CONTINUITY CONNECTION FOR CROSS LAMINATED TIMBER (CLT) FLOOR DIAPHRAGMS

by

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ABSTRACT

Cross Laminated Timber (CLT) is a lightweight construction material with a strength and stiffness comparable to Reinforced Concrete (RC). A crucial aspect of fully realizing the potential of CLT as a structural material is ability to interconnect it to similar and dissimilar materials. A study of connections was made through in-plane shear and tension tests on half-lapped and single-spline connections that make edge-to-edge jointing between CLT panels using screws. A novel aspect of the study is investigation of how placing washers under screw heads alters stiffness and strengths of connections. Subsidiary axial load tests on screws assisted explanation of the shear and tension test results. Conclusions include the importance of accounting for large displacement effects on how screws transfer forces across joint-planes, and need to improve current generation connection design methods so that they account for effects of eccentricities that result from construction arrangement and detailing decision.

Keywords: Cross Laminated Timber (CLT); connections; self-tapping screw; strength; stiffness.

DEDICATION

I dedicate my dissertation work to my loving wife, Mina. Without her patience, support, encouragement, and most of all love, the completion of this work would not have been possible.

I also dedicate this dissertation to my beloved parents and sisters for supporting and encouraging me all the way.

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1 Introduction

1.1 Background

Buildings are constructed using combinations of materials that take advantage of the best attributes of each and reduce the impact of their less desirable ones, with the result being said to be hybrid construction. Throughout the last century, construction of tall buildings has been concerned primarily with using steel or steel and concrete. In the structural engineering context this means that superstructure frameworks have been made from structural steel or reinforced concrete (RC) elements. Such frameworks usually act in combination with RC shear-walls and RC floor slabs to create complete superstructures (i.e. above ground parts of structural systems). However, attention has now begun to shift toward a wider range of possibilities that take advantage of availability of modern high performance materials like structural glass, structural plastics and engineered wood products.

Cross Laminated Timber (CLT) arrived on the Canadian timber market as a proprietary product in 2011 and use of it in low-rise construction has expanded rapidly since. A number of concepts have been developed for using CLT in high-rise applications and its availability may foreshadow a new golden era in timber construction. The tallest such building in the world is the recently completed ten-storey Forte Apartments building in Victoria Harbour, Melbourne, Australia, which has nine wood storeys on top of a concrete first floor. Relative to other materials, CLT has many advantages for high-rise urban construction. CLT has great potential as a slab construction material, because it can be manufactured to have rigidity and strength similar to that of an equal thickness of RC (Asiz & Smith, 2009b).

Attractiveness of CLT is further enhanced by it having only about one-third of the mass of normal-weight RC, and its availability in widths of 2-5m, lengths of up to 20m and thicknesses of up to 0.5m (Asiz & Smith, 2009a, 2010; Ceccotti, 2008; Smith, et al., 2014). Yet, as with other engineered-wood-products (EWP), the crucial structural questions about CLT are those concerning ability to interconnect discrete pieces of it to form superstructures or large substructures.

Joints between CLT panels play decisive roles in the structural performances of completed superstructures and define the limitations of suitable applications of the material from either Ultimate Limiting States (ULS or strength) or Serviceability Limiting States (SLS or stiffness) perspectives. In general, proper design and construction of joints is more challenging in CLT than for RC and steel. This reflects that CLT construction consist of assemblies of discrete elements/parts that are interconnected using fasteners and metal hardware, whereas RC can be cast to be monolithic and steel can be made monolithic, or effectively so, by welding or use of friction-grip bolts. Elements and joints made from steel and RC are inherently ductile at failure because steel is integral to those materials, while CLT has pseudo-brittle response characteristics and any system level ductility has to be derived from metal fasters or hardware in joints between elements. It is also to be noted that imparting high elastic stiffness to CLT joints can be extremely challenging (Haller, 1999; Jorissen & Fragiacomo, 2010, 2011; Joyce, 2014).

The project discussed throughout this thesis involves both experimental and theoretical investigations to develop new jointing technologies using mechanical fastenings. Joint behaviour under monotonic and cyclic loading are investigated. Subsidiary axial load tests on screws assisted explanation of the edge-to-edge connection test results. A novel aspect of the study is investigation of how placing washers under screw heads alters stiffness and strengths of joints. Although not the primary focus, attention will be given to fire and durability aspects of joint performance and cost issues. More generally intent is that what is done will mesh with related work by collaborators in Canada and beyond to create viable methods of using CLT as a hybrid construction material for high-rise superstructures (Asiz & Smith, 2009a, 2009b, 2010, 2011; Joyce, 2014; Naeim & Boppana, 2001; Smith & Asiz, 2008; Smith & Frangi, 2008).

