issue of differential shrinkage would not completely be addressed.

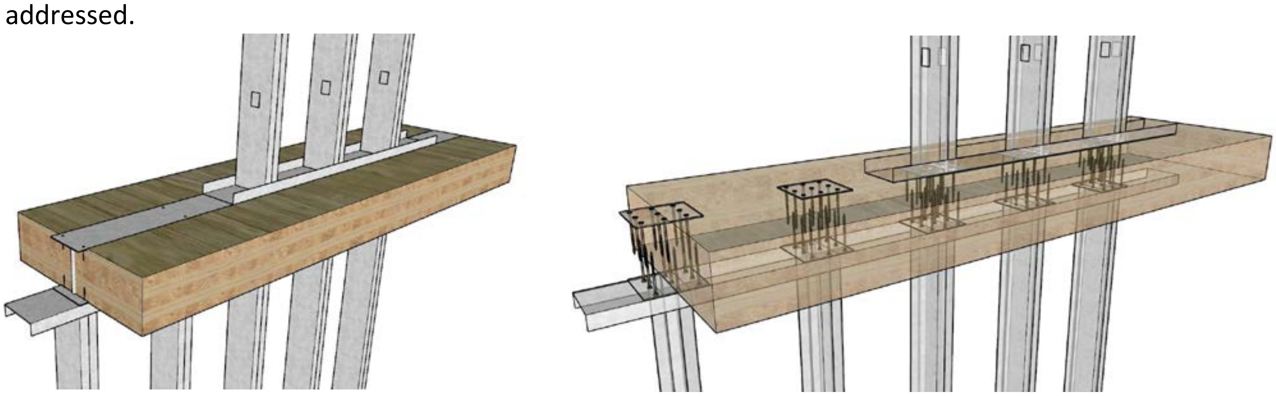


Figure 7-2: Option 1 - load transfer using STSs: continuous steel plate (left); and Discrete steel plates (right)

The proposed Option 2, as shown in Figure 7-3, considered using hardwood to transfer the load from the consecutive CFS walls above and below the CLT floor panels. Based on the applied loads at the lowest level, 150mm Φ (6" Φ) hardwood dowels would be required and placed directly under the CFS studs, e.g., at 400mm (16"). Steel plates on top and bottom of the CLT panels would still be required to not only prevent possible punching of the CFS studs on the wood dowels, but also to enable a uniform distribution of the loads on the CFS walls. When shrinkage occur on the CLT panels, the hardwood dowels which would have a much smaller shrinkage movement, would then be acting as short columns transferring the loads between the CFS walls and limiting all vertical movements within the individual levels.

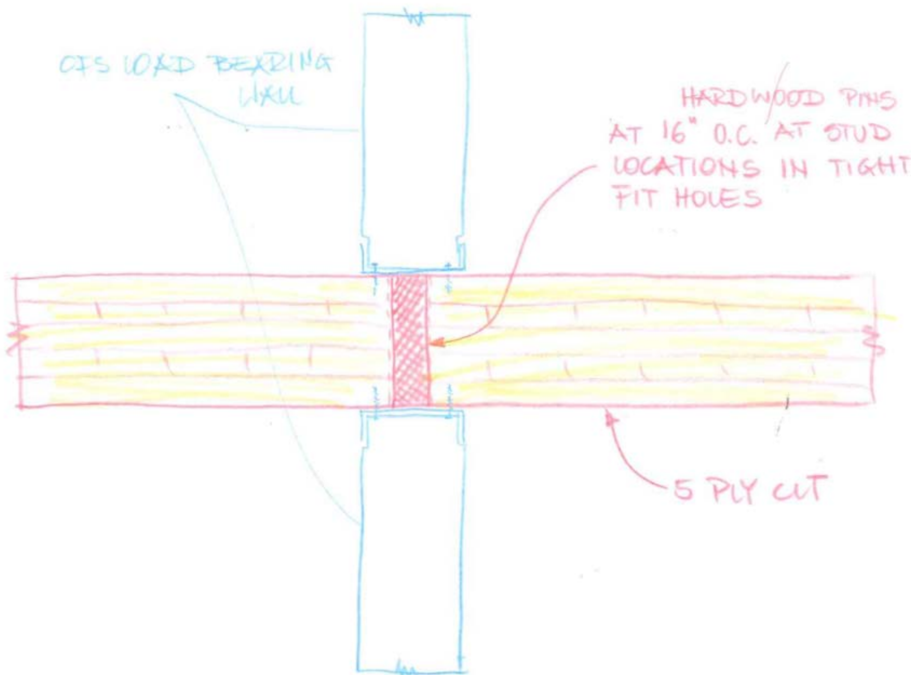


Figure 7-3: Option 2 - load transfer using hardwood dowels

Hardwood dowels are cost-effective off-the-shelf products that could be supplied locally. Just like CLT panels, the hardwood dowels improve the sustainability of the building, as discussed in section 2. Considering the installation sequence, the hardwood dowels would be tight fit within the CLT panels, whereas the steel plates can be pre-installed to the CFS wall tracks. Nevertheless, the main disadvantage is the low strength of hardwood, e.g., their compression strength parallel to the grain and modulus of elasticity. It was anticipated that beyond 150mm Φ (6" Φ), the hardwood dowel would become uneconomical, i.e., higher applied loads would require dowel with diameter bigger than the width of the CFS walls, as they would complicate fire detailing and could render the overall system more expensive.

