Terminus – Timber Office Building with an innovative Seismic Force Resisting System

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1. Team-Work and Innovative Solutions in Solving a Mass Timber Challenge

In the Spring of 2020 around the time the scale and severity of the Covid Pandemic was being realized worldwide, ASPECT Structural Engineers (ASPECT) of Vancouver, Canada was busy coordinating the final details for an exciting and challenging new mass timber building. Aptly named Terminus, this was one of the last projects that ASPECT would provide structural engineering services for in the pre-Pandemic landscape. Now complete, Terminus is a 5-storey commercial building featuring a novel steel buckling-restrained brace lateral system framed within its mass timber superstructure. This marriage of two complex systems required the design, installation, and fabrication of many difficult details. Despite these and other hurdles faced by the project, the design team comprising ASPECT (structural engineer), Jack James (Architect), DB Services (DBS) of Victoria, BC (developer, building designer, and general contractor), Structurlam Mass Timber Corporation (mass timber supplier/fabricator and 3D modeler), and CoreBrace (steel brace designer and supplier) proved well prepared to ensure a smooth delivery. Employing a combination of close collaboration, precise modelling, and multiple rounds of thorough review, Terminus was constructed by the Spring of 2021 on time and well within budget.

Figure 1: District 56, Terminus

2. Motivation

Located in the City of Langford, BC at the Southern tip of Vancouver Island, Terminus is situated in one of the most seismically demanding regions in North America. According to the Structural Engineers Association of British Columbia, the West Coast of Canada is one of the few areas in the world where all three major categories of tectonic plate boundaries are present: convergent, divergent, and transform. Movements between the Juan De Fuca, North American, and Pacific Plates along these boundaries have resulted in more than 100 recorded earthquakes of magnitude 5 or greater in this region over the past 70 years, many of which have occurred near Vancouver Island [1]. The seismicity of the region was the primary issue facing the project team leading into Terminus' design phase. Aggravated further by a very wet Pacific Northwest climate and a construction industry that is still rather new to mass timber, the decision to proceed with a mass timber superstructure and novel lateral system required some compelling motivations to justify.

First, it was DBS' intent from the outset to establish themselves as leaders and innovators in the mass timber industry with this project. Having already gotten their feet wet with mass timber in a handful of hybrid light-wood frame and mass timber projects, and realizing the benefits of mass timber construction, DBS was ready to make a splash with Terminus, especially given the prominent location in downtown Langford. Given that they intended to occupy the top floor of the building and additionally motivated by a desire to provide future tenants with a beautiful and resilient building, they conveyed a willingness early in the project to explore various state-of-the-art options for the building's lateral force resisting system. Effectively, it was DBS' expectation that the design of this building's structural systems was not going to be conventional, and that it would celebrate timber as a structural and architectural feature.

Although the additional upfront effort and coordination required to design a building of this nature was clearly going to cost more than a conventional build, the potential savings during the construction process provided more than enough justification for DBS to pursue a mass timber assembly. Prefabricated CLT panels and pre-installed hardware for both gravity and lateral connections would facilitate a predictable, efficient, and quick erection process requiring much less construction coordination, a smaller erection team, smaller equipment, and lighter requirements (timber projects require comparatively smaller cranes). All these aspects of the mass timber installation process presented significant cost benefits to DBS on previous residential projects, and it was their expectation that they would be able to reap the same benefits on this project, despite the complex nature of certain facets of its design.

Lastly, one of the additional motivating factors that drove the decision to incorporate a mass timber superstructure was the environmental benefits of this type of construction. By replacing what would otherwise be a structure comprised entirely of concrete, Terminus' hybrid design offered potential savings in embodied carbon. To assess this impact, ASPECT performed an embodied carbon calculation using a tool developed specifically for Canadian design and materials (based on the IStructE Guide - How to Calculate Embodied Carbon) [2]. The total embodied carbon of the structure amounted to approximately 2,149 tCO2e for Modules A1-5. A GWP rate of 232 kgCO2e/m^2 was calculated using the GIFA of the building (total internal floor area including basement). If the area of covered parking under the transfer slab was also included, this rate would be 220 kgCO2e/m^2. The calculation included all structural elements but excluded interior partitions and building envelope (such as façade, insulation, glazing etc.). The values were calculated using EPDs for materials in Canada so may not be directly comparable to buildings in other countries.