As structural efficiency of any floor system that also acts as a diaphragm depends on the choice of fastening systems that interconnect CLT elements and connect them to the rest of the superstructure, it is important to study intra-floor connections and boundary connections. Past studies have provided part but not all the necessary information and knowhow. The tasks addressed here are aimed at filling gaps and consolidating all the available information to enable design, manufacture and installation of connections that are effective at simultaneously fulfilling needs associated with floor and diaphragm functions. Therefore focus is on effectiveness of joints to transfer shear, tensile and bending forces associated with out-of-plane loads (i.e. effects of dead-weight and live-weight on floor diaphragms) and axial, tensile and shear forces associated with effects of in-plane loads (i.e. effects of lateral loads caused by a wind or seismic event on buildings). Conclusions include the importance of accounting for large displacement effects on how screws transfer forces across joint-planes, and need to improve current generation joint design methods so that they account for effects of eccentricities that result from construction arrangement and detailing decision.

1.2 Scope of Study and Objectives

Connections between CLT plates within CLT diaphragms play a key role in the overall diaphragm performance. This study was aimed at investigating the mechanical properties of joints between adjacent CLT plates within CLT slab system known as edge-to-edge connections. This study also was aimed at developing CLT edge-to-edge jointing methods that enable creation of continuous slab systems. Such methods are termed Continuity Connections that can transfer three-dimensional thrust, shear, tension, and moment forces associated with ULS and SLS performances of slabs. Although focus is on floor slabs that also function as diaphragms, the connection techniques envisaged would also be suitable with or without modification for wall slabs in general (e.g. high performance shear-walls).

The project discussed in this thesis involves both experimental and theoretical investigations of common connections and development of new connection technologies using mechanical fastenings to improve the mechanical properties of typical connections. Joint behavior under static and cyclic loading are investigated. Additionally, Influences of number of factors including; fastener diameter, and length as well as panel orientation with respect to load direction are investigated on connection properties.

In this research project, the specific objective to develop the continuity connection methods was transferring of shear and tension forces along and through connections between CLT elements; so that the CLT flooring system exhibit high strength and stiffness in-plane, making them excellently suited as diaphragms.

1.3 Overview of the Thesis

The material presented in this thesis is organized into five chapters. The next chapter is literature review which provides background and rationale behind the research detailed in this study with the focus on mechanical behavior of CLT panels and the connections in CLT assemblies. The following chapter is methods and materials which primarily explores and describes the timber material and fasteners tested, Test apparatuses, and the loading procedures employed. The results and discussion chapter presents the analyzed data and results accompany with discussion which compares the results, and behavior of the different joint configurations against theoretical design predictions. The conclusions are provided in the final chapter, along with suggestions for future work.

2 Literature Review

2.1 Cross Laminated Timber (CLT)

CLT panels have three or more layers (also known as plies) of softwood lumbers glued together, with such panels manufactured in Canada conforming to the requirements of ANSI/APA PRG 320-2012 (ANSI, 2012). Panels are usually manufactured with their outer layers oriented in the same direction and alternating layers at right-angles to create the cross-laminating effect from which the material derives its name, Figure 2-1. The cross-lamination toughens CLT against through thickness splitting due to tension or shear. This overcomes what has proven to be the primary weakness of most other types of EWP, and that has limited their usage as general purpose structural materials. Products bonded with melamineurea-formaldehyde or polyurethane adhesive are most common, because that maximizes both rigidity and strength. Panel thicknesses range from less than 100mm to over 500mm depending on the manufacturer.

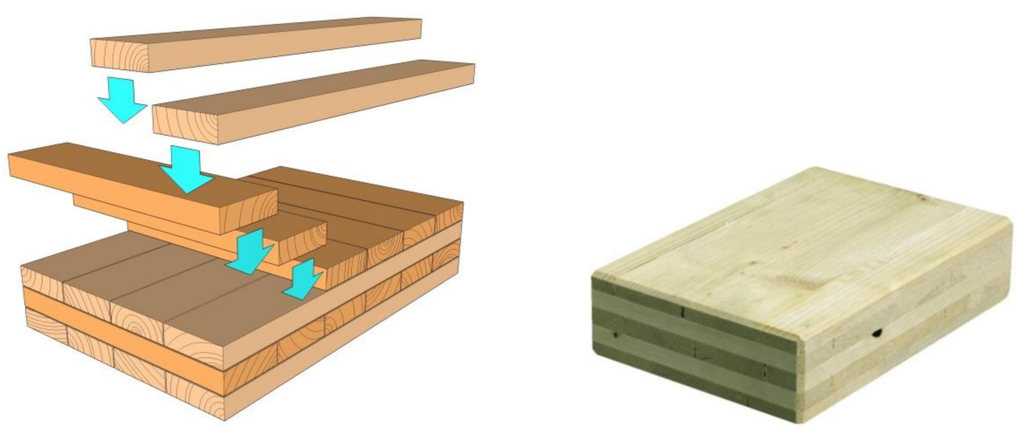


Figure 2-1: Typical Cross Laminated Timber (CLT)

Wood that is used in production of CLT is commonly spruce, but larch, pine and douglas fir may also be used (ANSI, 2012; FPInnovations, 2013). CLT products are only intended for dry service applications, which in practice means enclosed heated buildings or well ventilated unenclosed buildings. At delivery moisture content is 10 – 14 percent and typically will reduce in service to 8 - 12 percent.

