Material Testing

State of Research for Shear Connector Performance in Cross Laminated Timber Composite or Hybrid Framing

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The emergence of cross-laminated timber (CLT) as a sustainable construction material in the United States is opening commercial and industrial building stock to the timber industry, an area otherwise currently dominated by structural steel and reinforced concrete. CLT panels are limited in span, requiring the use of timber or steel beams and columns. This paper presents an in-depth review of existing research focused on shear connector performance with respect to composite beam action between CLT panels and structural steel beams. Numerous conclusions are presented alongside commonly indicated areas for future work resulting in a "state of research" for steel-CLT composites.

Keywords: *Mass Timber Construction; Cross Laminated Timber, Steel-timber, Steel-CLT, Composite Beam, timber construction*

The timber construction industry is currently undergoing a seismic shift in capacity and relevance. When managed responsibly, timber is continuously viewed as the leader in sustainable construction in many aspects. The Institute for Sustainable Infrastructure Envision Sustainability Rating System [1] identifies quality of life, leadership, resource allocation, the natural world, and climate and risk as the primary indicators of a sustainable engineering project. Timber construction excels in at least three of these areas; quality of life, resource allocation, and climate and risk. First, research by Song and Fei [2] indicate a clear human psychological preference for timber structures due to their perceived and measured increase in "warmth", leading clearly to an increased quality of life. Second, timber can often be locally sourced and has a high affinity for reuse, both of which improve resource allocation.

Lastly, and perhaps most notably, timber is a renewable resource which offers significant benefits with respect to climate risk as compared with other building materials [3]. Trees are exceptional carbon capture systems, which are estimated to hold approximately 1.10 tons of CO_2 per cubic meter. Considering further the life-cycle of timber structures, specifically the construction phase, timber buildings require 30% less energy than concrete framed buildings. Steel requires 19.520 GJ/t of energy consumption, concrete 0.764 GJ/t, whereas timber requires 0.545 GJ/t [4]. Due to the increased insulation properties of wood compared to steel, the energy within the operational phase is also significantly less than its competitors.

While timber dominates the residential construction industry, by square footage timber is significantly outpaced by other building materials such as structural steel, reinforced concrete, and structural masonry. One reason behind this imbalance is a code [5] mean height restriction on light-framed (and thereby significantly flexible) structures of 20 meters; it becomes unrealistic to resist structural demands beyond this height with a light-framed structure. For many decades designers have used glue-laminated beams to handle substantial flexural and shear demands in lieu of large, old growth trees; effective lateral force-resisting systems have lagged. However, in recent years cross-laminated timber (CLT) panels have allowed engineers to reimagine high-rise timber. CLT panels, such as those in Figure 1 are a close cousin of glue-laminated beams, consisting of alternating layers of small dimensional lumber, resulting in panels (or slabs) with significant strength and stiffness characteristics. CLT panels can be used both for floor and roof diaphragms, as well as shear walls.

Figure 1: Stacked CLT Panels [6]

Innovations in this sector have resulted in a steady increase in "high-rise" structures across Europe, now also emerging in the United States. As a result, the building stock available to timber continues to increase, which in turn means more expansive use of a sustainable construction material. Of many obstacles, span length is identified as a design limitation of CLT construction; most feasible CLT panels can only span between 3 and 5 meters. Designers have turned therefore to either glue-laminated beams or steel beams to increase floor systems spans.

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In an effort to increase efficiency, research is currently underway investigating using CLT panels and steel beams as a composite system, similar to steel and reinforced concrete composite floor systems common in many commercial and industrial buildings.

The research in this area is relatively new, and therefore sparse. The purpose of this paper is identify existing research in the area of composite CLT connections, and identify areas where more research is needed. The paper is broken into three specific sections: steel-timber composite components, steel-timber composite/hybrid structures, and timber-timber and timber-concrete composite components. The authors of this paper are specifically interested in CLT-structural steel composites, however due to the infancy of the research area, it is important to understand the common connection methods across a wide range of CLT applications. After a thorough review of the existing literature, the authors offer recommendations on future research in the area of CLT-structural steel composites.

