# Developing a Large Span Timber-based Composite Floor System for Highrise Office Buildings

## Phase I

by

Chao (Tom) Zhang
George Lee
Dr. Frank Lam

Prepared for

Forestry Innovation Investment
1130 W Pender St, Vancouver
BC V6E 4A4

Timber Engineering and Applied Mechanics
(TEAM) Laboratory
Department of Wood Science
Faculty of Forestry
University of British Columbia
Vancouver, B.C., Canada

April 9, 2021

## EXECUTIVE SUMMARY

This project proposes a timber-based composite floor that can span 12 m and be used in the construction of 40+ story office buildings. This floor system integrates timber panels and timber beams to form a continuous box girder structure. The timber panels function as the flanges and the timber beams as the web. The beams are spaced and connected to the flange panels so that sufficient bending stiffness of a 12 m span can be achieved via the development of composite action.

The current phase of this project studied the performance of the connections between timber elements in the proposed composite member. Six types of connections using different flange material and connection techniques were tested: Cross Laminated Timber (CLT), Laminated Strand Lumber (LSL), Laminated Veneer Lumber (LVL), and Post Laminated Veneer Lumber (PLVL). Glulam was used as the web. The majority of the connections used self-tapping wood screws except one had notches. The load-carrying capacity, stiffness, and ductility of the connections were measured. The stiffness of CLT, LSL, and PLVL connections was in the same range, 19-20 kN/mm per screw. Amongst the three, LSL had the highest peak load and PLVL had the highest proportional limit. The stiffness of the two LVL screw connections was around 13 kN/mm. The notched LVL connection had significantly higher stiffness than the rest, and its peak load was in the same range as LSL, but the failure was brittle.

LVL was used to manufacture the full scale timber composite floor element. With a spacing of 400 mm, the overall stiffness reached 33689 N•mm$^2\times10^9$, which was 2.5 times the combined stiffness of two Glulam beams. The predicted overall stiffness based on Gamma method was within 5% of the tested value, and the estimated degree of composite action was 68%. From both the test results and analytical modeling, the number of screws may be further reduced to 50% or less of the current amount, while maintaining a high level of stiffness.

Future work includes testing the composite floor under different screw spacings, investigating the effect of concrete topping, and the connections between floor members and other structural elements.

Reported by:

Chao (Tom) Zhang
Research Engineer

George Lee
Wood Engineering Scientist

Reviewed by:

Frank C.F. Lam, Ph.D., P. Eng.
Professor

# TABLE OF CONTENT

## LIST OF TABLES



## LIST OF FIGURES

# 1 INTRODUCTION

Mass timber technology is behind the fast growth of timber construction during the last decades. The National Building Code of Canada and provincial building codes have been updated to encourage the use of timber in large and tall buildings. Although using mass timber in multi-purpose high-rises have been envisioned by architects in recent years, most high-profile timber projects are 10-20 stories residential buildings with short-span interior spaces. There are engineering as well as financial concerns behind such choices. A pure wood solution for 25+ stories may not be practical as extreme member sizes may be needed to account for some of the relatively weak structural properties of wood. The current span limit of timber floor is 8-9 m, and for longer spans it normally requires the use of deep drop beams. The recent booming office market in North America creates vast opportunities for the use of timber and timber-based building solutions. A particular challenge of using timber in high-rise office buildings involves the floor span. A typical office setting requires a clear floor span of 12 m, which is beyond the current 8-9 m limit of timber floors. To add drop beams supporting timber floor is not an option since it would reduce the valuable head space.

This project proposes a timber-based composite floor that can span 12 m and be used in the construction of 40+ story office buildings. The load-bearing walls and columns are made of reinforced concrete or steel, while the floors and infill walls are made from timber. Concrete/steel will mitigate the fire risks and isolate the fire if properly designed. The composite floor system will be prefabricated and assembled onsite, which significantly reduces construction time while maintains a high quality control. For a 40+ story project, the time saving of a timber solution would be amplified to the extent that the financial savings alone would justify the use of timber.

This floor system integrates timber panels and timber beams to form a continuous box girder structure. The timber panels function as the flanges and the timber beams as the web. The beams are spaced and connected to the flange panels so that composite action is created to provide enough bending stiffness for a 12 m span.

Currently for Nail Laminated Timber (NLT) floor made from 2×8 lumber, the typical span is 4-6 m (14-21 ft.). When 2×12 lumber is used, the span could increase to 6-8 m (20-26 ft.). For a 7-ply Cross Laminated Timber (CLT) floor, the span is in the range of 5-7 m (17-21 ft.). With a 9-layer CLT, the span may come to 8 m (26 ft.). The Cree system developed in Europe is a series of closely spaced drop beams with concrete topping and concrete ring elements, and the maximum span is 9 m.

There have been some studies on generating composite action using timber elements in order to create longer spans, mostly as beams. Masoudnia et. al. (2016) investigated the composite T-beam made of CLT and glulam with self-tapping wood screws. A 6 m span beam was tested and the results were used to validate a computer model. The depth of the system was 800 mm. It was found that using CLT panels with higher modulus of elasticity improved the effective flange width. The results indicated that considering a full composite action remarkably reduces the amount of material needed and the related costs. Jacquier and Girhammar (2015) evaluated a connection made out of inclined screws and double-side punched metal plates for composite T beams. The T beams tested were 6.5 m long. Experimental results showed that the level of composite action achieved between the glulam beam and the CLT panels can be high when using the double sided nail plates (with screws or not) and that this type of fastener was suitable for relatively long composite timber floor elements. Chen and Lam (2013) tested a box-based CLT system, with different material and configurations. The cross section tested was not suitable for long span applications. But the results indicated the potential of this box shaped configuration.

