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CASE STUDY: TERMINUS – NEW FRONTIERS IN HYBRID MASS TIMBER SEISMIC DESIGN

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ABSTRACT: Terminus is a recently completed 5-storey mass timber commercial building in one of the highest seismic regions in Canada. The seismic demand and the exposed timber drove ASPECT Structural Engineers to undertake a thorough investigation to select a lateral load resisting system that would complement the building's mass timber superstructure, maximize use of timber, and provide a high level of ductility. The selected system involved the novel integration of steel buckling restrained brace frames within a timber post and beam frame. During design and construction ASPECT worked closely with the builder and the mass timber supplier to ensure that all elements of the lateral system were detailed carefully and that all components fit together seamlessly during installation.

KEYWORDS: Mass Timber, Seismic, Innovation, BRB, Hybrid

1 INTRODUCTION

Terminus is a 5-storey mass timber commercial building designed and constructed by a project team consisting of ASPECT Structural Engineers, Jack James Architecture, Design Build Services (DBS), and Structurlam. Located in one of North America's highest seismic regions on Vancouver Island, BC, Terminus' lateral design warranted a lengthy investigation of various systems. Vancouver Island's code-based seismic design parameters are some of the most demanding in North America. According to the Structural Engineers Association of British Columbia, the West Coast of Canada is one of the few locations in the world where all three major categories of tectonic plate boundaries occur: convergent, divergent, and transform. Over the past 70 years these plate boundaries have accounted for more than 100 recorded earthquakes of magnitude 5 or greater [1]. The investigation undertook by the project team involved a selection of different lateral systems that would simultaneously satisfy the onerous seismic loads of the region and meet the client's desire for an aesthetically interesting structure – one that would complement the building's mass timber superstructure.

Terminus' gravity load resisting system is composed of four levels of glulam columns and beams sitting atop a concrete podium and underground parking structure. The diaphragm at each timber level comprises one-way spanning CLT panels, all of which are connected with plywood splines and a matrix of steel plate drag straps fastened to the top of the panels. ASPECT and DBS worked closely in sizing all gravity members and designing all gravity connections to satisfy the building's loading demands and one hour fire rating. The time and effort that went into detailing Terminus' timber components and connections helped motivate the project team in choosing a lateral system that would celebrate the beautiful exposed west coast timber in the building.

Figure 1: *Terminus, Finished Building*

The Buckling Restrained Brace (BRB) timber hybrid system that was ultimately chosen was decidedly best suited to satisfy these requirements, and allowed for a well-integrated, ductile, and highly architectural lateral load resisting system.

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2 LATERAL SCHEMES AND SELECTED SYSTEM

As developer, designer, builder, and eventually, occupant for the project, DBS was committed to a mass timber structure that was highly architectural, safe, and celebrated the best of what timber can be. Coupled with their desire to furnish themselves and future tenants with a beautiful and robust building, DBS' stake in the project bolstered their willingness to explore various state-of-the-art options for the building's lateral force resisting system. Working together ASPECT and DBS identified cost, aesthetics, ductility, post-earthquake repairability, and precedence as the guiding criteria that would be used to make their selection. ASPECT undertook an investigation of potential candidates for the lateral system, and with DBS' help they shortlisted four options that were determined to best meet the associated parameters. The proposed systems are summarized below, including a list of advantages and disadvantages associated with each option:

2.1 Glulam Brace Frames with Quaketek Friction Dampers

This proprietary system manufactured by Quaketek (a Canadian based seismic protection technology company) is a steel Seismic Friction Damper that is installed at the brace/column interface within a glulam braced frame. The dampers are fuses, dissipating energy induced by the earthquake via friction. The dampers respond symmetrically throughout their cycle (in compression and tension), offering energy dissipation through a range of building motions [2].

The advantages offered by this system include:
-High ductility and offers substantial energy dissipation, which accordingly reduces forces on the other elements in the brace frame.
-Post-earthquake reusability (they can also be easily replaced if necessary).
-Quaketek offers in-house testing to suit a project's specific needs (helps to streamline the design process).

The disadvantages associated with this system include:
-It is not currently codified in Canada (although some research has shown that this system performs similarly to buckling restrained braces, which are an available option in the Canadian Code) [3].
-This product requires additional moment frames for optimal performance, including self-centring, which comes at a high cost in a mass timber building.