Steel-Timber Composite Beams

The primary objective of this paper is to collect and review existing data on CLT-steel composite components. This section focuses specifically on this objective, and also includes review of other types of metal-timber connections for completeness and to identify other potential means for CLT-steel connections. Mechanical fasteners are a prime candidate for shear transfer between steel beams and CLT panels due to their ease of installation, low cost, and availability onsite. However, installation tolerances increase the likelihood that some initial slip occurs upon loading, which in turn may result in unintentionally lower initial bending stiffness.

Dowel-Type Mechanical Fasters

The majority of steel-CLT composite beam shear connectors tested in the literature are some form of mechanical dowel-type fasteners. Some researchers reviewed modifications to dowel-type fasteners, including adhesive at the interface, or grouted pockets; results of these efforts are discussed in the section on Intended Improvements to Mechanical Fasteners.

Hassanieh et. al [7] investigated the performance of dog screws and coach screws as shear connectors for use in composite steel-CLT sections. A series of laboratory double-shear pushout tests were performed using CLT-steel-CLT specimens with a variety of the connectors listed above, as summarized in Table 1. The objective of this research was to determine the effects of fastener type, diameter, length, and grade as well as the use of a grout pocket and the CLT grain direction at the interface on the overall stiffness and strength of the shear connection.

The authors made several pertinent observations and conclusions based on the test results. First, the loading direction (with respect to CLT grain direction) of the fasteners had little effect on the ultimate strength of the steel-CLT joints, but the initial stiffness of the fasteners loaded perpendicular was significantly lower than those loaded parallel to grain. This was a substantial finding considering the importance in initial stiffness with respect to composite action. In addition, the stiffness and ultimate strength of the coach screw and dog screw specimens were similar, with the dog screw specimens being slightly higher. The yield strength also had little to do with overall stiffness and strength in these specimens as local effects such as timber crushing typically governed.

Building on their previous research, Hassanieh et al. [8] investigated the performance of full-length steel-timber composite (STC) beams using various mechanical fasteners with and without supplemental grip resistance. Discussion in this section is limited to those specimens without supplemental grip resistance; specimens with additional grip resistance (such as nailer plates and glue) are discussed further in n the section on Intended Improvements to Mechanical Fasteners. Four-point bending tests were performed on several full-size samples, which were evaluated for structural performance based on the load-deflection response, short-term stiffness, peak load capacity, and failure modes. The main variables of the test were connection type, the direction of loading in the CLT panels (parallel or perpendicular to the grain), and the size of the steel girders.

A major outcome of this research focused on composite efficiency, which is a measure of how close different connection methods were to full composite action (zero-slip at shear interface). This efficiency was based on analytical determinations of fully composite, and fully non-composite flexural strengths, as compared with the flexural strength determined through testing. All STC beams exhibited a composite efficiency (CE) of 70% or higher. It is noted that tolerance issues (that may cause slip at initial loading) and much more pronounced in double-shear pushout tests as compared to these full-size beam tests.

Loss et. al [9] investigated various mechanical fasteners and techniques for use in assembling prefabricated hybrid steel-CLT structures. The authors looked specifically at splicing CLT panels longitudinally, but also reviewed fasteners used for positive connection with steel girders (not necessarily composite action). The primary focus of the review in this paper is to identify performance of the mechanical fasteners based on their installation methods (and geometry). This research program also investigated the impact of supplemental grip resistance, which is discussed later.

Table 1: Experimental Test Matrix [7]

Fastener Type	Diameter (mm)	Length (mm)	Connector Grade	Grout Pocket Size (mm)	Grain Direction
Coach Screw	12 16 20	100	4.6	N/A	Perpendicular
Dog Screw	16 19	125 135	5.8	N/A	Parallel

Double shear push-out tests were used in conjunction with monotonic and cyclic loading procedures. Each specimen was constructed using 5 layered CLT panels of C24 [10] class timber. The panels had nominal thicknesses of 100 mm with three layers in the longitudinal direction and two layers in the traverse direction with the grain of the outer layers aligned with the beam's main axis.