Montgomery (2014) tested a series of timber to timber connections that were aimed for a hollow mass timber panel. Only CLT was used as flange and most of the high stiffness connections were complicated to install. No floor test was conducted and the application was verified by computer models. Gu (2017) developed a composite box floor using CLT made from southern yellow pine, a configuration similar to what was proposed in this project. The beam was 12 m (40 ft.) long, but due to the connection and material used, the beam did not have sufficient stiffness. Others tried to use steel bars or steel cables to increase the stiffness of timber beams, such as Esteves-Cimadevila et. al. (2018), Martin-Gtierrez et. al. (2018), and McConnel et. al. (2014). Some improvement in stiffness and strength was found, up to 30%. But the cost, labor involved, and long term performance of this system are obstacles for wide application. Natalini (2020) studied the feasibility of using self-tapping wood screws to create a composite T-beam by connecting a CLT flange and Glulam web. The stiffness was measured under different screw spacing and the results were compared to different analytical models.

In Phase I of this project (2020-21), various flange-web connections were tested to quantify its mechanical performance and identify the failure mode. Based on the results, one combination was chosen to manufacture a 12 m long composite floor. The composite floor was tested under third-point bending to measure its overall stiffness, deflection, and the relative displacement between flanges and the web. The analytical model based on Euro Code 5 was verified by the test results, and then the model was used to predict the performance of long span floors with other configurations.

## 2 MATERIAL AND METHODS

The flange material considered in this project included Cross Laminated Timber (CLT), Laminated Strand Lumber (LSL), Laminated Veneer Lumber (LVL), and Post Laminated Veneer Lumber (PLVL). The Glulam used in the test was Douglas-fir 24f-E: one depth for small scale tests and one for the full scale test. The characteristics of the wood material, screws, and adhesives are shown in Table 1.

Table 1 Material characteristics

| Material | Characteristics |
|---|---|
| CLT | 105 mm thick, V105 Grade V2M1.1, Spruce-Pine-Fir, by Structurlam |
| LSL | 89 mm (3-1/2 in) thick, 1.35E TimberStrand (9.31 GPa) |
| LVL | 44.5 mm (1-3/4 in) thick, 2.0E Microllam LVL (13.79 GPa) |
| PLVL | 83 mm (3-1/4 in) thick, Brisco Fine Line™ Panels |
| Glulam | For small scale tests, 195 mm depth, DF 24f-E |
| Glulam | For full scale, 80 mm by 418 mm by 12 m, DF 24f-E |
| Screws | ASSY VG CSK Ø12 mm×160, Ø10 mm×300, Ø10 mm×380<br>ASSY 3.0 Washer head, Ø10 mm×200, thread length 100 mm |
| Epoxy | System Three General Purpose Epoxy, 2:1 mixing ratio |

The small scale connection test was conducted on an H-shaped specimen: one center member connected to two side members, as shown in Figure 1. Two screws were driven at 45° into each side member and the screws were under tension during the loading. Two transducers were mounted on the center member to measure the relative displacement between the center member and side members.