The proposed Option 3 uses the same idea/principle as Option 2 by replacing hardwood dowels by concrete spacer as shown in Figure 7-4. This detail would be similar to the details used for Dalston Lane (see Figure 7-1-bottom), with the main difference being that the proposed connection detail in Figure 7-4 employs precast concrete rather than cast in-place concrete as used for the Dalston Lane. Herein, using the applied load at the lowest level, a 100mm Φ (4” Φ) concrete spacers would be required at every CFS studs (e.g., 400mm (16”) or 600mm (24”)). With pre-cast concrete, the spacers can be pre-installed and brought to site with the CLT panels. To prevent them from falling-off, the concrete spacers would be tapered, i.e., the top cross-section would be slightly bigger (125mm Φ or 5” Φ) than the required cross-section (100mm Φ or 5” Φ) at the bottom. A tape can be used to seal the concrete spacers from the top and prevent them from falling-off during transportation and construction. The steel plate at top and bottom of the CLT panels, which would allow a uniformly distributed loads on the CFS walls, could therefore be pre-assembled with the CFS walls at the factory, just as proposed for the previous options.

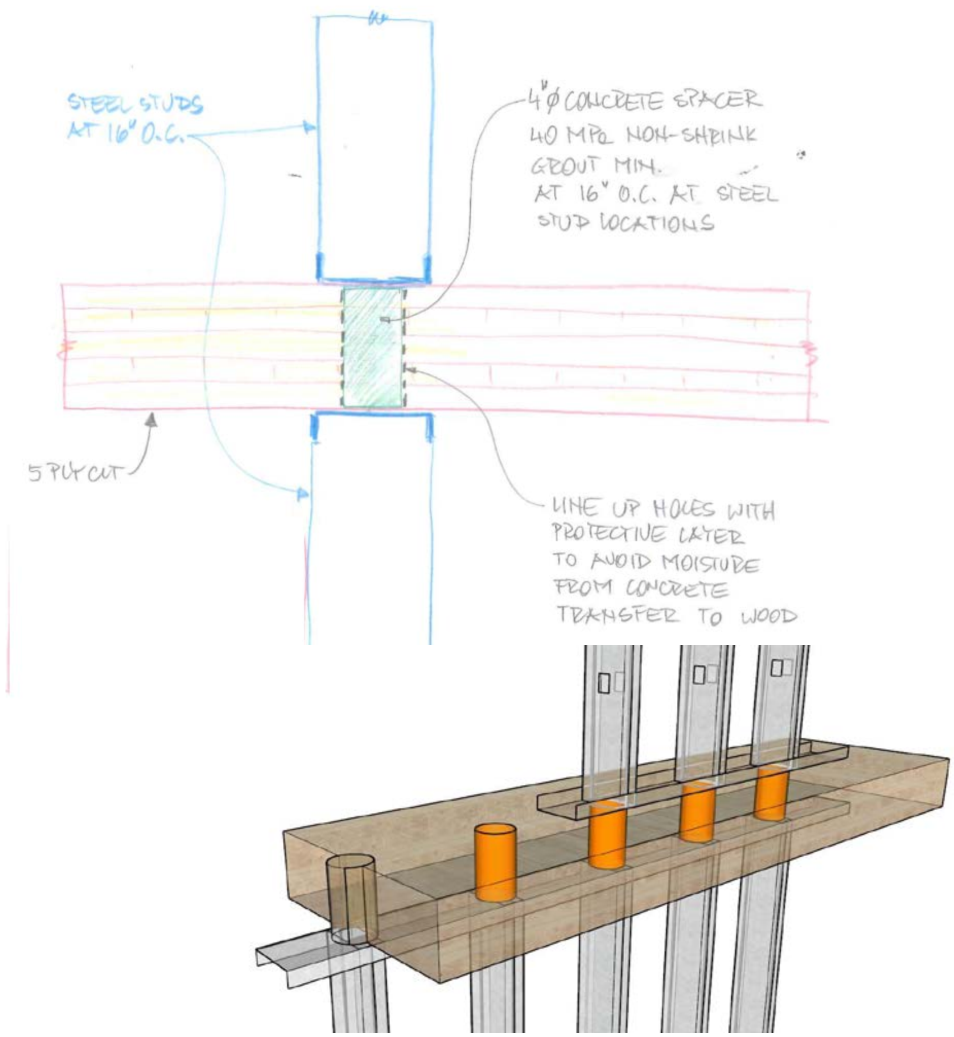


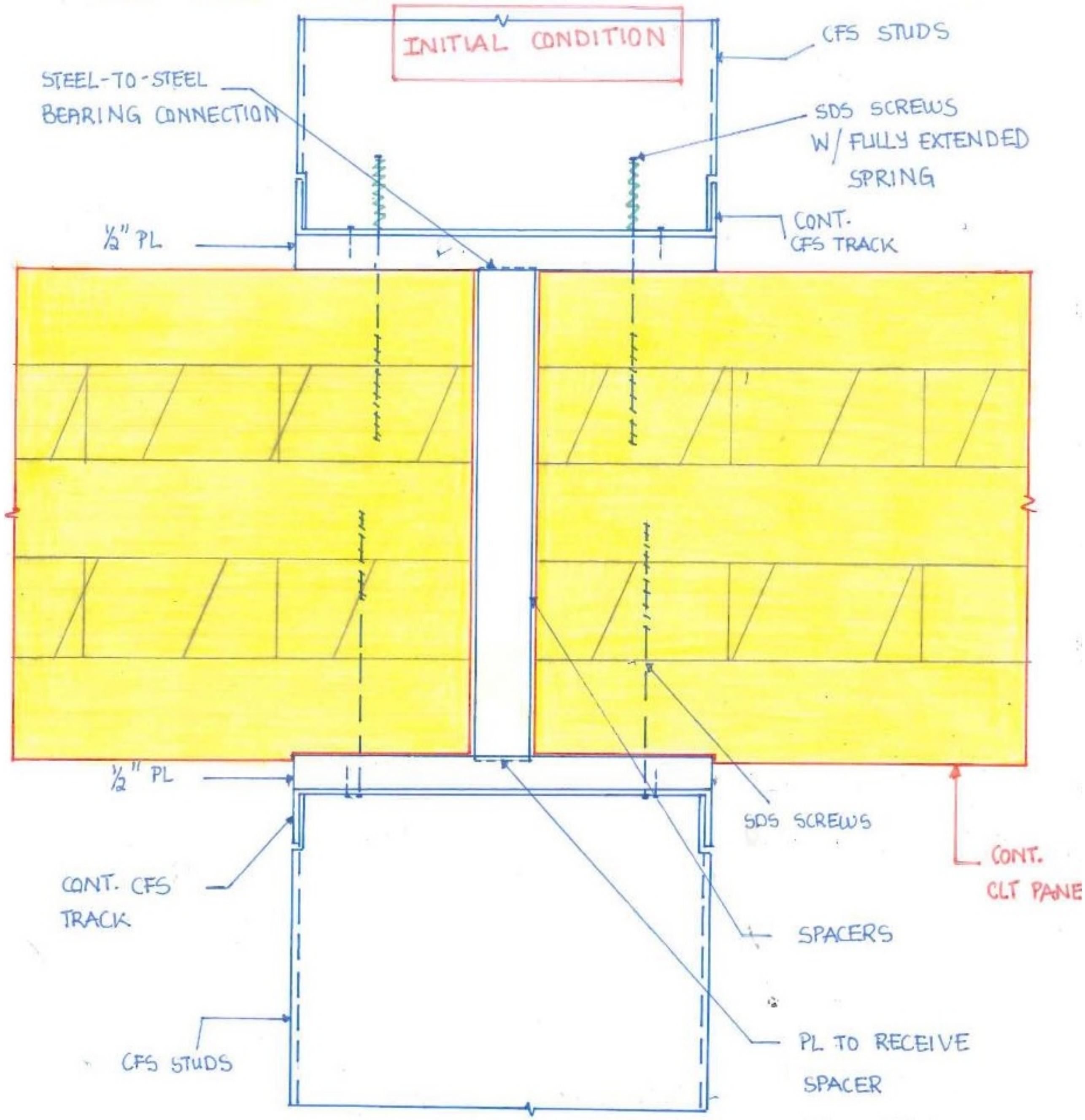
Figure 7-4: Option 3 - load transfer using precast concrete spacers

7.4 Novel Structural Detail for CLT/CFS System

For the MAC building, the proposed and considered structural detail for the CLT/CFS system, Option 4, uses steel spacers within the CLT panels to contain shrinkage and other vertical movements within the individual floor levels, while allowing direct gravity load transfer between consecutive CFS studs above and below the CLT floor panel. The novel connection details also use STSs (6mm Φ or ¼" Φ SDS screws) complete with springs to accommodate shrinkage. As shown in Figure 7-5-top, at the initial condition the springs are fully extended. When shrinkage occurs, see Figure 7-5-bottom, the springs compress to accommodate the vertical movements and maintain a tight and robust connection.