The mechanical connections were found to fail in shear-tensile rupture of the screws or bolts. Overall, screw based mechanical connections performed better than steel bar connections. The strongest mechanical connection tested featured steel brackets welded on both sides with fully threaded self-tapping that were installed on an incline with respect to the slip interface between the steel and CLT members.

Chybinski and Polus [11] investigated the strength and stiffness of screw-type connectors for use in composite aluminum-timber beam (ATC) sections. The authors of this work proposed a method for calculating the bending resistance of the ATC beams as well as the strength and stiffness of the connection type.

The theoretical analysis was performed assuming normal stress in aluminum beam flanges did not exceed yield strength of aluminum, and the normal stress in timber did not exceed the compressive strength of timber. To estimate the behavior of the fasteners, the authors used previously developed modeling techniques for steel-timber composite (STC) beams [11] and applied them to the ATC beams. In order to predict the behavior of the composite beam, the cross-section of the ATC beam was replaced with an ideal cross section with a reduced slab by way of modified elastic moduli. The plastic resistance to bending of the beam was calculated assuming equal normal force in the aluminum beam and the timber slab, thereby assuming full composite action.

The experimental program included both pushout tests and four-point bending tests. Two pushout specimens were tests, each constructed of two LVL timber panels and eight hexagonal, hot dip galvanized steel, and wood screws. In addition to pushout tests, two specimens were subjected to a four-point bending test to investigate the behavior of the composite beam.

From the tests and analysis above, the authors drew several conclusions. Based on the experimental investigations, the serviceability limit of the ATC beams was reached at approximately 30% of the ultimate load capacity. Future work will possibly investigate the effect of the spacing of the connectors on performance. Although the modeled plastic bending strength was similar to the mean value from the tests, the model should be improved to account for sudden tensile fracture and the slip; the elastic model appears to be sufficient for designing ATC structures of this type. The formulas proposed in this paper for the slip moduli and peak load performance of the connections are worth considering when designing screwed connections.

Lastly, Atei et. al [12] investigated the cyclic behavior of dowel and screw-type fasteners in steel-timber composite beams. A total of 12 test specimens (summarized in Table 2) were fabricated in which two CLT panels were secured to the flanges of a steel profile. Each specimen was subjected to a low-cycle, high-amplitude loading regime. A variety of specimens were fabricated in order to investigate the effect of the connector type, size of connector, and the orientation of the CLT panels with respect to the direction of loading.

Failure modes I to IV recognized by the European Yield Model (EYM) were observed in the tests. The failure modes for each specimen are shown in Table 2. The performance of the shear connectors under cyclic loading was defined by three main parameters. The first was the ductility index which is the ratio of the ultimate slip to ultimate yield, both of which are defined in EN 12512 [13].

Table 2: Experimental Test Matrix and Failure Mode Analysis [12]

Specimen	Grain Direction	Connector Type and Size	Failure Mode
CS12-Par	Parallel	12 mm Coach Screw	IV
CS12-Per	Perpendicular		III
CS16-Par	Parallel	16 mm Coach Screw	II
CS16-Per	Perpendicular		I
CS20-Par	Parallel	20 mm Coach Screw	I
CS20-Per	Perpendicular		I
DS16-Par	Parallel	16 mm Dog Screw	II
DS16-Per	Perpendicular		I
DS19-Par	Parallel	19 mm Dog Screw	I
DS19-Par	Parallel	19 mm Dog Screw	I
DS19-Per	Perpendicular		I
PB16-Par	Parallel	M16 High Strength Bolts	IV
PB16-Per	Perpendicular		II

The second parameter, impairment of strength, can be expressed as the reduction in the load from the first to the third cycle of the same amplitude. Finally, the third parameter, the equivalent viscous damping, is defined as the ratio of dissipated energy to available potential energy multiplied by 2π. The composite action between the CLT and the steel flanges was modeled in OpenSEES using a zero-length spring. The authors used a simple analytical hysteretic model developed by Folz and Filiatrault [14] in their analyses.