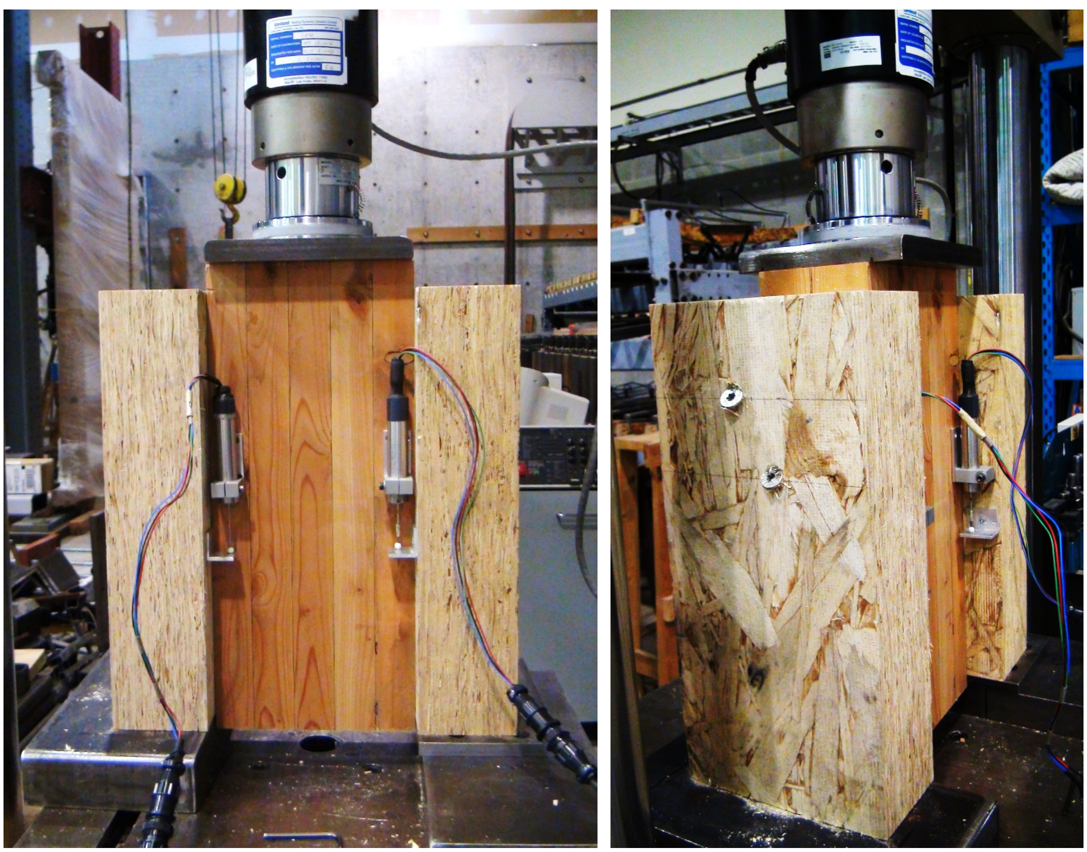

Figure 1 Setup for connection tests

Six types of connections were tested as shown in Table 2. The wood members were clamped together during installation to ensure there was no gap between them. The screw spacing met the requirements specified by the manufacturer. The screws were offset from the center to prevent crossing the screws on the other side. The LVL also had a notched configuration: both the LVL and Glulam were notched 12.7 mm (1/2 in) deep to have a tight fit, and the two were joined together by two partially threaded screws. After notching, the effective length of each side member under shear was 200 mm. For PLVL, the screw was driven in parallel to the face of the veneer.

Table 2 Connection configurations and replicates

| Flange Material (width in mm) | CLT (130) | LSL (184) | LVL (184) | PLVL (102) |
|---|---|---|---|---|
| Ø12 mm×160 | / | / | 3 | / |
| Ø10 mm×300 | 5 | / | 3 | |
| Ø10 mm×380 | / | 5 | / | 5 |
| Notched | / | / | 5 | / |

The full scale composite floor was made from 457 mm (18 in) wide LVL panels and 80 mm by 418 mm Glulam beams. Since the longest LVL commonly available on the market is 7.3 m (24 ft.), each flange member was made by joining at least two pieces of LVL, as shown in Figure 2. It should be noted, however, LVL can be made in longer lengths as its manufacturing involves continuous pressing. In such cases connecting short pieces of LVL will not be needed. Here LVL strips of the same grade were glued to top and bottom of the long LVL panels with epoxy. The length of the LVL strips was 750 mm and it was centered at the joint. The connection was at the midspan of the top flange and was at the quarter length of the bottom flange, so that the maximum tensile stress was not the joint. The gaps on the flange connections were for positioning the two Glulam beams.

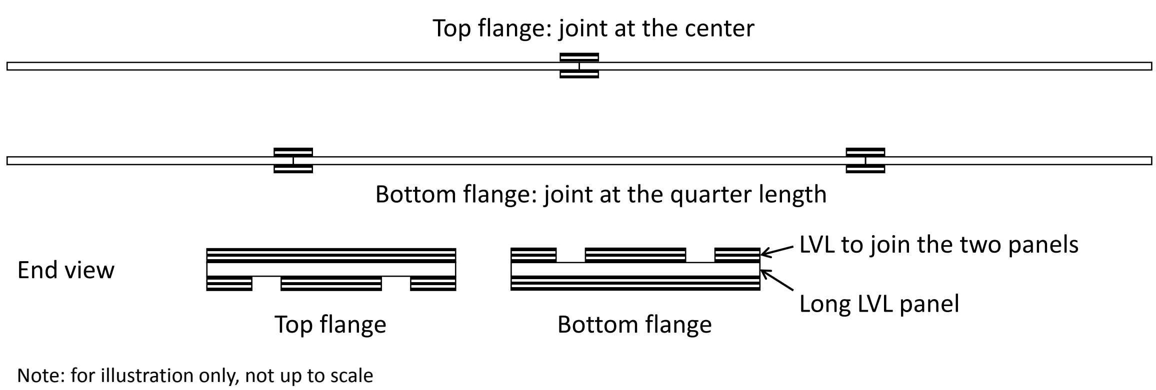


Figure 2 Making a long flange member

The two Glulam beams were then connected to the flanges with Ø10×380 fully threaded self-tapping wood screws. The screws were driven at 45° and the screws were under tension-shear during the loading. The screw spacing was 500 mm within the shear-free zone and 400 mm outside the shear free zone.