2.2 Glulam Brace Frames with Tectonus Resilient Slip Friction Joints (RSFJ)

The RSFJ is manufactured by New Zealand based company Tectonus Resilient Seismic Solutions. This system can be installed at the brace/column interface within a glulam brace frame, and it works by dissipating energy via slip friction as its tightly clamped grooved components move across each other. During a seismic event, the RSFJ will slip and re-centre cyclically before any of the other brace components yield [4].

The advantages offered by this system include:
-High ductility and offers substantial energy dissipation, which accordingly reduces forces on the other elements in the brace frame and other building elements such as the foundations and diaphragms.
-Self-centring capability, which helps to limit residual drifts and associated repair costs post-earthquake.
-Replaceable after an earthquake.
-All RSFJs are tested to suit a project's specific needs.

The disadvantages associated with this system include:
-It is not currently codified in Canada (although to-date there are some recent Canadian projects that have successfully employed this system) [3].
-This system presents higher associated costs relative to the other solutions listed herein.

2.3 Moderately Ductile Glulam Brace Frames (R_D = 2.0, R_O = 1.5)

This codified system features a glulam frame complete with glulam brace members connected to the columns and beams with detailed steel components designed to yield, dissipating energy during an earthquake.

The advantages offered by this system include:
-It is currently codified in Canada (although the code does not provide design guidance) [3].
-Not a proprietary system, so it would be easy to source and detail the component materials and parts. It is also a system that is relatively popular as a mass timber lateral scheme, so there are precedent projects that would offer design guidance.

The disadvantages associated with this system include:
-Lower ductility and energy dissipation than other options, which would increase the cost of the other frame components, and other building elements such as the foundations and diaphragms.
-It is not self-centring, and it is not easily replaced or repaired following an earthquake. This implication could result in substantial post-earthquake costs and could potentially require demolishing the building.

2.4 Steel Buckling Restrained Braces (BRB) in a Timber Frame (R_D = 4.0, R_O = 1.2)

A BRB is a steel section (highlighted in red and blue in Figure 2, below) that is encased in a concrete sleeve (shown in grey in figure 2, below), thus restrained from buckling. The centre of the steel section is slender and designed to yield in both tension and compression during an earthquake [5]. Incorporating a BRB in a timber frame is a unique approach that allows designers the opportunity to preserve the timber structure (incorporating only a limited amount of steel), whilst achieving an impressive level of ductility. Within the BRB braced frame, columns and beams are timber, and the diagonal brace elements are steel encased in concrete.

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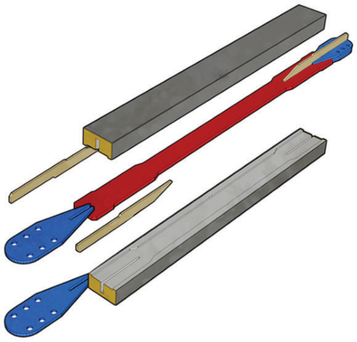

Figure 2: *BRB Cross-Section*

The advantages offered by this system include:
-It is currently codified in Canada (as an all-steel system) [3].
-Comparatively low costs (especially relative to the level of ductility that it achieves).
-High ductility and offers substantial energy dissipation, which accordingly reduces forces on the other elements in the brace frame and other building elements such as the foundations and diaphragms.
-Does not require backup moment resisting frames (as is the case with other lateral systems, such as the Quaketeck dampers).

The disadvantages associated with this system include:
-It is not self-centring. This implication could result in substantial post-earthquake costs and could potentially require demolishing the building.
-There are no precedents for using BRBs in a timber frame.

Following much deliberation between ASPECT, DBS, and Jack James, the timber-BRB hybrid was selected for Terminus' lateral system. Despite the lack of precedence for this type of system (steel BRBs are codified in Canada as an all-steel system, but no other project in North America has featured buckling restrained braces within a timber frame), the project team agreed that the high ductility and the low associated costs would be appropriate for the high seismic loads and the project budget. Furthermore, the opportunity to integrate the steel braces within the timber superstructure meant that DBS' design preference to maximize the amount of timber on the project would be fulfilled.