Table 1: Terminus: Embodied Carbon Calculation Breakdown

Element	A1-A3	A4	A5	A1-A5		
				$kgCO_2e$	[$kgCO_2e/m^2$]*	[$kgCO_2e/m^2$]**
Foundations	272,233	3,654	9,505	285,392	31	29
Basement	699,242	7,629	22,637	729,508	79	75
Ground floor slab	281,651	3,052	9,055	293,758	32	30
Glulam frame	54,891	8,786	1,807	65,483	7	7
CLT slabs	147,045	22,244	4,710	173,998	19	18
Floor build-up (Screed)	55,727	935	2,433	59,096	6	6
First floor transfer system	503,858	5,460	16,200	525,517	57	54
Stability system	14,565	272	604	15,441	2	2
Other structure	437	35	12	485	0.05	0
TOTAL				**2,148,678**	**232**	**220**

* Rate based on GIFA only

** Rate based on GFIA + Covered Parking

Based on the SCORS rating outlined by IStructE [3] and Leti [4], the rate was higher than one would hope for a mass timber building. Key design requirements such as large unobstructed floor plates for commercial tenants and extensive underground parking meant that a large volume of concrete was required, contributing significantly to the building's total embodied carbon (*Table 1*). Nonetheless, ASPECT's calculations concluded that the mass timber system above podium level offered roughly 60% saving in carbon compared to an equivalent concrete system above podium (concrete shear walls, columns and flat slab were schematically designed for a direct comparison model). However, with the vast majority of embodied carbon coming from the podium and structure below, using mass timber translated to a net 14% reduction when comparing the hybrid scheme against the full concrete scheme.
This still represented a saving of around 300 tCO_2e (equivalent to 65 cars [US] off the road for 1 year) [5] and provided additional motivation for DBS to proceed with a design featuring a mass timber superstructure.

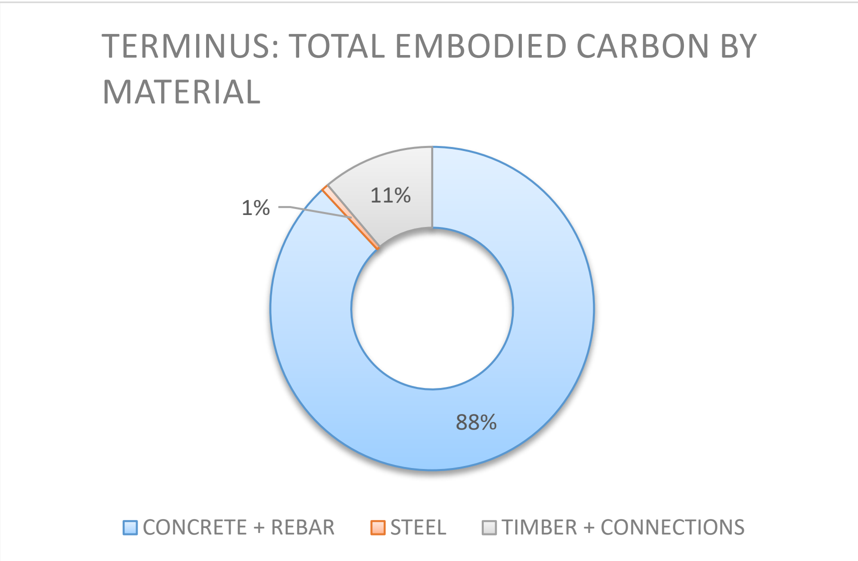


Figure 2: Terminus: Total Embodied Carbon by Material

3. Design & Detailing

DBS engaged two additional parties to support the design of Terminus' hybrid mass timber/steel assembly. Structurlam Mass Timber Corporation (based in British Columbia) was brought on to 3D model and fabricate the mass timber and CoreBrace (based in Utah) was brought on to supply and design the steel buckling restrained braces. To successfully coordinate the design of the building's different systems and materials (steel, timber, concrete), ASPECT facilitated frequent coordination meetings with all project team members.

3.1. Gravity Load Resisting System

Terminus' gravity system is composed of glulam columns and beams, complete with one-way spanning CLT floor and roof panels. Working closely with DBS, ASPECT sized all gravity members and detailed all gravity connections ensuring that they would satisfy the building's loads, fire rating, and further, that all components of the gravity system would be easily installed during construction. The West Coast of Canada is notoriously rainy during much of the year, so it was expected from the start of the project that at least a portion of the timber erection process would occur in wet conditions. As such, frequent discussions were held between ASPECT and DBS during the design process on the topic of constructability, namely focused on detailing the building to expedite the installation process as much as possible. Accordingly, all gravity connections were designed with shop installed components that would permit the timber elements to slip into place onsite; these connections were accomplished with slip fit concealed beam hangers and column splice details that could be quickly installed with a few site-installed pins.