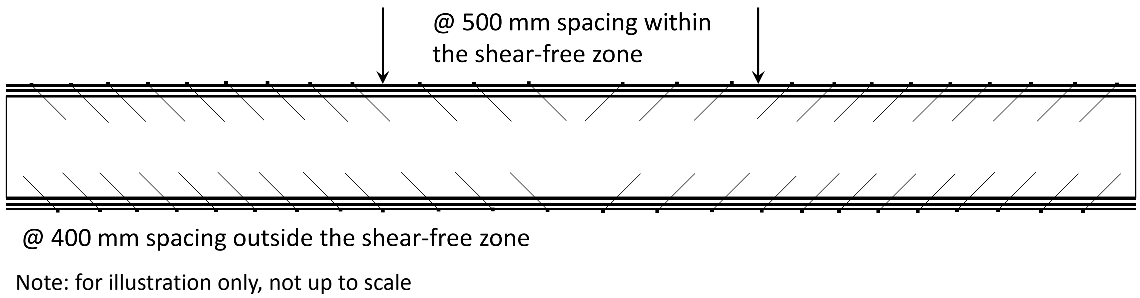


Figure 3 Screw spacing for the composite floor

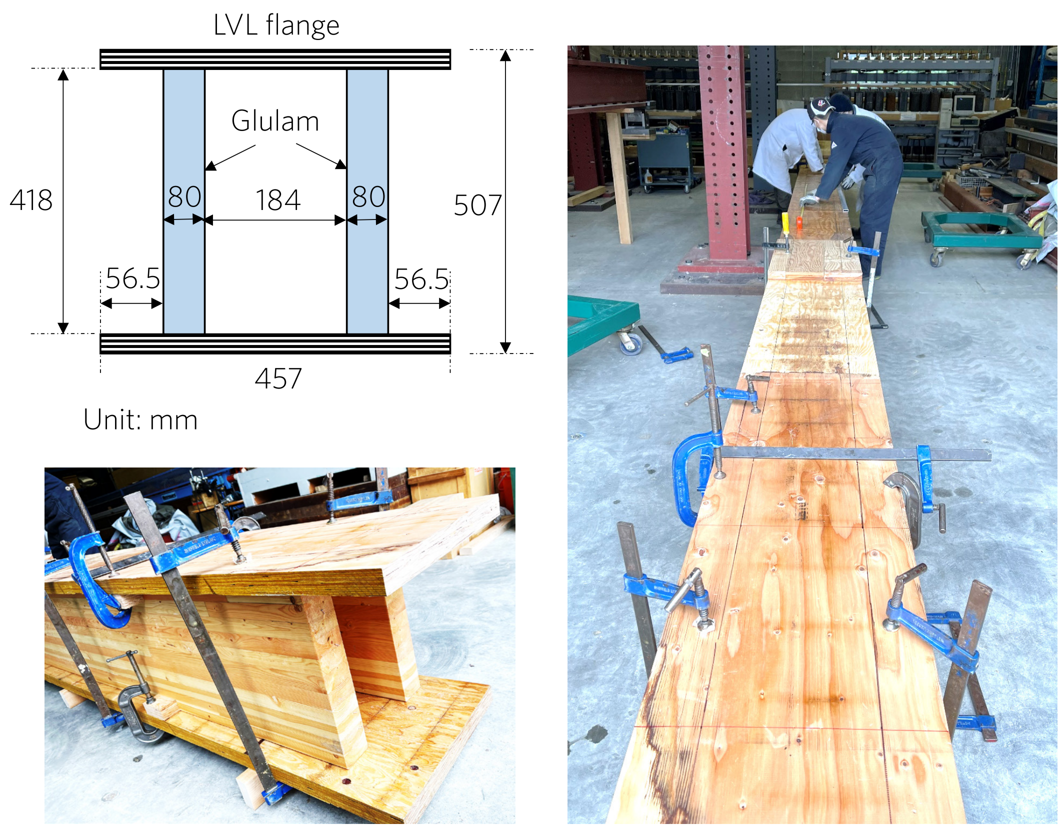


Figure 4 Configuration and manufacturing of the composite floor

The composite floor was tested under third-bending with a span of 11.7 m (150 mm overhang on each end). The loading rate was 3 mm/min and the specimen was loaded to 25 kN. Eleven transducers were installed to measure the deflection of the composite floor on its neutral axis, the relative displacement between flanges and the web, and the bonding of LVL, as shown in Figure 5. The test setup is shown in Figure 6.