Several conclusions were drawn from this research. First, most of the STC connections maintained load carrying capacity at slip displacements larger than needed for composite action, indicating effective composite behavior. Second, the composite joints that were loaded parallel to the wood grains of the outer lamellas had a lower yield than those loaded perpendicular. Third, near to full composite action was achieved for the samples using the 16mm HSS pre-tensioned bolts. Also, post-peak strength reduction generally decreases as the ratio of final slip to yield slip increases; almost all the connections lost less than 20% of peak strength at failure slips near 6 times the yield slip. All tested specimens demonstrated a ductility index greater than 6. The final equivalent viscous damping of the connection for the STC connections with screws was in the range of 5-10% and the bolted shear connectors was within the range of 10-15%. It was also observed that the strength deterioration in cyclic loading is much higher than that of monotonic loading. Lastly, the analytical model calibrated in this study can accurately predict the cyclic load-slip behavior of the STC composite connections.

Intended Improvements to Mechanical Fasteners

There are a number of drawbacks to using mechanical fasteners as shear connectors for steel-CLT composite beams. Notably, holes must be pre-drilled in the steel, which results in tolerance issues that can cause slip at the interface upon initial loading. In addition, mechanical fasteners would typically be installed from below the CLT panel, which presents constructability and safety issues. As such, some researchers reviewed various means to improve on simple mechanical fasteners.

In an effort to improve initial slip performance, Hassanieh et. al. [7] supplemented their research by reviewing a structural bolt in a grouted pocket connection between the steel beam and the CLT panel. The concept behind these tests was based on common concrete slab on steel beam composite beams, where the shear studs are encased in concrete. Furthermore, the connection allows for topside construction, as the beam could arrive on site with studs preinstalled, and the CLT panel could arrive on site with pockets pre-drilled; construction workers would need only fill the pockets (from above) with a non-shrink grout. The experimental program is summarized in Table 3; specimens were tested in a double-shear pushout setup.

The authors made several pertinent observations and conclusions based on the test results. The bolt and grout pocket specimens proved to have the significantly higher stiffness and peak load capacities as compared with specimens using only mechanical fasteners. The size of the grout pocket showed minimal effect except that smaller pockets were slightly more brittle. Zero-tolerance holes and encasement in grout both likely resulted in minimal initial slip, and therefore significantly contributed to their improved performance, at the expense of construction effort. Increasing the yield strength of the bolt did little to influence the stiffness but did increase the ultimate capacity of the joints indicating that the bolt strength governed failure as opposed to the CLT panel as in the other specimens. The authors also showed consistent experimental performance as compared with existing analytical models. It is important to note the actual fasteners were different in the purely dowel-type connections than those in the group pocket specimens, and therefore it is difficult to draw a direct comparison or conclusion.

Hassanieh et. al. [15] also reviewed the use of nailer plates and adhesives at the slip interface to determine if any improvement would be observed in the initial stiffness of the composite beam. In this study nine different bolts and screws used as steel-CLT composite joints were tested for short term load-slip behavior, peak load carrying capacity, stiffness, and failure mode. Each specimen tested contained two CLT panels connected with steel as the diameter and type of connection varied. The specimens were loaded parallel to the grain of the CLT's first layer for all tests following the Eurocode loading procedure for timber structures. The experimental program is summarized in Table 4.

Four distinct modes of failure were identified from the tests which include crushing of timber near the connection, formation of a single plastic hinge in the connectors with timber crushing near the surface, timber crushing due to two plastic hinges in the connectors located at the middle and at the interface, and fracture of the connections. The screws were found to have a ductile behavior, failing after a large post-peak branch of the load slip curve. The specimen in this case had an overall failure due to plastic hinges and timber crushing. The pre-stressed bolts also exhibited a ductile behavior but failed with fracture and a sudden drop in load slip response. Overall, the glue was found to stiffen and strengthen connections but caused brittle failures. The coach screws reinforced with nail plates showed increased strength and stiffness as well with enhanced load carrying capacity but decreased ductility.