The first function of the STSs is to prevent horizontal movements of the CFS studs, e.g., accidental horizontal forces that would kick the CFS wall/studs off its plane or position at the top or bottom of the wall/studs. The second function of the STSs is to ensure a positive connection, whereby the walls can hang on the floor panel above to ensure structural robustness and prevent progressive and/or disproportionate collapse in the event of element loss. In other words, both the STSs and the springs would ensure a tight and stable connection before and after shrinkage and other vertical movements have occurred.

Figure 7-6 and Figure 7-7 show the details of the novel CLT/CFS connection details with notations based on Table 7-1. From Table 7-1, it is worth noting that the steel spacers have the same spacing as the consecutive CFS studs above and below the CLT floor, e.g., 400mm (16") or 600mm (24") spacing. Just like the CFS studs, the diameters of the steel spacers are optimised, and increase further down the building. The thickness of the steel plate on top and below the CLT panel were designed to accommodate a maximum of 10mm (3/8") misalignment between consecutive CFS studs. Furthermore, at Level 09, where the spacing suddenly changes from 600mm (24") to 400mm (16"), thicker (12mm or ½") steel plates were required, to enable that abrupt transition without needing a different connection detail.


INITIAL CONDITION
CFS STUDS
STEEL-TO-STEEL BEARING CONNECTION
SDS SCREWS W/ FULLY EXTENDED SPRING
½" PL
CONT. CFS TRACK
½" PL
SDS SCREWS
CONT. CLT PANE
CONT. CFS TRACK
SPACERS
CFS STUDS
PL TO RECEIVE SPACER