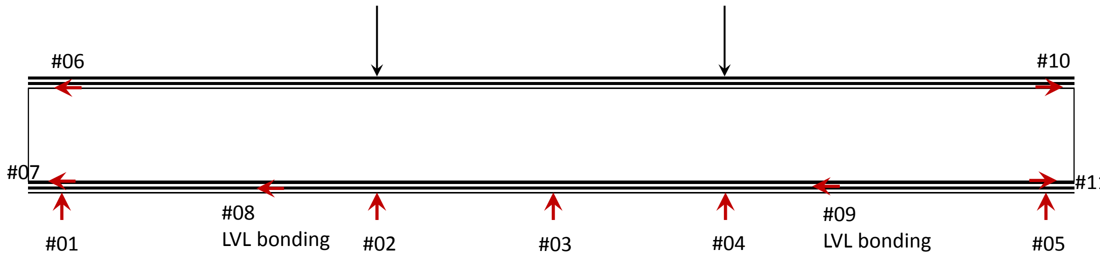


Figure 5 Transducer locations

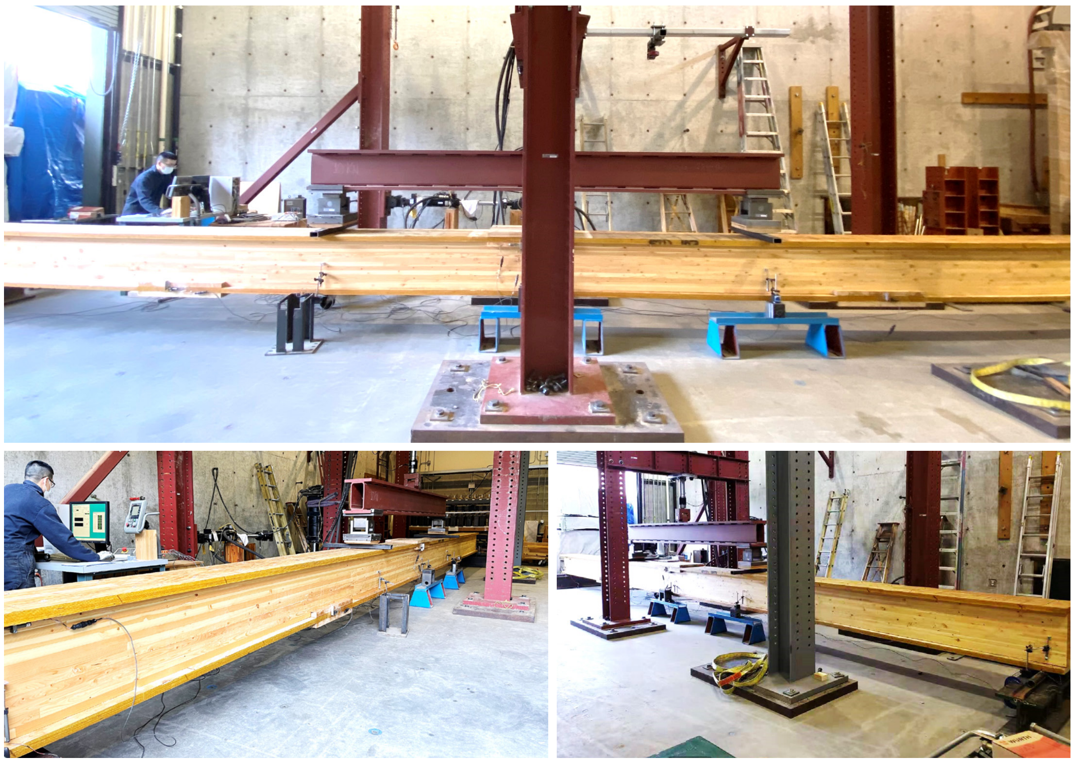

Figure 6 Full scale floor bending test setup

# 3 RESULTS AND DISCUSSIONS

The results of the connection tests are shown in Table 3. The stiffness was calculated by the linear portion of load-displacement relationship between 10% and 60% of the peak load. It is to be noted that the peak load, stiffness, and proportional limit in Table 3 are for one screw except for the notched connection. The stiffness of CLT, LSL, and PLVL connections was in the same range, 19-20 kN/mm per screw, while LSL had the highest peak load and PLVL had the lowest displacement at the peak. The peak load of CLT was lower since the density of CLT was lower than LSL and PLVL. The two LVL screw connections had similar stiffness at around 13 kN/mm. The notched connection had a significantly higher stiffness than the rest, and its peak load was about equal to the peak load of LSL with four screws.

The load-displacement relationships of representative specimens of each cell are shown in Figure 7. The LVL screw connections had lower stiffness/strength but the load retained at a high level after the peak, indicating good ductility. The performance of CLT and PLVL connections was similar. PLVL had the highest proportional limit over all, which meant it could maintain a high stiffness within a large deformation. The LSL and LVL-notch had the highest load capacity but the failure of LVL-notch was brittle, besides the fact that its performance was closely related to the dimensional accuracy of the notches.

Table 3 Summary of connection test results

| Connection type | Average peak load $P_{max}$ (kN) | Average stiffness $K$ (kN/mm) | $\Delta_{Pmax}$ (mm) | Proportional limit (kN) | $\Delta_{0.8Pmax}$ (mm) |
|---|---|---|---|---|---|
| CLT Ø10 mm×300 | 28.3 | 19.1 | 3.2 | 19.1 | 7.9 |
| LSL Ø10 mm×380 | 39.0 | 19.9 | 3.5 | 19.9 | 7.4 |
| LVL Ø12 mm×160 | 19.8 | 13.1 | 4.2 | 12.7 | / |
| LVL Ø10 mm×300 | 17.8 | 13.5 | 2.5 | 12.5 | / |
| LVL Notched | 168.2 | 184.5 | 3.1 | / | / |
| PLVL Ø10 mm×380 | 30.6 | 19.6 | 2.1 | 28.3 | 5.3 |

Note: $\Delta_{Pmax}$: displacement at peak load; $\Delta_{0.8Pmax}$: displacement when load dropped to 80% of the peak
The peak load and stiffness of LVL Notched are for the whole connection.