Terminus' gravity system components and connections were designed with a 1-hour fire rating. All glulam and CLT members were sized with additional charring layers on exposed faces using specified charring rates in accordance with the British Columbia Building Code [6]. Aspect coordinated closely with Structurlam to ensure that all steel gravity connections remained concealed with appropriate cover (typically 45mm from exposed glulam faces, based on a codified charring rate of between 0.7mm and 0.8mm/minute [7], including a zero-strength layer) to ensure adequate fire protection.

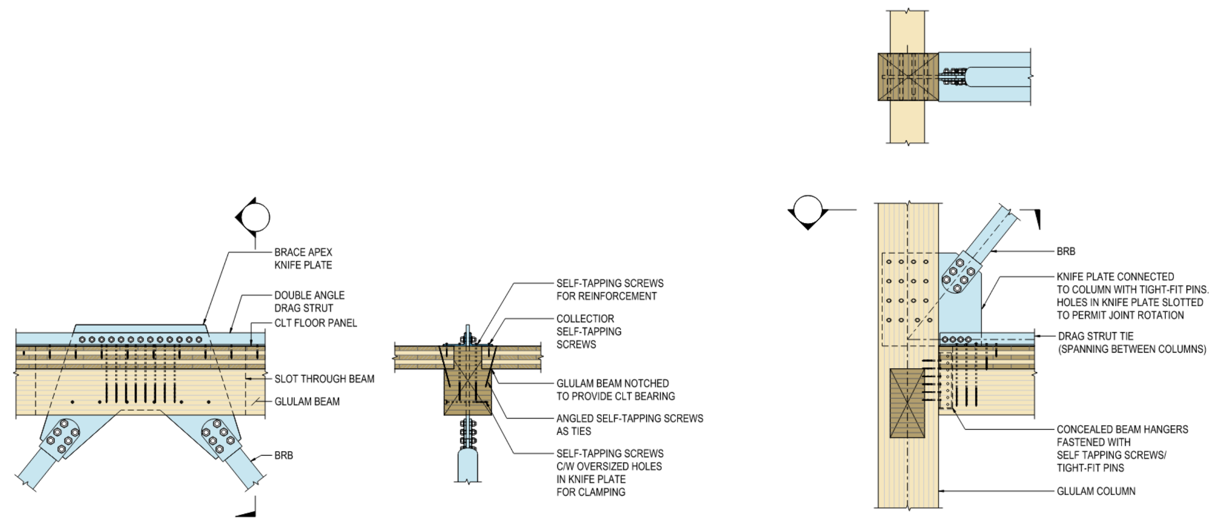
Unlike other many other jurisdictions around the world (including Europe and the U.S.), building codes in Canada do not stipulate any specific requirements for robustness design. The British Columbia Building Code [6] includes a clause stating that gravity systems be designed with inherent robustness but does not include design provisions. Due to the inherent structural continuity provided by the building's lateral system (drag straps and splines across the entire diaphragm), and because close attention was paid by the project team in designing the seismic and gravity connections (with continuity in mind), Aspect was able to positively conclude that the structure would be sufficiently robust.

3.2. Lateral Load Resisting System

Figure 3: Terminus Brace Frame

Terminus' lateral system features several sets of chevron-oriented steel buckling-restrained braces framed within glulam columns and beams at each level. Each brace features a ductile steel plate core enclosed within an outer steel casing, a grout fill, and a proprietary debonding interface material. The ends of the ductile steel plate core are connected to steel lug plates extending out beyond the ends of the outer casing, complete with bolt holes for connecting to the knife plates withing the timber superstructure. As shown on the detail below (*figure 4*), Terminus' typical brace-column connection consists of double 25mm thick steel knife plates fastened to the glulam columns with several rows of 16mm diameter stainless steel tight fit pins. The knife plates project inwards from the columns to receive the end of the braces, which connect to the lug plates with 28mm diameter F3125 heavy hex head steel bolts. The typical connection at the top of the brace consists of a 25mm diameter steel v-shaped knife plate, which extends up through a slot in the glulam beam to the floor above. Atop the beam, the knife plate connects to a steel drag strut tie consisting of two angles fastened to the top of CLT floor/roof plate running between the adjacent columns. Because each of Terminus' storeys features a raised floor system, this drag strut tie is effectively hidden from sight at each level. With this tie in-place, the glulam beam does not need to be used as a frame member, which drastically reduces the complexity of the beam/column connections required for this system.