CLT has several structural benefits such as having a relatively high in-plane and out-of-plane strength and stiffness (Popovski et al., 2010). Another advantage of CLT is its high shear strength that enables it to resist diaphragm forces as occur in floor slabs and shear-walls (Smith and Asiz, 2008; Smith et al., 2014). Panels exhibit high in-plane strength and stiffness which makes them excellently suited to both carrying gravity and lateral design loads (Ceccotti, 2008).

To date the most critical SLS tends to be vibration serviceability of floors, with a design criterion intended to avoid problems being specified in the CLT Handbook (FPInnovations, 2013). However, the criterion is simplistic and feedback from CLT manufacturers and designers indicates that its use leads to economically unacceptable solutions and inhibits use of CLT for long-span applications.

Previous studies have already shown releasing the true potential of CLT as an engineering material is to do with jointing it rather than its direct mechanical properties (Asiz & Smith, 2009b, 2011; Joyce, 2014; Mohammed & Munoz, 2011; Sadeghi & Smith, 2014).

2.2 CLT Diaphragms

The main purpose of every roof and floor systems in structures are; support and transfer of gravity loads to other structural elements such as walls and columns and distribute the wind and seismic loads to the vertical members of the structure such as shear walls to resist the lateral loads (Naeim & Boppana, 2001).

In structural engineering, a diaphragm is a structural subsystem used to transfer effects of lateral loads to shear walls or frames primarily through in-plane shear stress. Common dominance of shear flows as the critical structural forces reflects that usually diaphragms act like very deep and thin beams [this does not of course mean that consideration of factors like bending forces and lateral buckling should be discounted] (Naeim & Boppana, 2001). The lateral load effects are usually the result of wind and earthquake events, but other lateral loads such as pressures due to retained earth and fluids or blasts may be resisted by diaphragm action. The diaphragm of a structure often does double duty as the floor system or roof system in a building, or the deck of a bridge, which simultaneously supports gravity loads, Figure 2-2.

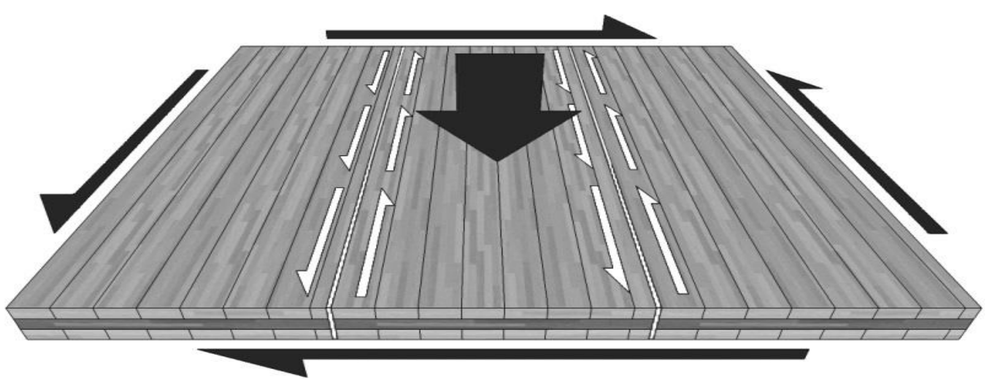


Figure 2-2: Portion of a CLT floor diaphragm (applied loads and shear flow in panel edge-to-edge connections)

For simplicity, the traditional approach in structural engineering is to consider diaphragms acting as though they are flexible or rigid. Flexible diaphragm assumptions amount to ignoring any continuity of floors (or roofs) across bays defined by the positions of supporting walls or frames.