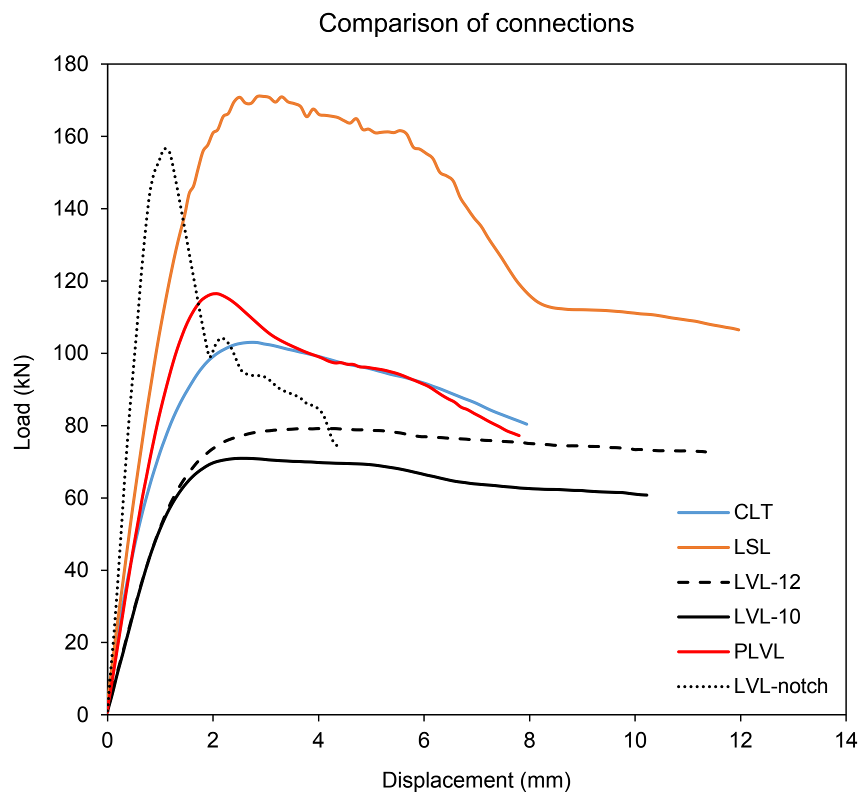


Figure 7 Load-displacement relationships for different connections

The majority of the failure was screw head pull-through, as shown in Figure 8, except that LVL Ø12 mm×160 was withdrawal and LVL Notched was wood shear failure at the notches. The screws had no visible deformation laterally.

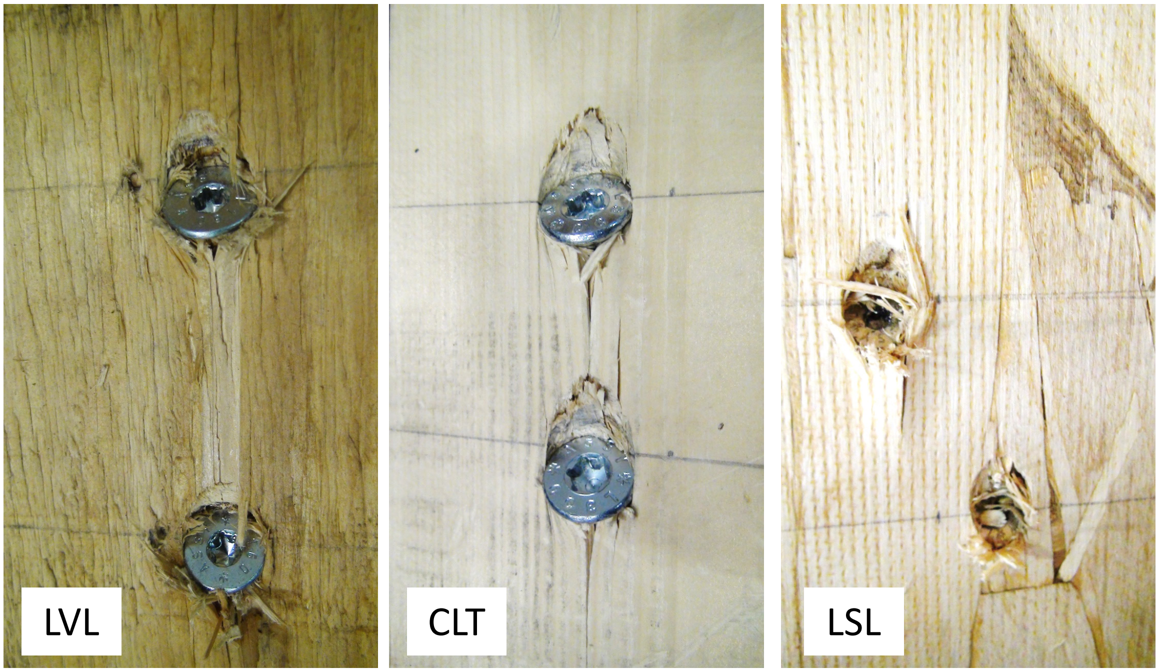


Figure 8 Head pull-through failure

The application of these connections in the long span floor system was then evaluated based on the connection and material properties. CLT is currently the most widely used mass timber floor material on the market, and its connection stiffness measured here was reasonably high. Due to the existence of cross layers, it is not as efficient in bearing tension/compression load and moment as the other material. However, its two-way action capability could be important if the flange is very wide. With a relatively low density, CLT is also easy for fasteners to penetrate into. LSL, often used as framing studs, beams, or rim boards, could be converted for floor applications. Its width is up to 600 mm and the grade is from 1.3E to 2.1E (though 1.35E and 1.55E are mostly common). The higher grade LVL is suitable as a flange in the composite floor, but the corresponding high density should be noted, especially when working with fasteners. PLVL has a strong resistance for axial load or moment as a result of its vertical veneer alignment. The stiffness and ductility of its connection is also good, but the availability and cost of PLVL may become an issue for mass production. LVL notched connection is difficult to manufacture for a long panel, and at least 6-10 mm depth is cut off due to notches. Therefore, it is not recommended unless automated manufacturing system is established to maintain a consistent notching quality. Its brittle failure may be mitigated by adding screws. LVL is available for a wide range of dimensions and grades. Its higher grade products, for example 2.0E or above, do not have any problem for large diameter fasteners, as found in this test.

Therefore, LVL and Ø10 mm×380 were selected to make the full scale long span floor. Compared to Ø10 mm×300 used in the connection test, the longer embedment length would not increase its withdrawal capacity since the embedment length of Ø10 mm×300 in Glulam already exceeded 16D. Thus the stiffness would not change. The longer screws were used for future investigation in the reinforcing mechanism of screws to the performance of Glulam.