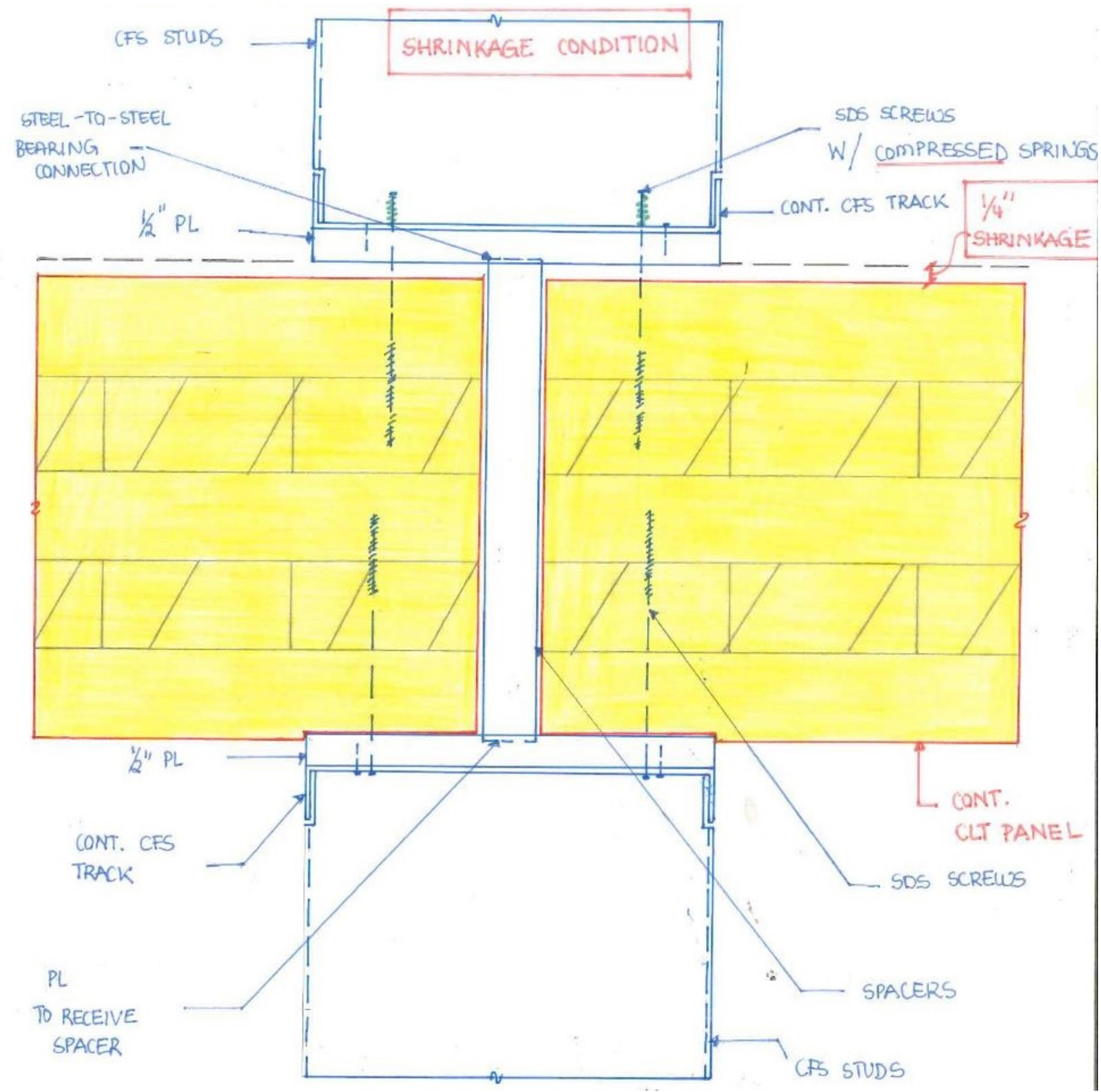


Figure 7-5: Option 4 - load transfer using precast steel spacers
Initial condition (previous page); shrinkage condition (above)

Table 7-11: Sizes and spacing of steel studs, spacers, and plates for novel CLT/CFS detail

Level	Studs [-]	Stud spacing (mm)	Steel spacer (mm)	Spacer spacing (mm)	Plate thick (mm)
Roof	600S137-54	600	-	600	-
Level 11	600S162-97	600	12	600	6
Level 10	600S200-97	600	15	600	10
Level 09	600S200-97	400	15	400	12
Level 08	600S200-97	400	15	400	10
Level 07	600S250-97	400	15	400	10
Level 06	600S350-97	400	19	400	10
Level 05	600S162-97 (B2B)	400	19	400	12
Level 04	600S162-97 (B2B)	400	19	400	12

This novel connection details for CLT/CFS system using steel spacers and STSs complete with springs have similar advantages than Option 3 which uses precast concrete spacers. The main clear difference was the size of the spacers. The steel spacers, maximum 19mm, were much thinner the concrete spacers, maximum 100mm. Structurally, thinner spacer means less cutting of the CLT diaphragms, which would result in negligible strength and stiffness loss. With respect to production and manufacturing, thinner spacer also means less routing.

Among the key considerations for steel spacers, which had thinner cross-sections, was the locations where the CLT floor panels would be discontinuous above the CFS walls. Herein, the thinner steel spacer would make it possible to keep the same detail for special conditions, i.e., panel joints, where two different CLT panels, bear on the same CFS wall as shown in Figure 7-8. The construction sequence would be similar to the previous options, whereby the tight-fit steel spacers may be pre-installed off-site within the CLT floor panels whereas the steel plates above and below can be pre-assembled with their respective CFS walls.