3 DETAILING OF STEEL/TIMBER CONNECTIONS

Following a linear dynamic analysis of the structure, ASPECT established brace loads, and worked with CoreBrace (the BRB designer and supplier) to finalize the brace dimensions. To optimize geometry and aesthetics, ASPECT and DBS elected to position the braces in a chevron orientation, spanning from floor to ceiling. Framed within glulam columns and beams, the BRBs are the only primary steel elements in the building. Evident in figure 3 below, the integration of the steel braces within the building's timber gravity elements presented the unique opportunity to showcase its mass timber with only minimal additional lateral steel (or concrete) components. CoreBrace's BRB design 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 a bolt hole pattern for connection to the timber columns and beams.

Figure 3: *Newly Installed Braces*

The Canadian engineering steel design standard [3], requires suppliers to perform qualification tests on proprietary buckling restrained braces to demonstrate that design resistances can be developed without buckling the braces under deformations of 2x the design storey drift. CoreBrace performed these tests in-house and used the results to ascertain tensile and compressive strength design factors that were necessary to approximate the design overstrength factors for the brace connections. In compression, the overstrength factor is calculated as the product of three design parameters: ω (a strain hardening adjustment factor equal to approximately 1.4), β (a friction adjustment factor ranging from approximately 1.2 to 1.4), and Ry (the probably yield stress material factor equal to 1.1). In tension the overstrength factor is calculated similarly, without the inclusion of β. The resulting overstrength factors for the braces in compression and tension respectively are 2.1 and 1.6. Accordingly, all the timber connections and timber elements within the frame were designed to the probable capacities of the braces, including the overstrength factors noted above.

As shown in the following figures (4 and 5), ASPECT designed the typical brace connections using steel knife plates projecting from the ends of the braces, complete with multiple rows of stainless steel tight fit pins fastening the plates to the timber frame elements. All these connections were designed in accordance with the Canadian Engineering Wood Design Standard [6].

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***Figure 4:** Painted Brace Apex Connection*

***Figure 5:** Painted Brace-Column Connection*

Figures 6 and 7 show typical details for the brace apex and brace column connections. The brace-column connection features a 25mm thick steel knife plates fastened to the column with large groups of 16mm diameter tight fit pins. The plates project from the base of the columns to receive the end of the braces where they are fastened with 28mm diameter heavy hex bolts. The brace apex connection features a V-shaped 25mm thick steel knife plate that projects through a slot in the bottom of the beam and extends up to the top of CLT where it connects with a steel drag element running along the top of the floor. The steel drag strut eliminates the need to utilize the beam as a tie member, which greatly reducing the number and complexity of connections in the system. Whereas conventional chevron brace frames typically require large beams to resolve net vertical forces resulting when one brace buckles in compression and the other yields in tension, BRB's allow designers to avoid this design challenge as the compression capacity and the tension capacity are much closer. Accordingly, the glulam beam was simply designed to resist the comparatively small vertical reaction at the brace apex resulting from the brace action. As shown in figure 6, the beam is top flush with the floor panels. Shifting the beam upwards facilitated higher ductility in the braces by increasing their length, reducing the amount of steel required at the connections. Self-tapping screws installed through the depth of the beam serve to reinforce it against perpendicular to grain splitting, and screws installed through its width effectively clamp the beam and knife plate.

With deformation compatibility in mind, the intersections between the braces and the timber frame elements were detailed to accommodate sufficient rotation such that they could be idealized (as much as possible) as pinned connections. Horizontally slotted holes in the steel knife plates and the use of small diameter stainless steel tight fit pins help to prevent the connections from attracting moment and protect the timber elements from brittle failures. Researchers at the University of Canterbury performed a test program with a glulam frame BRB mock up comprising tight fit pin connections similar to those designed by ASPECT on this project. Their study investigated the cyclic performance of this type of system, and it demonstrated that the tight fit pins connecting the braces to the timber frame elements provided a decent amount of auxiliary ductility to the system while also carrying adequate strength to ensure the primary ductility mechanism would occur in the braces [7]. Additional ductility in a structure that is susceptible to significant earthquake effects is an invaluable benefit that can set the highest performing structures apart in a seismic event.