Shear flows in diaphragm under the flexible response assumption are taken to be proportional to tributary areas calculated from floor bay plan dimensions and storey heights. Rigid diaphragms assumptions amount to assuming that the diaphragms prevent all in plan warping of building shapes and that all lateral force resisting systems (i.e. supporting walls and frames) move in unison horizontally at the levels of the diaphragm(s). For multi-storey structures this assumption might or might not be reliable, and it can have strong implications for accuracy of either wind or seismic ULS design calculations (Asiz & Smith, 2009a, 2009b, 2011). The rigid diaphragm presumption is very commonly applied by engineers who design steel or RC frameworks that work in conjunction with RC floor slabs/diaphragms and RC shear-walls. However extrapolation of such practice to situations where CLT slabs are substituted for RC slabs should not be assumed to be appropriate, because there is no assurance that completed superstructure systems will respond in an equivalent manner in the two cases. It is apparently believed by some engineers that taking the worst case effects of building design loads determined based on flexible and rigid diaphragm responses yields a conservative solution, but in general that is incorrect (Al Harash et al., 2010; Paevere et al., 2003). Actually the presence of joints and potentially openings in a CLT floor diaphragm may result in reduction of stiffness which may lead to the CLT diaphragm to become “semi-rigid” in a sense. A large part of any differences should expect to be related to the behavior of connections that attach CLT plates together or attach them to other types of materials (Asiz & Smith, 2009a, 2009b, 2010, 2011).

2.3 CLT Joint

CLT panels cannot be used effectively without efficient and cost effective ways of fastening them together. A combination of metal/LVL/plywood brackets and self-tapping screws are commonly recommended by the CLT manufacturers and are commonly used for connecting panels to panels in floors assemblies. However there are other types of traditional and innovative fasteners and fastening systems that can be used efficiently in CLT assemblies. To date only relatively simple techniques like half-lapped and single-spline connections that employ self-tapping screws have found their way into common construction practice, Figure 2-3 (Joyce, 2014; Sadeghi & Smith, 2014; Smith et al., 2014; Uibel & Blaß, 2007). Such techniques are able to effectively transfer in-plane shear force flows; and in some instances also in-plane tension and in-plane and out-of-plane bending/torsion force flows. However, the stiffness and strength of such connections tends to be limited (FPInnovations, 2013; Joyce, 2014; Sadeghi et al., 2015; Sadeghi & Smith, 2014; Uibel & Blaß, 2006).

Most past work on CLT connections was focused on connections in buildings where CLT plates form both walls and floors of superstructure systems in which room sizes are limited there are long lengths of line contacts/junctions between plates. That means that use of simple fasteners like long slender screws of quite modest diameter and simple bolts/dowels have become preferred plate to connection methods, supplemented by use of hold-down anchors and shear connector brackets when base sliding or overturning are design issues for particular storeys or complete superstructures (Ceccotti, 2008).

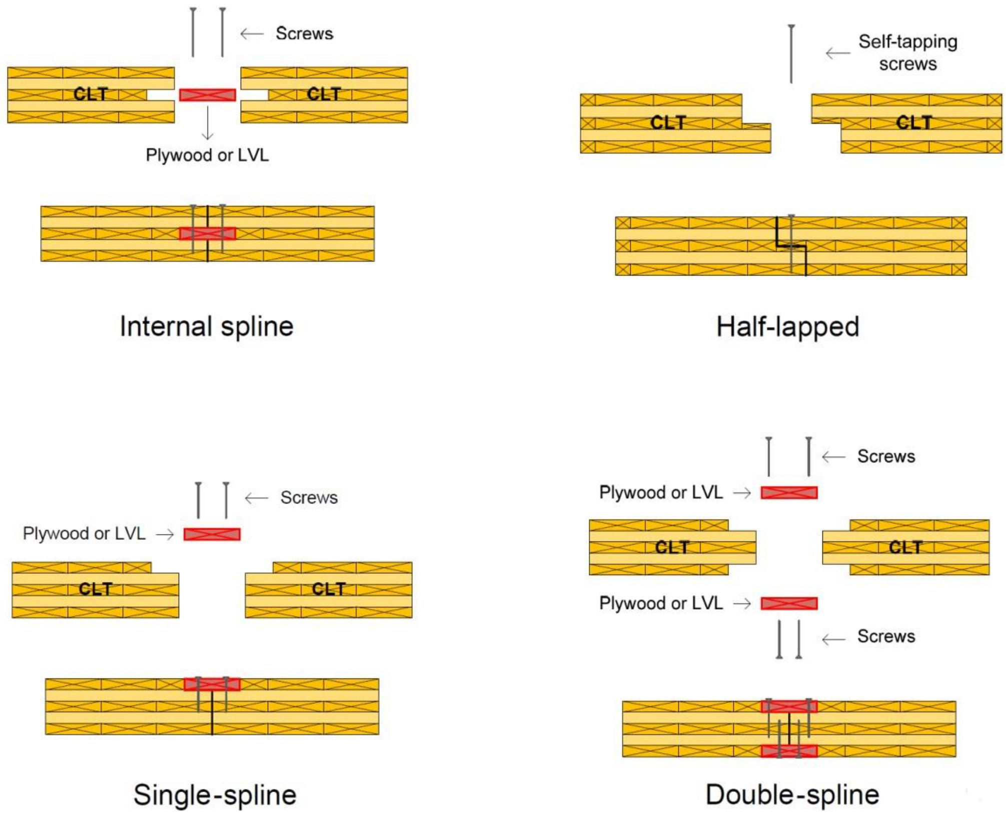


Figure 2-3: Most common types of connections in CLT Flooring systems (Mohammad, 2010)