Load slip models were created from the push out test results using non-linear regression in order to derive an empirical load-slip formula to be used with finite element analysis in order to calculate ultimate load carrying capacity. It was noted by the research team that the effective penetration length seems to influence the load-slip behavior and overall capacity, and that this

Table 3: Experimental Test Matrix [7]

Fastener Type	Diameter (mm)	Length (mm)	Connector Grade	Grout Pocket Size (mm)	Grain Direction
Bolt with Grout Pocket	12	130	8.8	60 x 135	Parallel
	16	130	4.6	80 x 135	
			8.8	80 x 135	
	20	130	8.8	60 x 135	
			8.8	80 x 135	

Table 4: Experimental Test Matrix [15]

Fastener Type	Diameter of Connector (mm)	Additional Slip Resistance	Length of Connector (mm)	Connector Grade
Screw	12	N/A Nail Plate	100	8.8
	16	N/A Nail Plate Adhesive		
	20	Nail Plate		
Bolt	12	Nail Plate	110	4.6
	16	Nail Plate		

is an area of discussion requiring future research.

Hassanieh et. al [16] performed similar experiments, however in this case using cross-branded laminated veneer lumber (LVL) connections at opposed to CLT panels. While this may lie outside of the direct scope of the paper, it provides pertinent information related to the performance of mechanical fasteners as shear connectors in composite steel-timber beams. Observations on mode of failure, composite efficiency, load deflection, load-slip response, and strain distribution were recorded for bolts and self-tapping screws of various diameters with and without adhesives or nail plates. There were seven different specimens tested, each comprised of an LVL panel, hot rolled steel, and fasteners as summarized in Table 5.

The STC beams displayed 4 modes of failure ranging from ductile to brittle. Shorter beams with parallel loading and mechanical connections exhibited ductile failure with plastic hinges at the connections, deformation at the connections, and tensile fracture in the LVL panels. The addition of adhesive to the interface significantly improved initial stiffness and resulted in nearly full composite action while nail plates had a minor to negligible impact on performance. Shorter beams with loading perpendicular to the grain had fracture in the glue and the soffit of the LVL with a curvature of the wood beam but no damage to the shear connections between the LVL and steel. The longer beams tested with parallel loading and only mechanical connections had a ductile failure but with an increase in deformation. Bolted specimens appeared to show improved initial stiffnesses as compared with screw fasteners.

Table 5: Experimental Test Matrix [16]

CLT panel orientation	Length of STC Beam (mm)	Specimen No.	Steel Profile	Connection Type	Spacing (mm)
Parallel	3000	1	200UB25.4	16 mm screw	250
		2		16 mm Screw + nail plate	250
		3		16 mm screw + glue	500
	6000	4	250UB25.7	12 mm screw	250
		5		M12 bolt	250
Perpendicular	3000	6	200UB25.4	16 mm screw	400
		7		16 mm screw + glue	400

Hassanieh et. al [8] also reviewed the impact of supplemental grip resistance in full length STC beams. The experimental program and details for this work are discussed further in the section on Dowel-Type Mechanical Fasters, and therefore this discussion is limited to observations from the research team. A major outcome of this research focused on composite efficiency, which is a measure of how close different connection methods were to full composite action (zero-slip at shear interface). This efficiency was based on analytical determinations of fully composite, and fully non-composite flexural strengths, as compared with the flexural strength determined through testing. All STC beams exhibited a composite efficiency (CE) of 70% or higher. The STC beams with a combination of glue and coach screws proved to have the highest CE of 91%, whereas the specimens with coach screws loaded perpendicular to grain (of the nearest CLT lamination) exhibited the lowest CE of 73%. As a result, a minimum strength enhancement (as measured by peak strength) of approximately 40% was observed through use of composite action with the CLT slab.

Timber-Timber & Timber-Concrete Composite Beams

The focus of this review is on steel-timber composite beams; however it is also prudent to sample other composites such as timber-timber and timber-concrete. Such a review may yield additional insights into the behavior of composite sections involving timber. This section represents a selection of literature on alternative timber composite beams in lieu of existing reviews [17].

Bedon and Fragiacomo, 2019 [18] investigated timber-timber composite beams using inclined self-tapping screws as shear connectors. The focus of this research was to develop a finite element model of different screw configurations. A numerical investigation was performed using ABAQUS and the results were compared to experimental data from timber-to-timber push-out specimens and full-scale beams, previously tested. The screws were installed in various orientations in parallel rows at an angle of 0, 15, 30, and 45 degrees from the cross section. The parameters of interest in this study included vertical deflection, beam elastic stiffness, ultimate load, tensile stress, and the collapse mechanism.