Due to the complexity and tight tolerances involved with the brace connections, ASPECT worked closely with CoreBrace and Structurlam during the design phase to ensure that all components would fit together seamlessly during installation. Following the preliminary design of the lateral system, ASPECT worked with CoreBrace to design and test the steel brace members. To meet the requirements of the Canadian code and standards [8], CoreBrace performed inhouse testing of the selected braces to verify the brace mechanical properties. At the same time, ASPECT collaborated with Structurlam to design and detail the typical connections between the steel elements of the lateral system and the mass timber frame members.



TYPICAL BRACE FRAME APEX DETAIL

TYPICAL BRACE FRAME COLUMN CONNECTION

Figure 4: Terminus Brace Frame Connection Details

3.2.1. Lateral System Design Challenges and Solutions

Terminus' lateral system is the first example in North America of steel buckling-restrained braces integrated within a timber frame. Consequently, there were various unforeseen detailing challenges faced by the project team during the design process that had to be resolved quickly and without any precedents to lean on.

Brace Apex Connection: The chevron orientation of the braces, while architecturally appealing resulted in rather short braces. A shorter brace allows less yield length for the BRB core, which results in higher brace strains and overstrength connection forces much higher than could otherwise be achieved with a longer brace. Whereas the beams at the top of the brace frames were originally positioned directly below the CLT floor panels at each level, the project team devised a solution to slightly increase the length of the braces by shifting the beams upwards to be top flush with the top of the CLT. The additional brace length facilitated a higher level of ductility in the braces and helped reduce the amount of steel required for the apex connection. Conventional chevron brace frames typically require rather large beams to resolve the net vertical component arising from one brace buckling in compression and the other yielding in tension. BRB's allow designers to largely circumvent this design challenge, because the compression capacity and the tension capacity are much closer. In this case, the glulam beam was easily designed to resist the comparatively smaller vertical reaction at the brace apex.

Deformation Compatibility: All timber connections within the brace frames were designed to the probable capacities of the braces, as required by CSA S16-14: Design of Steel Structures [8]. Deformation compatibility principles were important to ensure the connections between timber elements did not attract moment during the building's drift and therefore joint rotation was not restrained. To ensure that the connections at either ends of the braces (at the columns and at the brace apex) would achieve this deformation compatibility, the steel knife plates were fabricated with slotted holes to allow some rotation.

Fastener type: Early in the design of the buckling restrained braces, the project team collaborated to determine what type of fastener would be employed in connecting the braces and the glulam frame members. This decision required a lot of coordination and careful analysis, as the frame members and their connections needed to be designed to resist relatively high forces (for example, the brace frame columns on the 1st floor needed to be designed to resist 3280kN compression and the connections between these columns and the base plates needed to be designed for 1565kN uplift). After some deliberation, the team settled on knife plate connections either involving tight fit pins or self- tapping screws. Further research and coordination led to the decision to proceed with tight fit pins, as it was determined that the pins, if detailed correctly, could provide additional ductility to the system, and could be pre-installed in Structurlam's shop. Additionally, it was decided that providing ductility in the connections via slender tight fit pins through multiple knife plates meant that a secondary fuse would protect the timber during a seismic event. This assumption was later verified by Dong et.al. at the University of Canterbury in an experimental study involving this type of system [9].

3.3. Modelling and Shop Drawing Review

Following the design of the gravity and lateral systems, ASPECT and CoreBrace sent coordination drawings to Structurlam so that they could begin modelling the building and assembling shop drawings. ASPECT would typically draft all the connection details for any building designed in-house, but the project team decided to hire Structurlam to draft and prepare all of Terminus' connection details for inclusion in the final construction drawing set. Instead of drafting the same details twice (first by ASPECT in-house and then by Structurlam for their shop drawing submittal), the project team recognized that this approach would save time and eliminate a layer of complexity. ASPECT thus would draft typical details for the straightforward mass timber connections and then issue design sketches to Structurlam for the remaining atypical connections, namely those occurring within the lateral system.
Accordingly, ASPECT worked closely with Structurlam while they modelled the structure, answering multiple rounds of questions via remote meetings and frequently cooperating via Zoom to solve any tricky connection details. Thanks to the accurate building model, several connection challenges were realized and solved by the project team during the shop drawing process. In addition to frequent collaboration between ASPECT and Structurlam, the project team relied on a thorough review by ASPECT and DBS to ensure that any loose ends were captured and addressed in Structurlam's shop drawings. Once the building model was complete and all the shop drawings were reviewed, ASPECT inserted all the necessary details from the shop drawing package into their own final construction drawing set for record and to prepare the drawings for submittal to the jurisdiction.