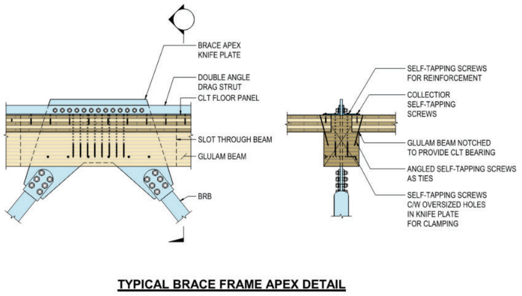

***Figure 6:** Brace Apex Detail*

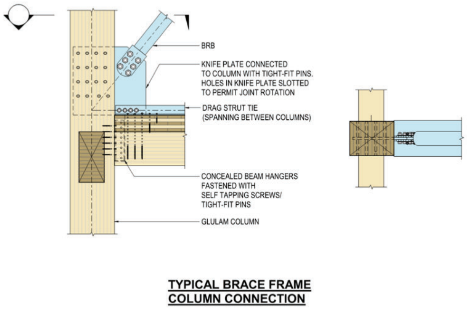

***Figure 7:** Brace-Column Detail*

4 FABRICATION AND ERECTION OF TIMBER STRUCTURE

Following the design process, ASPECT worked closely with Structurlam (the timber supplier) for modelling, fabrication, and shop installation of the lateral system components and connections. A steady supply of detail sketches delivered by ASPECT coupled with frequent coordination meetings between the two teams aided Structurlam as they modelled the structure and prepared a

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comprehensive shop drawing package. Despite the difficulties associated with having to navigate most of the design process during the early months of the Covid Pandemic, the help of remote meetings and a cohesive coordination schedule assisted the project team in successfully delivering construction drawings on time from their temporary home offices. The coordination between ASPECT and Structurlam aided to ensure accuracy in the fabricated components, and it helped to expedite and ease the installation process.

Structurlam assembled the largest and most critical lateral system connections in their shop. An example of this is observed in figure 8, where the large pre-installed column/brace knife plates located at the tops of the columns can be seen awaiting installation of the braces for the storey above. The pre-installation of the most complex components (notably the tight fit pin column-brace connections) saved a significant amount of onsite installation time and ensured that each of these critical connections was installed in a controlled environment by individuals with abundant mass timber experience.

Figure 8: *Brace Installation*

Tight fit connections demand very strict tolerances in both the steel and timber, and routinely this type of connection has shown to be quite difficult to install in-situ. Being installed in the shop meant that the exposed column faces housing the tight fit pin connections would not be subject to hammer blows by contractors with less experience during installation. To further alleviate the difficulty of installing some of the complex connections onsite, as shown in figure 9 below, the columns were fabricated and installed continuous over the building's first three storeys. Reducing the number of column splices also helped to provide as direct a load-path as possible, which was ultimately a huge benefit due to the high axial forces present in the columns towards the base of the structure.

Figure 9: *Continuous Column Installation*

Despite concerns about inclement weather and moisture management leading into the installation process, DBS's experience in mass timber construction ensured that due care was taken to protect the timber elements and all the crucial lateral system connections from damaging water ingress. Thanks to a carefully planned and executed moisture management strategy (one which included frequent squeegeeing, temporary rainwater leaders, coverings for the vital steel components, and an aggressive installation process) DBS was able to meet their erection goals even though installation occurred during a particularly rainy Pacific Northwest Winter (DBS' team had to deal with a combination of intense rains, snow, and driving winds throughout the mass timber installation process). Terminus' superstructure (including all gravity and lateral system elements) was assembled and erected over a span of roughly 2.5 months (this included 3 occupiable levels of mass timber and the roof, each of which comprise close to 1250m^2).

5 CONCLUSION

Several factors threatened to dampen progress on this building throughout design and construction, including the seismic demands of the region, the complexity of the lateral system connections, low tolerances in the system, a tight construction schedule, and the threat of inclement weather. Despite all these complications, the combination of collaboration, motivation, and experience displayed by the project team ultimately propelled this beautiful mass timber structure and its innovative lateral system to a timely completion. Opened in May 2021, Terminus' beautiful timber structure houses several new tenants, including DBS' entire design office. As the first of its kind in North America, the timber-BRB hybrid lateral system serves as a benchmark for success and innovation in modern mass timber.

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Figure 10: *Terminus Interior, DBS Office Space 1*

Figure 11: *Terminus Interior, DBS Office Space 2*

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