The most important aspects of the FE model proved to be proper modeling of the timber material properties especially at the ‘cohesive interface’ where the most damage occurred. A fictitious ‘soft layer’, when calibrated correctly, properly takes into account local effects at and around the joints. This FE model gave a fairly close correlation to the results observed during the experimental tests of the push-out specimens and full-scale beams. Major deviations from the FE model were observed mostly of the small scale specimens with a high screw inclination, greater than 40 degrees. However, given the limited number of experimental tests performed for each geometric configuration, the FE model generally achieved a good simulation.

The FE model matched well with the full-scale beam tests, especially in terms of stiffness and configuration at collapse. The model demonstrated well the effects of damage propagation in the beams and the effects of possible non-structural elements such as floor boards. This study presents good potential for using a FE model for timber connections. However, in order for this to be used as a robust tool to replace costly experimental testing, more tests with more geometric configurations need to be tested and used for comparison to dial in the calibration of this FE model.

Boccadoro and Frangi, 2014 [19] investigated timber-concrete composite floor systems relying on a notched shear transfer mechanism at the interface. In this experiment, four notch designs were investigated using two specimens for each. The first group of specimens had rectangular notches perpendicular to the span of the slab and extended across the width of the panels. The second specimens had a double sinusoidal wave notch extending the length of the panel. The third and fourth groups of specimens had a single sinusoidal wave notch, the fourth group’s being wider than the third. The timber used was 40 mm thick beech-LVL with a tensile strength of 58.8 MPa. The concrete was poured directly over the LVL panel, using plates to reinforce the sides.

The specimens were subjected to a four-point bending test. Several failure modes were observed in the samples. The specimens with the rectangular notches failed in the cross section and achieved the highest failure loads. Five of the six specimens showed a high load carrying capacity, 2 to 3 times higher than what is required of typical office buildings. All the specimens exhibited stiffness in the connection with the rectangular notches being stiffer than the sinusoidal waves.

Jorge et. al., 2010 [20] investigated the time-dependent behavior of timber-concrete (lightweight) composite sections using various connection methods focusing on SFS screw joints installed on an incline with respect to the interface with the LWAC (light weight aggregate concrete). Three series of four girder elements were tested for creep coefficient and slip. Analytically, the experimental data was extrapolated logarithmically to allow for the determination of creep coefficients outside of the experimental range.

From a long-term perspective, LWAC improves performance and time dependent behavior. 50% of the expected creep had occurred on the connections after 600 days. This creep was found to be unaffected by concrete type but to rather directly related to compressive strength. When compressive strength is increased the creep coefficient values were found to decrease. The concrete type does affect shrinkage however and the increased strain due to shrinkage in LWAC is not negligible.

Structural Behavior of Steel-Timber Hybrid Structures

While little research exists specifically on steel-CLT composite beams, some research on hybrid steel-timber structures exists that may help identify other potential means for connection not yet considered. This section is a review of identified research pertaining to the structural behavior of hybrid steel-timber buildings.

He et. al., 2014 [21] investigated the lateral drift performance of steel-timber hybrid shear wall systems using two full-scale, single-story hybrid structures. Each structure contained three steel-timber hybrid shear wall systems. The structures were subjected to both monotonic loading and reversed cyclic loading to determine their performance under earthquake conditions. The materials used in this study were H-section mild carbon steel members, grade 8.8 bolts and anchor bolts, and No. 2 or better grade spruce-pine-fur solid sawn lumber. Performance rated 19/32 (Engineered Wood Association panel grade) oriented strand board was used for the infill wood frames. Spiral nails were used for the wood-wood connections and their mechanical properties were tested in accordance with ASTM F1575 [22]. Both specimens were composed of a one-bay by two-bay steel moment-resisting frames. The wood infill of specimen A was single-sheathed while the wood infill of specimen B was double-sheathed. Each specimen contained three identical infill shear wall systems along the primary orthogonal axes.