The already mentioned work by Asiz and Smith (2009a, 2009b, and 2011) has determined that in some instances even for large buildings, i.e. high-rise up to 24 storeys, simple fasteners are adequate as means of attaching CLT slab elements to steel or RC superstructure frameworks. However, the situations they considered were ones where the CLT plates attached to quite closely spaced secondary floor beams, and other construction arrangements and different overall building design parameters would preclude suitability of such simple connection methods. What is discussed in this thesis would address situations where demands on connections could be far more critical and limiting on the suitability of CLT.

Ideally intra-slab CLT edge-to-edge connections would enable creation of slabs/plates that act monolithically under effects of serviceability loadings or effects of ultimate seismic loadings when used as diaphragms. Plus, ideally intra-slab edge-to-edge connections and/or boundary connections would form yield zones in any other situation (Shukla, 1973; Smith et al., 2014). Importance of these attributes would be that would ensure that CLT would perform in a manner equivalent to RC slabs, thereby avoiding a gamut of potential problems, especially in the case of hybrid superstructure systems (Smith et al., 2014).

To activate toughening against splitting caused by laterally loaded fasteners, it necessary that fasteners penetrate sufficiently deeply into CLT to be anchored into at least one lamination that cross-reinforces a face lamination, Figure 2-4 (Joyce, 2014). How deeply fasteners must penetrate to be suitably anchored depends on the layups of particular CLT products, but it is usually necessary to penetrate two or three laminations at one side of a joint plane. Lamination thicknesses vary between 17mm and 38mm, meaning that suitable fasteners are quite long. Proprietary self-tapping screws are a common choice of fastener because they are available in suitably large lengths and their threads cause them to anchor properly in CLT (DIBT, 2013). Also, preferences commonly favour use of relatively small diameter self-tapping screws (~ 10mm) because that mitigates proneness to intra-lamination splitting when lateral forces on screws makes them embed into CLT (Joyce, 2014).

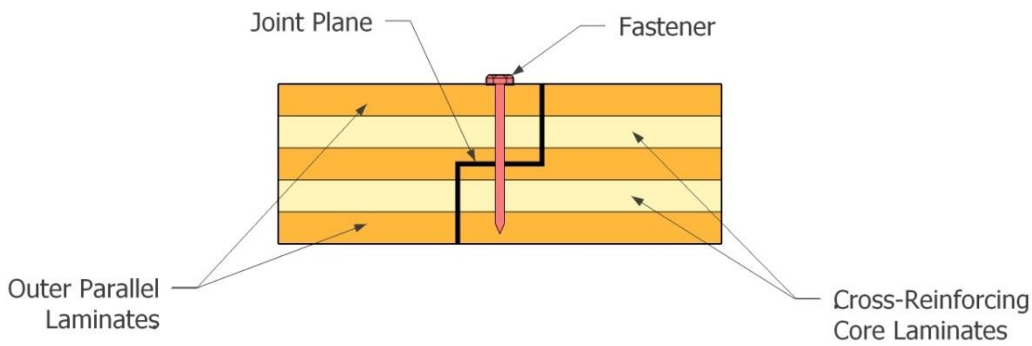


Figure 2-4: Example of necessary penetration of fastener to mobilize cross-reinforcement toughening in CLT

The lateral load resistance of dowel-type fasteners (nails, screws, plain dowels, bolts, etc.) is widely taken to be adequately explained by so-called European Yield Models (EYM). The original EYM (Johansen, 1949), and variants of it assume an ideal rigid-plastic response of fasteners in bending and wood material on which they bear, Figure 2-5-b and 2-5-d. Were fasteners and CLT to have such ideal responses it would give engineers ability to create connections in CLT slabs that could result in ideal elastic-plastic slab responses to in-plane or out-of-place forces. Realistically however fasteners loaded in bending and embedment responses of CLT elements are not ideal rigid plastic and instead approximate elasto-plastic behaviours, Figure 2-5-a and 2-5-c. Nevertheless real behaviours of fasteners and CLT are close enough to the ideal that EYM models have been found estimate failure loads quite well (Joyce, 2014). This statement comes however with the proviso that fasteners must penetrate laminations sufficiently to mobilize cross-reinforcement within CLT. Plus as discussion below shows capabilities of EYM to accurately predict joint capacities also comes with other provisos related to how forces will flow within slabs/plates containing joints.