4. Fabrication & Installation

Close coordination amongst the project team during the design and shop drawing phases of the project helped to ensure a high degree of accuracy in the fabrication of the building components. This accuracy was an essential factor in ensuring a timely and relatively pain free installation process, as the integration of timber and steel elements in the building's lateral system required very tight connection tolerances.

Figure 5: Terminus During Construction

Figure 6: Terminus Brace Frame During Construction

In addition to manufacturing the mass timber elements for the project, Structurlam fabricated all the steel components for the lateral system (outside of the steel braces), including the drag struts and all of the large steel connections between the braces and the timber frame members. To simplify the onsite installation of the lateral system components, Structurlam assembled the knife-plate/column connections (the largest and most critical lateral system components) in their shop. Figure 4 below shows the large shop installed steel knife plates protruding from the recently installed timber brace frame columns. Because these large connections involve many tight fit pins, each requiring very strict tolerances in both the timber and the steel elements, the pre-installation of these knife plates saved a substantial amount of time onsite and guaranteed that these crucial connections were assembled in a controlled environment by individuals with abundant mass timber experience. Despite periods of inclement weather (including intense rains, snow, and driving winds), once all the components for the gravity and lateral systems arrived onsite, everything was installed by DBS' team quickly and with ease. Aided not only by the precision of the prefabricated elements, but also by a carefully formulated approach during installation, the building was erected in a timely manner; the installation of all timber and steel components for both the gravity and lateral systems was completed in a timeframe tallying roughly 2.5 months (this included 3 levels and the roof, each comprising roughly 1230m^2 in area). Frequent onsite reviews by ASPECT and DBS' team, as well as a solid moisture management plan helped to ensure that all the building's critical connections remained sufficiently dry during erection. Whereas some mass timber projects in Europe may employ the use of a temporary tent structure during construction to protect a superstructure from rain, this is not common in North America. During Terminus' erection DBS employed a moisture mitigation strategy involving frequent squeegeeing, temporary rainwater leaders, coverings for important steel components, and an expedited installation process to help them mitigate moisture concerns until they could apply a waterproof membrane on the building's roof panels. Even though the structure was partially erected during a rainy Pacific Northwest winter, DBS managed to install all the building components without significant moisture damage.

5. Conclusion

Terminus is now complete almost two years after its inception. Standing tall in one of Canada's most seismically and climatically demanding jurisdictions, its precedent setting lateral system and beautiful superstructure shine brightly as benchmarks for future mass timber projects. Despite the many challenges faced by the design team from the outset, its success represents what any mass timber project should strive for: teamwork, precision, and care.

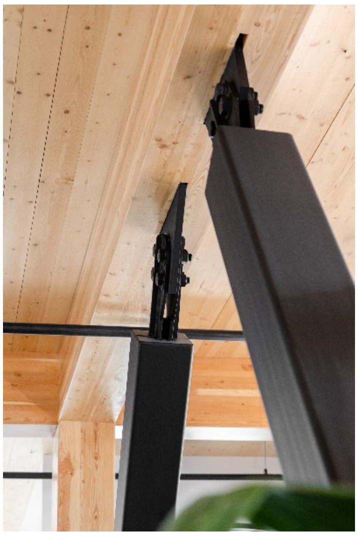


Figure 7: Terminus Painted Braces

Figure 8: Terminus Finished Interior

6. References

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[3] IStructE, «Setting Carbon Targets: An Introduction to the Proposed SCORS Rating Scheme,» 2020. [Online]. Available: https://www.istructe.org/journal/volumes/volume-98-(2020)/issue-10/setting-carbon-targets-an-introduction-to-scors/. [Accessed 01 2022].

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7. PROJECT CREDITS

Structural engineer: Aspect Structural Engineers
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Developer, building designer and general contractor: Design Build Services (DBS)
Mass timber supplier/fabricator and 3D modeller: Structurlam Mass Timber Corporation
Steel brace designer and supplier: CoreBrace