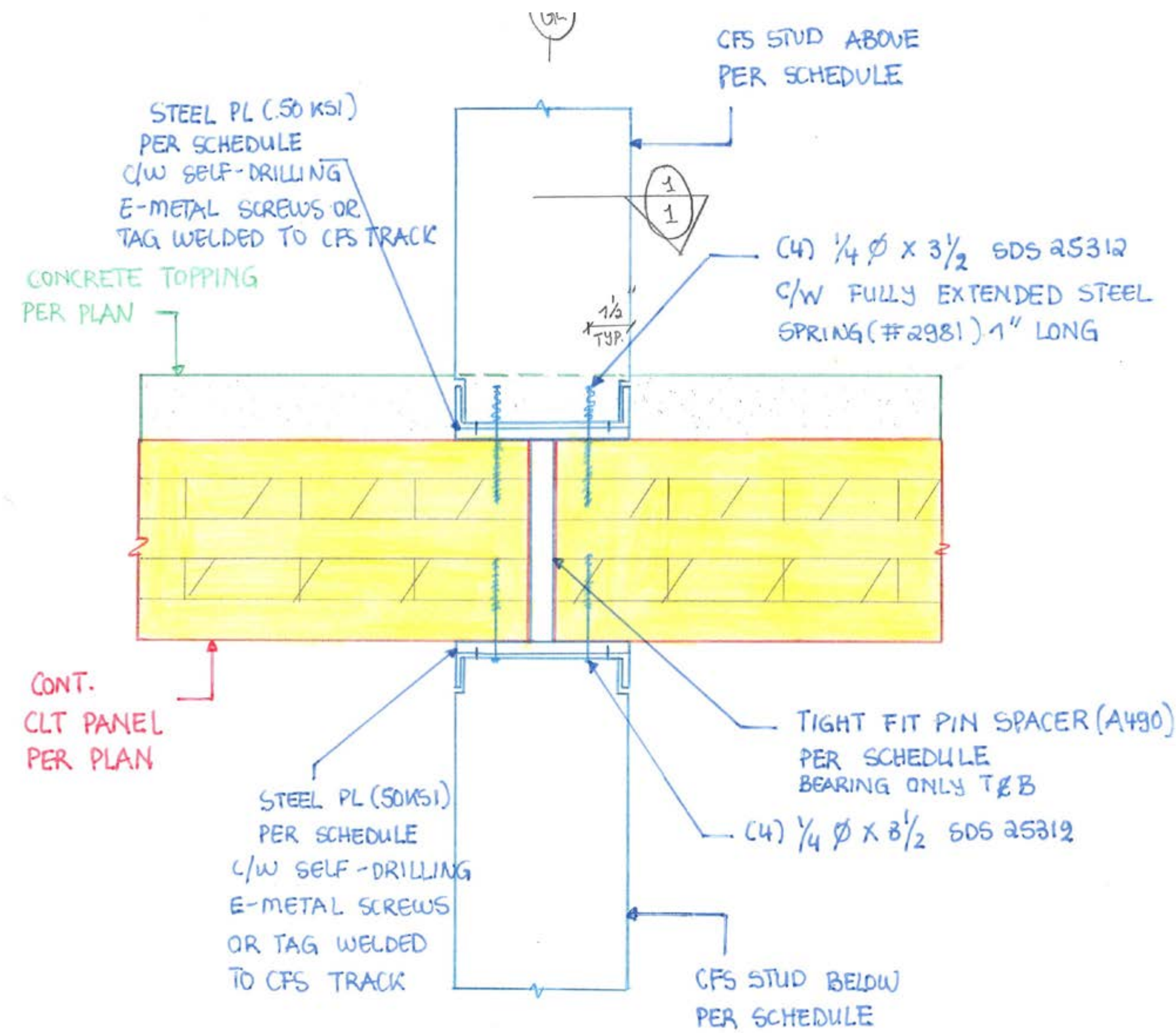


Figure 7-6: Novel Connection detail for CLT/CFS System

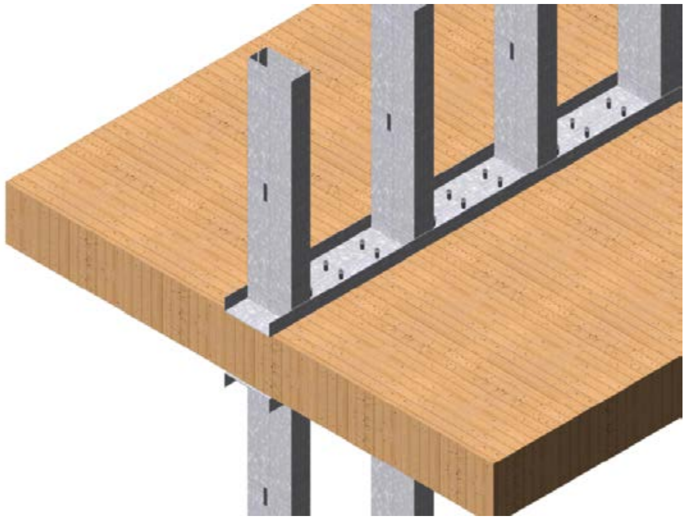


Figure 7-7: 3D view of novel Connection detail for CLT/CFS System

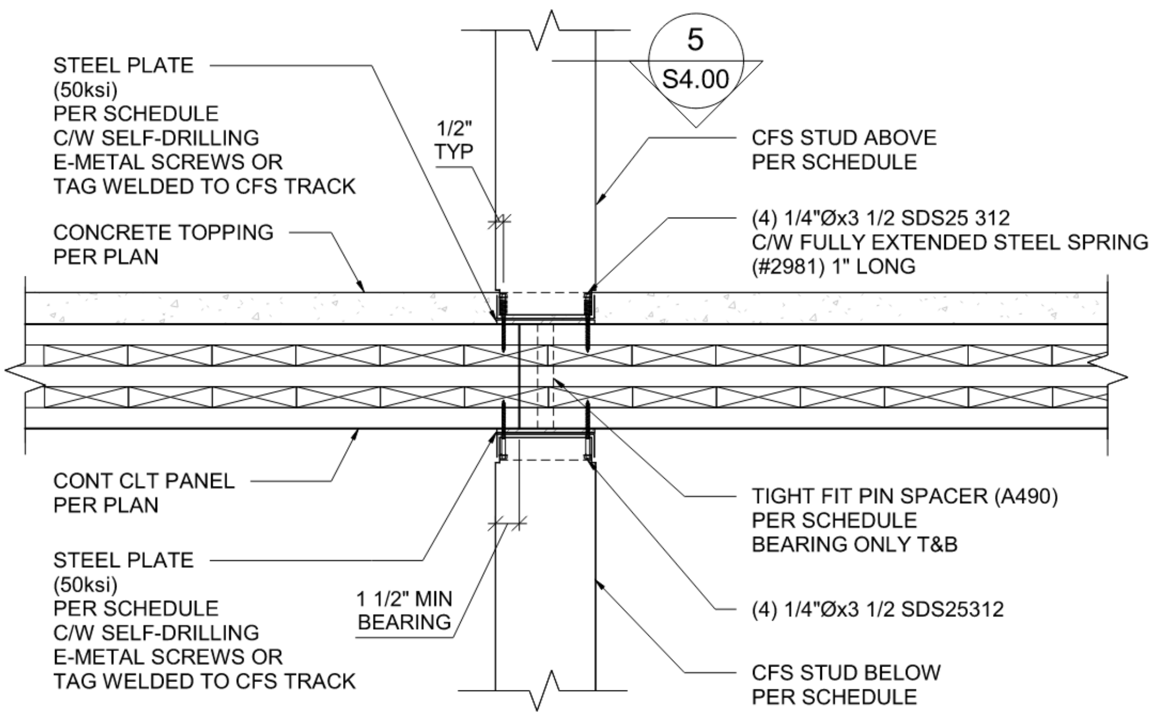


Figure 7-8: Novel Connection detail for CLT/CFS System at panel joint

8 Strategy for Implementation in Canada

8.1 Code Approval

Although the CLT/CFS system is a novel structural system, the performance of the individual structural materials, i.e., CLT floor panels and CFS walls, have been extensively researched and put into practice for over a decade. The necessary tools for structural analysis and design for both CLT and CFS systems are included in current North American building codes, within their respective material standards and guidelines. And designing and building CLT and CFS buildings, even in earthquake-prone regions, is currently part of regular engineering practice.

The novel CLT/CFS system, as a system that combine the advantages of the separate material, i.e., CLT and CFS, is proposed as a cost-effective alternative solution for the gravity load resisting system (GLRS) of hybrid mass timber buildings. The system is initially intended to not be part of the lateral load resisting system (LLRS). In other words, the LLRS would be analysed and designed as typically done for any hybrid constructions.

Furthermore, the proposed CLT/CFS system applies a platform-type construction, whereby the CFS walls and the CLT floor panels may be designed and analysed separately as done for any typical all-CFS or -CLT buildings. Consequently, since there are no fundamental changes to the design and analysis of the CLT/CFS system as per Canadian building codes, Alternative Solutions are not needed for this system, i.e., LLR and GLRS, as well as the individual structural components, i.e., CLT and CFS. The code approval in Canada of buildings with the CLT/CFS system would be the same as for other hybrid mass timber building systems.

8.2 Tests of Novel Connection Detail

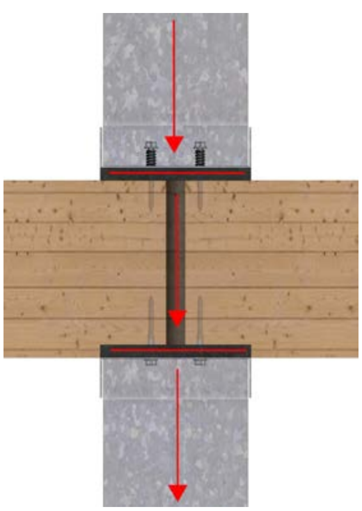


Figure 8-1: Novel CLT/CFS connection detail.