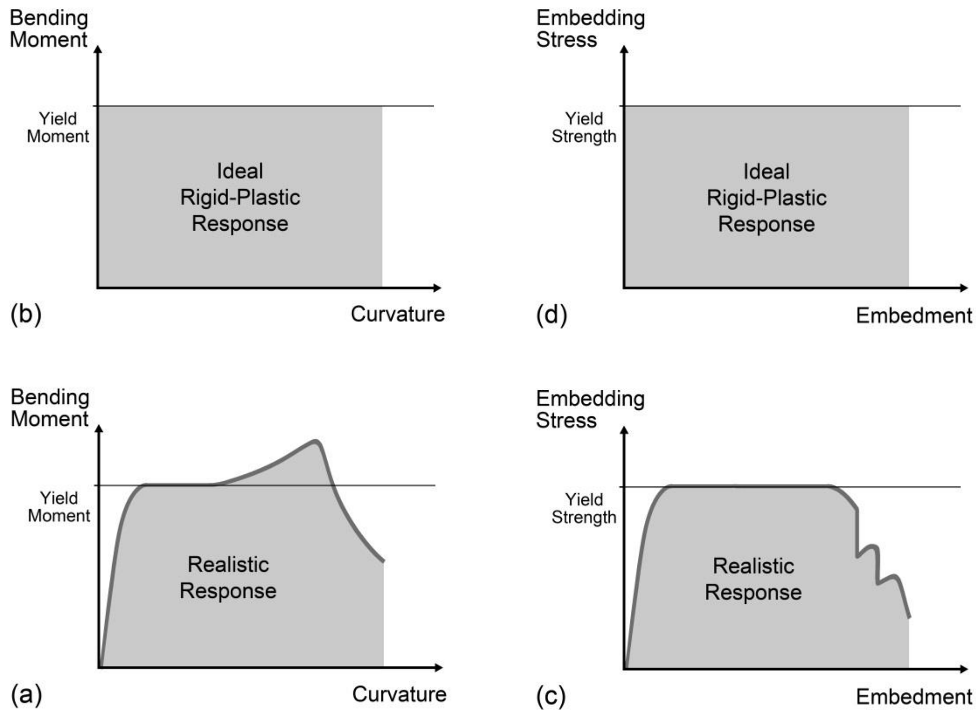


Figure 2-5: EYM and realistic joint component responses

Various timber design codes use EYM capacities directly as the basis of design strengths of joints (CSA O86, 2014), while others supplement EYM capacities with an allowance for rope effect resistance (Eurocode V, 2004). Codes that base design strengths on yield capacities nominally attempt to replicate the load value beyond which deformation would result in irrecoverable damage. Those that add an allowance for rope effect resistance attempt to replicate the ultimate load capacities of joints. Engineers also need to consider whether structural systems can accommodate large deformations associated with realization of rope effect resistances (Smith & Frangi, 2008; Smith et al., 2014).

Figure 2-6 shows possible lateral loading failure mechanisms considered under EYM models (i.e. defining joint yield strength). Which mechanism governs (i.e.

produces the lowest estimate of strength) is determined by geometric variables and fastener yield moment and wood/CLT embedment strength. However, with slender fasteners mechanism III and IV often governs EYM calculations.

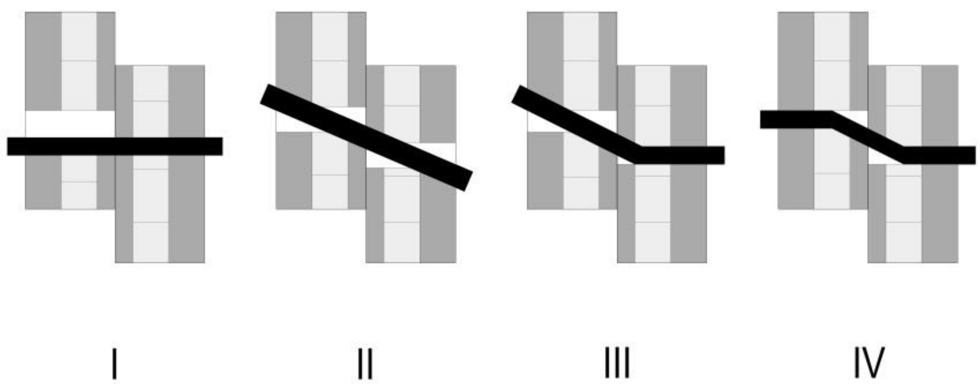


Figure 2-6: EYM mechanisms for a single-shear CLT edge-to-edge connection

3 Research Methods and Materials

3.1 Experimental Design

In this chapter, a series of monotonic and cyclic tests were conducted on two types of most common edge-to-edge connections employing self-tapping screws: Single-Spline connection (Figure 3-1-a), in which a strip of OSB, plywood or LVL inserted in an slot on one side of the plate along the joint; and Half-Lapped connection (Figure 3-1-b), in which two CLT plates joining together by overlapping half lap edges. The selection and details of these connections were based on literature review (Mohammed & Munoz, 2011) and the suggestions of CLT producer, Nordic Engineered Wood Products (Nordic, 2014a).