From this paper, several conclusions were drawn. It was observed that the addition of the wood infill significantly increased initial lateral stiffness. Stronger infill led to higher initial stiffness and yield load of the hybrid system. The ductility factor of the system was mainly influenced by the behavior of the steel moment-resisting frame. Stiffness degradation occurred mostly in the in initial loading cycles as the wood infill was damaged. The presence of double sheathing essentially doubles the lateral stiffness. The wood infill was effective in sharing the lateral load during initial stages. However, once the wood infill was damaged, it provided little resistance. It is noted that effectiveness of the wood infill shear wall is closely related to the steel-timber connection and that more research into steel-timber connections should be conducted.

Asiz and Smith, 2011 [23] investigated screw-type connectors for use in CLT panel to steel girder connections. The authors did not specifically review composite action, moreover the purpose of the investigation was to present feasibility for steel-CLT connections. Experimental analysis of 10 to 12 mm diameter screws at 200 mm spacing was completed to ensure that simple connections such as those selected would have capacities exceeding the respective demands. Table 6 shows the test matrix for this experimental program. The experimental tests were performed using symmetric double shear specimens (as seen in previous works discussed in this paper) to avoid rotations at the joints; plastic sheets were inserted between members to prevent friction forces. Loading was intended to represent gravity loads, seismic, and wind forces.

Table 6: Geometry and Material Properties of Screw Fasteners [23]

Fastener Type	Length (mm)	Diameter (mm)	Yield Strength (MPa)	Parallel Loading		Perpendicular Loading	
				Ultimate Load (kN)	Stiffness (kN/mm)	Ultimate Load (kN)	Stiffness (kN/mm)
“Long” SFS-screw	127	10	480	17.0	2.96	23.1	1.33
“Short” SFS-screw	89	10	480	12.5	1.15	16.6	1.08
Lag screw	127	9.5	310	13.8	2.93	20.4	2.06

All three screw types were found to be stronger in the perpendicular loading direction with respect to the major axis of the CLT, in addition to exhibiting a ductile failure mode. However, the stiffness for all three specimens was superior in the parallel loading direction. Increasing the length of the screws increased both the strength and stiffness of the shear connection.

Lastly, Dickof et. al., 2014 [24] investigated the structural performance of hybrid steel-CLT systems including steel moment resisting frames with CLT infill. The CLT panels were connected to the steel frame with steel brackets nailed to the CLT and bolted to the steel frames. The effects of panel strength, panel thickness, gap distance between frame and panel, infilled frame bay configuration, building height, and frame ductility were assessed analytically for buildings between one and nine stories in height. A sensitivity analysis of the variables was performed on both single and multi-story buildings using OpenSEES. In the analysis, the steel members were modeled using a combination of linear and nonlinear displacement-based beam-column elements, whereas the CLT infill panels were modeled using elastic quad elements. The bracket connections were assigned as node link elements.

It was determined that the addition of infill bays has the greatest effect on the strength and stiffness of the structure for all building heights tested. A less significant, sometimes negligible, decrease in drift capacity also resulted from increasing the number infilled bays in the structure. Ductility values of 2.5 were found to be reasonable for all infilled frames. For systems with a single bay of infill the first yield in the steel beam is the yield of the system, whereas systems with a greater number of infilled bays especially in taller buildings do not have a correlation between point of first yield and system yielding. To optimize ductility a gap size close in value to the deflection capacity of the steel bracket used is recommended.

Summary and Conclusions

This paper is intended to provide a review of existing literature on steel-CLT composite beams, and also touches on ancillary topics of specific interest. CLT is already an established building material around the globe, specifically in Europe; it is gaining momentum in the United States as a sustainable alternative to conventional building materials such as structural steel and reinforced concrete. CLT is a renewable, sustainable building material that is manufactured in a manner that encourages modular construction, improving relative costs and scheduling. However, CLT panels of reasonable thickness (5-ply) are limited in span, requiring generous use of either glulam timber or structural steel beams and columns to accommodate commercial and industrial architecture. As a first cousin of conventional concrete slab on steel deck to structural steel composite beams, CLT-steel composite beams offer an opportunity to significantly reduce the necessary volume (and weight) of steel in a CLT structure, which provides clear advantages both in cost and in structural demands.