The maximum moment applied on the composite floor was 48.8 kN•m (25 kN), which was 1.3 times the maximum moment under a uniform load of 4.8 kPa. The results of the full scale composite floor test is shown in Figures 9 and 10. In Figure 9, the long yoke indicates the deflection of the midspan relative to the supports, and the short yoke indicates the deflection of the midspan relative to the loading points (within shear free zone). As expected, the load-displacement relationship was linear since the load was far below the ultimate capacity of the floor. The largest deformation between the flange and web measured at the two ends was 0.58 mm. The relative displacement between the jointed LVL panels was negligible, indicating a good bonding, based on which the jointed LVL panel was considered as a continuous slab in the analysis.

The deflection at the midspan was 20.7 mm at 25 kN. The overall stiffness of the composite floor was 33689 N•mm$^2$×10$^9$, which was 2.5 times the combined stiffness of two Glulam beams working without flanges. The stiffness measured at the shear-free zone was 34000 N•mm$^2$×10$^9$.

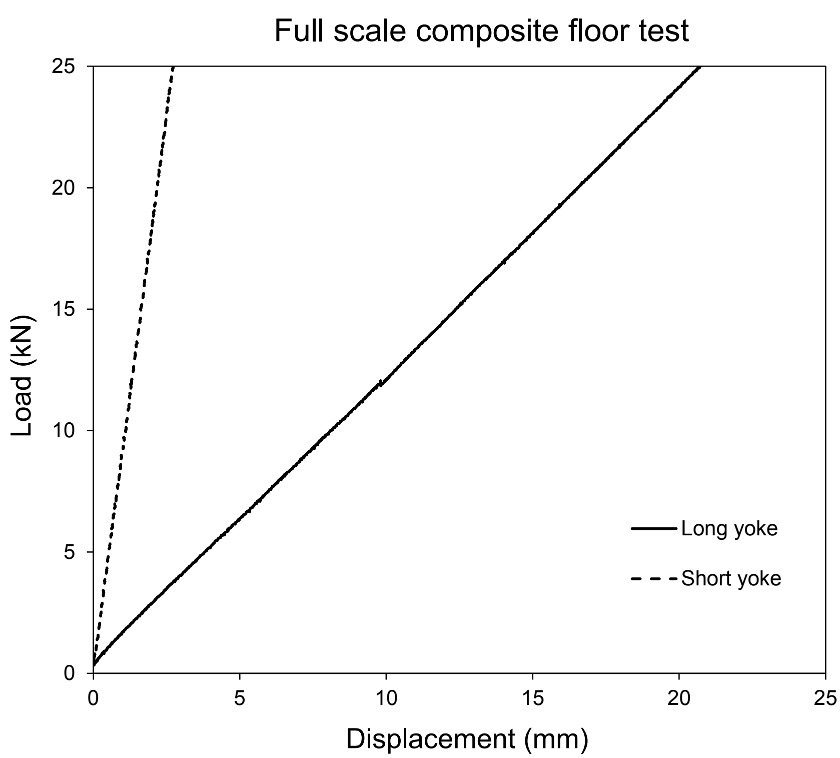


Figure 9 Load-displacement relationship of the full scale floor test

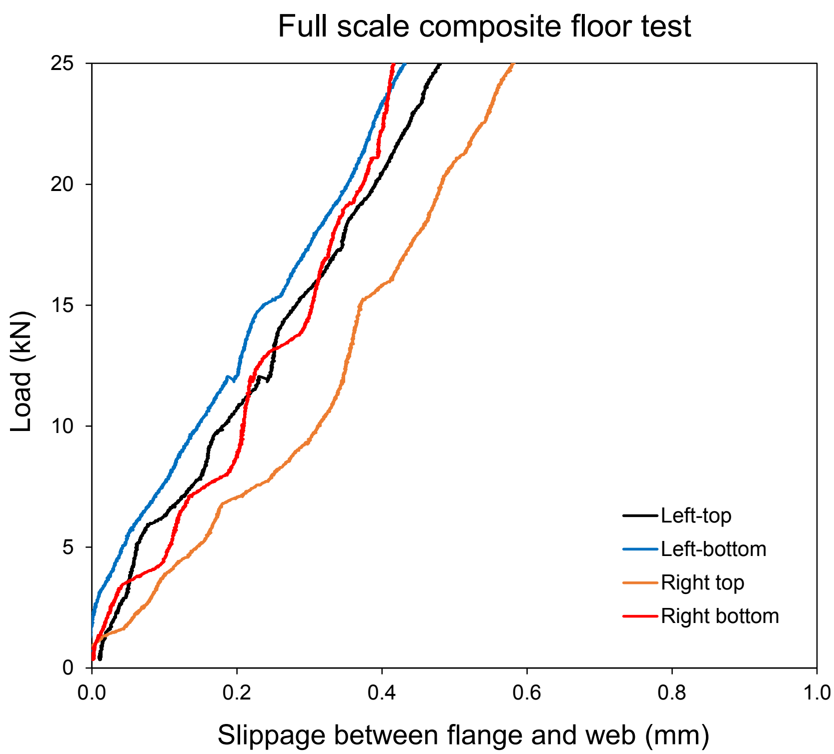


Figure 10 Slippage between flange and web at the highest shear stress zone

The mechanically jointed beams theory (Gamma method) in Eurocode 5 (2004) was used to predict the overall stiffness of the composite floor based on the stiffness obtained from the connection test. The difference between the predicted stiffness and the measured stiffness was 5%, and the difference of the corresponding deflection was 6%, as shown in Table 4.