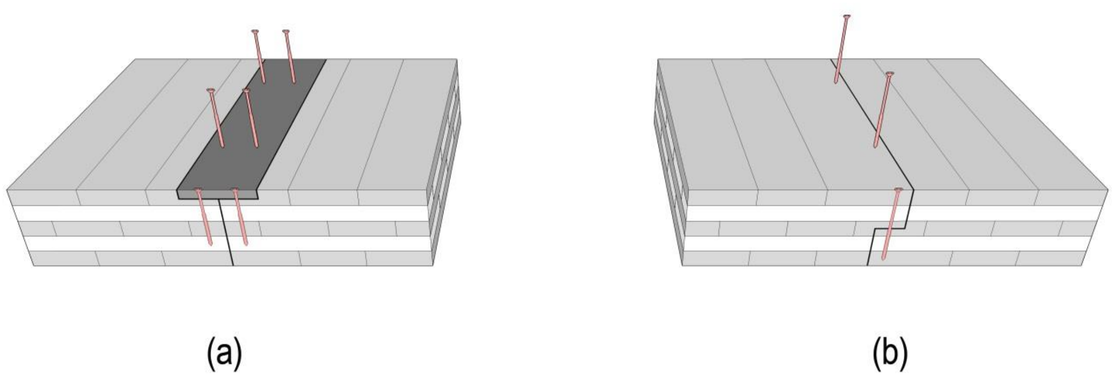


Figure 3-1: Edge-to-edge connections: (a) Single-Spline Connection; (b) Half-Lapped Connection.

A number of test series were designed to investigate the strength and stiffness of studied connections. Specimens were subjected to in-plane shear and tension forces that simulated force flows that would occur in edge-to-edge CLT plate connections within CLT slabs that perform diaphragm or shear wall functions. Supplementary screw withdrawal and pull through tests were carried out to facilitate explanation of the shear force test results. This thesis also investigates how placing washers under screw heads alters the strength and stiffness of studied connections. The schedule of tests is shown in Table 3-2.

3.2 Test Materials

3.2.1 Engineered Timber Material

3.2.1.1 CLT

Cross Laminated Timber material used for the tests was Nordic X-Lam manufactured in Canada (Nordic, 2014b). The material used through the shear and tension load resistance tests was 5-ply CLT which is suitable for floor diaphragms (Nordic, 2013), as discussed in Section 2.2, is the main focus of this thesis. The CLT material used for the screw thread withdrawal and screw head pull-through tests was 3-ply thick CLT which was a mid-span cut from 5-ply panel to represent the edge laps in the half-lapped connections or the notch cut edge of single-spline connections, Table 3-1.

Table 3-1: CLT panel properties.

Panel Layup *	Composition ** (L= longitudinal, T= transvers)	Number of plies	Thickness	
			(mm)	(inch)
180-5-s	36L - 36T - 36L - 36T - 36L	5	18	7 1/8
90-3-s	36L - 36T - 18L	3	90	3 9/16

* The grade designation refers to the panel thickness (mm), the number of layers, and the layup combination ("s" for standard perpendicular layers).

** Longitudinal refers to the major strength direction and transvers refers to minor strength direction of panel.

Table 3-2: Test Schedule.