The research presented in this paper is intended to be all-encompassing specifically for steel-CLT shear connection research, noting that ongoing research in this field is continuous. As a newly emerging field, the library of research is limited, which offers the potential for significant research contributions and creativity. The following is a summary of the conclusions drawn by the various researchers, which is followed by a summary of indicated future work recommendations.

Notable Outcomes and Reported Conclusions

- Loading direction of the shear connectors with the CLT grain direction has little impact on overall strength of the connection. However, connectors loaded parallel to grain showed significant improvement in initial stiffness, leading to higher composite efficiency.
- The mechanical properties of the shear connector typically had little impact on the overall strength or initial stiffness of the connection, however it should be noted that researchers often designed experiments such that the connections were controlled by the timber as opposed to fracture of the connector to encourage improved ductility.
- The use of grout pockets (surrounding the shear connector penetration in the CLT) showed significant benefits specifically with initial stiffness. Furthermore, this method provides a construction method more consistent with conventional concrete-steel composite beams, where most of the work can be accomplished from the top of the beam as opposed to from below. Zero-tolerance holes and adhesives used at the steel-CLT interface showed similar improvements in initial stiffness, however at a high cost of construction effort- Penetration depth and spacing of shear connectors appears

to impact the load-slip behavior as well as the failure mode. Eventual design guidance will need to accommodate failure analysis to determine connection strength, similar to what is provided in the National Design Specification (NDS) [25].

- Among others, the use of steel plates welded to the top of the steel beam (inline with the beam axis) with predrilled holes was investigated for use in joining CLT panels at a steel beam. This connection method was found to be optimal for both strength and stiffness, however does not necessarily translate directly to steel-CLT composites due to the need for a CLT panel seam directly over the steel beam.
- Steel moment frames with CLT infill panels showed great promise for increased strength and stiffness of lateral force resisting systems, however the authors noted that under cyclic demands initial damage to the CLT at the connection interfaces resulted in a loss of contribution to lateral strength from the CLT panel.

Future Work Recommendations

- The penetration depth and spacing of connectors was a common recommendation for future work. It is clear however, that this is quite specific to the type of mechanical connector selected. Different connectors with different mechanical properties will require different penetration and spacing to achieve failure in the timber as opposed to failure of the connector, which is commonly desirable as a ductile failure. Future work in this area should focus on testing commonly available connectors at various penetrations and spacing for consistency with provided literature and engineering reports from manufacturers to ensure common design practice will still apply for use in steel-CLT beams.
- Many researchers noted differences in the construction effort needed to develop certain connections. Mechanically driven connectors must be installed from below the beam, necessitating working and height resulting in added safety issues. In addition, it would require significant fabrication effort to predrill necessary holes. On the contrary, the use of top-side grout pockets offers the ability to have pre-installed shear studs aligned with pre-fabricated pockets in the CLT panels, again akin to conventional concrete-steel composite beams, where a laborer would simply need to fill the grout pockets from the top. Researchers indicate the need for future work to examine specifically connectors that reduce construction effort, as the cost savings of reducing the steel beam size (due to composite action) could be easily offset by the increased construction costs associated with connector installation.
- Much of the literature focuses specifically on the shear connectors between the steel and the CLT, and typically only in a double-shear or full-scale beam test. While this is an important start and provides preliminary data, more work on integration with the rest of the building is needed. CLT floor slabs are typically finished with a topping grout layer for acoustic and vibration control, which offers an opportunity for further composite action with the steel beam (beyond simply the CLT slab). Furthermore, future research should focus on the connections between the steel-CLT composite beams and their respective columns. Some research [26] [27] [28] exists in this area indicating a clear opportunity to provide quasi-moment frames at most of these connections, providing additional stiffness and strength to accommodate lateral demands.
- As discussed, cyclic demands appear to negatively impact steel-CLT connections, which is reasonable considering initial stiffness is paramount for composite action. While floor systems often do not experience cyclic lateral demands as compared with moment frames or shear walls, they do experience constant vibratory demands. Considering the findings from the steel moment frames with CLT infills, future work should focus on the impact of cyclic behavior on the composite behavior of steel-CLT composite beams as it is possible the composite efficiency could begin to degrade over the life of the structure.

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