Table 4 Comparison between the test results and predictions by Gamma method

| | Overall stiffness ($N\bullet mm^2 \times 10^9$) | Deflection at 25 kN (mm) |
|---|---|---|
| Gamma method | 32137 | 22.1 |
| Tested value | 33689 | 20.7 |
| Difference | +5% | -6% |

The degree of composite action (DCA in percentage) as defined by Jacquier (2015) was calculated by Equation (1) and the DCA for the current configuration was 68%.

$$DCA = \left[\frac{EI_m - EI_0}{EI_\infty - EI_0}\right] \times 100\% \tag{1}$$

where

$EI_{sf}$= measured overall stiffness of the composite floor;

$EI_0$= stiffness of the composite floor under non-composite action, that is, no connection between flanges and web; for now, this was predicted by Gamma method;

$EI_\infty$= stiffness of the composite floor under full composite section, that is, perfect bonding between flanges and web; this was also predicted by Gamma method.

Based on Gamma method, the performance of the composite floor under different screw spacing was predicted in Table 4 (the same connection as used here). The results indicate that the screw spacing could be increased to 800 mm or 1000 mm while still maintaining a high level of stiffness. This will be verified in Phase II of this project.

Table 4 Predicted overall stiffness and DCA

| Screw spacing (mm) | Overall stiffness (N•mm$^2$×10$^9$) | Degree of Composite Action | Deflection under uniform load 4.8 kPa (mm) |
|---|---|---|---|
| 200 | 36450 | 77 | 14.7 |
| 400 | 32137 | 63 | 16.7 |
| 800 | 27033 | 46 | 19.8 |
| 1000 | 25398 | 40 | 21.1 |
| No screw | 11387 | 0 | 40.0 |

## 4 CONCLUSIONS

The current phase of this project studied the connections between timber elements in the large span timber composite floor. Six types of connections using different flange material and connection techniques were tested. The load-carrying capacity, stiffness, and ductility of the connections were measured. All the fives screw connections had ductile failure and the stiffness per screws was in the range of 13-20 kN/mm. Generally the thicker and denser material would lead to higher stiffness and higher peak load. The advantages and potential issues related to each configuration were also identified.

LVL was used to manufacture the full scale timber composite floor. With a spacing of 400 mm, the overall stiffness reached 33689 N•mm$^2$×10$^9$, which was 2.5 times the combined stiffness of two Glulam beams. The predicted overall stiffness based on Gamma method was within 5% of the tested value, and the estimated degree of composite action was 68%. From both the test results and analytical modeling, the number of screws may be further reduced to 50% or less of the current amount.

## 5 FUTURE WORK

The screw spacing will be changed to investigate the composite action with large screw spacing, and to verify the analytical model under such conditions. Additional issues to be studied include the reinforcing effect of screws to the performance of Glulam, other connection techniques, and adding more replicates of the current configurations. Phase II of the project (2021-22) will also work on the reaction between timber floor with concrete toppings, the vibration performance, and the connection between the composite floor and concrete/steel members.

# 6 REFERENCES

Chen Yue, Lam Frank. (2013). Bending performance of box-based cross laminated timber systems. Journal of Structural Engineering. Vol. 139, Issue 12 (December 2013). https://doi.org/10.1061/(ASCE)ST.1943-541X.0000786

Estévez-Cimadevila, Javier & Riestra, Félix & Otero-chans, Dolores & Martín-Gutiérrez, Emilio. (2018). Experimental Analysis of Pretensioned CLT-Glulam T-Section Beams. Advances in Materials Science and Engineering. 2018. 1-12. 10.1155/2018/1528792.

European Committee for Standardization (2004). Eurocode 5: Design of timber structures—Part 1-1: General - Common rules and rules for buildings (EN 1995-1-1:2004/A2:2014 E).

Gu, Mengzhe. (2017). Strength and serviceability performances of southern yellow pine cross-laminated timber (CLT) and CLT-glulam composite beam. Clemson University. Clemson, South Carolina.

Jacquier, Nicolas & Girhammar, Ulf Arne. (2015). Evaluation of bending tests on composite glulam–CLT beams connected with double-sided punched metal plates and inclined screws. Construction and Building Materials. 2015. 95. 762-773. 10.1016/j.conbuildmat.2015.07.137.

Martín-Gutiérrez M, Estévez-Cimadevila J, Otero-Chans D, Suárez-Riestra F. (2018). Self-tensioning long-span T-shaped spruce and oak web floors with a CLT upper flange: An experimental approach. Engineering Structures. 2018. 168. 300-307. 10.1016/j.engstruct.2018.04.086

Masoudnia, Reza & Hasemi, Ashkan & Quenneville, Pierre. (2016). Evaluation of effective flange width in the CLT composite T-beams. World Conference on Timber Engineering. 2016. 4507-4514.

McConnell, E., McPolin, D., & Taylor, S. (2014). Post-tensioning of glulam timber with steel tendons. Construction and Building Materials, 73, 426-433. DOI: 10.1016/j.conbuildmat.2014.09.079

Montgomery, William Graham. (2014) Hollow massive timber panels: a high-performance, long-span alternative to cross laminated timber. M.Sc thesis. Clemson University.

Natalini, Giulia. (2020) Composite action in mass timber floor and beam systems connected with self-tapping wood screws. M.Sc Thesis. University of British Columbia.

THE END