The overall structural performance of the CLT/CFS system as a GLRS would depend on the connection/interface between the CLT floor and the CFS wall using the novel connection detail, see Figure 8-1. As described in section 6.4, this novel connection detail would prevent issues related to differential shrinkage of the CLT panel by containing all vertical movements within a single floor. The connection components, steel plates and steel spacers, can be analysed using the principle of engineering mechanics and designed as per the steel material design codes. The steel spacers might be assumed a short steel solid section in compression, whereas the steel plates are idealised as bending elements with loads and spans related to the maximum tolerance or allowable misalignments between CFS studs above and below.

The key issue of the novel detail is to ensure that the designed load path is followed and maintained throughout the entire life span of the building, i.e., forces travel from the CFS studs above, distributed through the top steel plate, then through the short column steel spacers, and then the steel plate below, and final distributed through the CFS stud below. This design load path, where the steel spacers act as short columns between the two steel plates, does not interfere with the CLT floor panels which are allowed to move as required when subjected to differential shrinkage.

The first check was to ensure that the performance of the SDS screws at the top steel plate would not negatively be affected by the springs, which were added to ensure structural integrity after shrinkage of CLT panel has occurred. To confirm performance, Simpson Strong-Tie carried out initial tests whereby the capacity, stiffness, and failure modes of the SDS screws without and with the springs, including the scenario where springs were compressed and uncompressed, were compared.

Figure 8-2 illustrates both photo and schematic drawing of the test setup. The test applied a lateral load (displacement) on the CFS track complete with SDS screws (without or without springs). The tests recorded the applied displacements and corresponding forces, as well as the relative displacement. The test stopped until failure was observed.

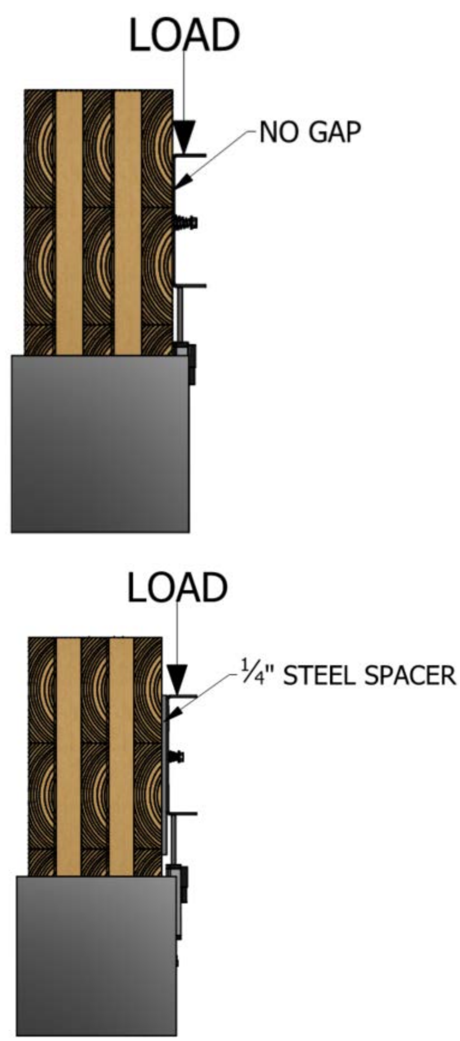


Figure 8-2: Test setup: Photo (left), schematic representation without gap (right top), schematic representation with ¼" gap (right bottom)

The tested specimens were as follows:

1) Single screw without springs, 10 tests per condition (cond.): cond.1-A) single screw with ¼" gap; and cond.1-B) single screw without gap.
2) Single screw with springs, 6 tests per cond.: cond.1-A) single screw with ¼" gap; and cond.1-B) single screw without gap.
3) Four (4) screws with springs, 6 tests per cond.: cond.1-A) single screw with ¼" gap; and cond.1-B) single screw without gap.

The specimens without gap, as shown in Figure 8-2, represented the condition before shrinkage. By leaving a gap of ¼" between the steel plate and the CLT panel, see Figure 8-2, the test setup idealised the situation after shrinkage has occurred, see section 6.4.3 how ¼" shrinkage deformation was determined.

Figure 8-3: Test results - failure modes: Without spring wood failure (top); with without spring CFS track failure (middle); with compressed springs (bottom)

The preliminary test results showed that, the design capacity of the SDS screw with and without springs was mostly similar. The design values of the SDS screws with steel side plate as per Simpson Strong-Tie USA product catalogue should be used, up to 1.87kN (420lb).

Figure 8-3 illustrates the different failure modes of tested specimens. Figure 8-3-top illustrates the wood failure when the SDS screws without springs were loaded in shear. Figure 8-3-middle illustrates the failure mode of the CFS bottom track when the SDS screws were loaded in shear. These failure modes confirm: 1) the need to have an additional steel plate between the CFS wall and CLT panels as the CFS tracks are so thin and provide negligible resistance; 2) the role of the additional springs.

As shown in Figure 8-3-bottom, for specimens with a 1/4:" gap idealising shrinkage conditions, the springs provided additional rigidity and integrity on the connection when loaded in shear. Herein, desired ductile failure modes, i.e., localised as bending/yielding of the screw, was observed. The connection was maintained in place without becoming loose until complete failure of the SDS screws occurred.

9 Conclusion

The report presented structural considerations of the novel cross-laminated timber and cold-formed steel hybrid system, also referred to as the CLT/CFS system. This first-of-its-kind hybrid system which uses CLT floor panels and CFS walls in a platform-type construction as a gravity load-resisting system was found to be cost-effective and structural efficient for mass timber buildings with 7 to 12 storeys. From preliminary analysis and design, based on the 11-storey MAC building in Vancouver, the structural efficiency of the CLT/CFS system was found when using a 3.7m (12') gridline to span continuous CLT floor panels over the CFS walls. A Novel connection details, which utilises steel studs, screws, and springs to ensure direct gravity load transfer between consecutive CFS walls without interfering with the CLT panels, was developed, and tested. This detail was designed to eliminate possible issues related to differential shrinkage and other vertical building movements, while ensuring structural integrity and robust connections between the CLT floor and the CFS walls at every level.

In this configuration, the system would therefore combine CLT and CFS components without fundamental changes in the design and analysis, as per the Canadian building codes. Lastly, the ability to prefabricate and pre-assemble both CLT floors and CFS walls would significantly reduce the overall installation time as well as on-site assembly, making the novel CLT/CFS system an efficient and cost-competitive solution for tall mass timber buildings.

10 Acknowledgements

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