Test Series	Type of test	Connection	Engineered Timber Material		Fastener	
			CLT	Plywood	Screw *	Washer **
Screw TC6	Screw Thread Withdrawal	-	90-3-s	-	6 x 160 x 70 mm	None
Screw TC8	Screw Thread Withdrawal	-	90-3-s	-	8 x 160 x 80 mm	None
Screw HP6N	Screw Head Pull-Through	-	-	18mm (3/4inch)	6 x 160 x 70 mm	None
Screw HP6W	Screw Head Pull-Through	-	-	18mm (3/4inch)	6 x 160 x 70 mm	6.4 x 18 mm (3/4inch)
Screw HP8N	Screw Head Pull-Through	-	-	25mm (1inch)	8 x 160 x 80 mm	None
Screw HP8W	Screw Head Pull-Through	-	-	25mm (1inch)	8 x 160 x 80 mm	8.4 x 25 mm (1inch)
Screw HC6N	Screw Head Pull-Through	-	90-3-s	-	6 x 160 x 70 mm	None
Screw HC6W	Screw Head Pull-Through	-	90-3-s	-	6 x 160 x 70 mm	6.4 x 18 mm (3/4inch)
Screw HC8N	Screw Head Pull-Through	-	90-3-s	-	8 x 160 x 80 mm	None
Screw HC8W	Screw Head Pull-Through	-	90-3-s	-	8 x 160 x 80 mm	8.4 x 25 mm (1inch)
SHL6N	Shear Load Resistance	Half-Lapped	180-5-s	-	6 x 160 x 70 mm	None
SHL6W	Shear Load Resistance	Half-Lapped	180-5-s	-	6 x 160 x 70 mm	6.4 x 18 mm (3/4inch)
SHL8N	Shear Load Resistance	Half-Lapped	180-5-s	-	8 x 160 x 80 mm	None
SHL8W	Shear Load Resistance	Half-Lapped	180-5-s	-	8 x 160 x 80 mm	8.4 x 25 mm (1inch)
SSS6N	Shear Load Resistance	Single-Spline	180-5-s	18mm (3/4inch)	6 x 160 x 70 mm	None
SSS6W	Shear Load Resistance	Single-Spline	180-5-s	18mm (3/4inch)	6 x 160 x 70 mm	6.4 x 18 mm (3/4inch)
SSS8N	Shear Load Resistance	Single-Spline	180-5-s	25mm (1inch)	8 x 160 x 80 mm	None
SSS8W	Shear Load Resistance	Single-Spline	180-5-s	25mm (1inch)	8 x 160 x 80 mm	8.4 x 25 mm (1inch)
THL6N	Tension Load Resistance	Half-Lapped	180-5-s	-	6 x 160 x 70 mm	None
THL6W	Tension Load Resistance	Half-Lapped	180-5-s	-	6 x 160 x 70 mm	6.4 x 18 mm (3/4inch)
THL8N	Tension Load Resistance	Half-Lapped	180-5-s	-	8 x 160 x 80 mm	None
THL8W	Tension Load Resistance	Half-Lapped	180-5-s	-	8 x 160 x 80 mm	8.4 x 25 mm (1inch)
TSS6N	Tension Load Resistance	Single-Spline	180-5-s	18mm (3/4inch)	6 x 160 x 70 mm	None
TSS6W	Tension Load Resistance	Single-Spline	180-5-s	18mm (3/4inch)	6 x 160 x 70 mm	6.4 x 18 mm (3/4inch)
TSS8N	Tension Load Resistance	Single-Spline	180-5-s	25mm (1inch)	8 x 160 x 80 mm	None
TSS8W	Tension Load Resistance	Single-Spline	180-5-s	25mm (1inch)	8 x 160 x 80 mm	8.4 x 25 mm (1inch)

Values in parentheses are nearest equivalent North American nominal product dimensions.

* The screw dimensioning nomenclature defines the diameter, overall length, and threaded length measured from the point.

** The Washer dimensioning nomenclature defines the inner and outer diameter of washer.

The characteristics/stress class and species of material used in the longitudinal laminates were 1950Fb MSR S-P-F and the Transverse laminates were No. 3/Stud S-P-F (Nordic, 2013). The adhesive applied to bond the laminates was Polyurethane (PU) which is waterproof and creates a rigid glue line (Nordic, 2013). The adhesive was applied just to the broad surface of laminates and not to the edges. Table 3-3 shows the CLT material design properties.

Table 3-3: CLT material properties (Nordic, 2013).

Stress Grade	E1	
Orientation	Longitudinal	Transversal
Species Group	S-P-F	S-P-F
Stress Class	1950Fb MSR	No 3/Stud
Bending at extreme fibre, b (MPa)	28.2	7
Longitudinal shear, v (MPa)	1.5	1.5
Rolling shear, s (MPa)	0.5	0.5
Compression parallel to grain, c (MPa)	19.3	9
Compression prep. to grain, cp (MPa)	5.3	5.3
Tension parallel to grain, t (MPa)	15.4	3.2
Modulus of elasticity, E_0 (MPa)	11700	9000
Shear modulus, G_0 (MPa)	731	563
Rolling shear module, Gs (MPa)	73.1	56.3

Because of the grade variation in wood materials used in laminations, oven dry density of whole panel was calculated based on the ratio of the oven dry weight by the oven dry volume. In addition, the moisture content of the panels was calculated as shown in Figure 3-3.

The average density of the CLT materials used for fasteners axial load tests was 498kg/m^3 (COV: 9%) and the moisture content was 11.2% (COV: 10%). Respectively, values of average oven dry and moisture content for CLT materials used in edge-to-edge connection tests was 507kg/m^3 (COV: 9%) and 11.7% (COV: 12%). In general, the measured values for the densities are within 4.5% agreement with derived values in the technical data released by the CLT manufacturer (Nordic, 2013).

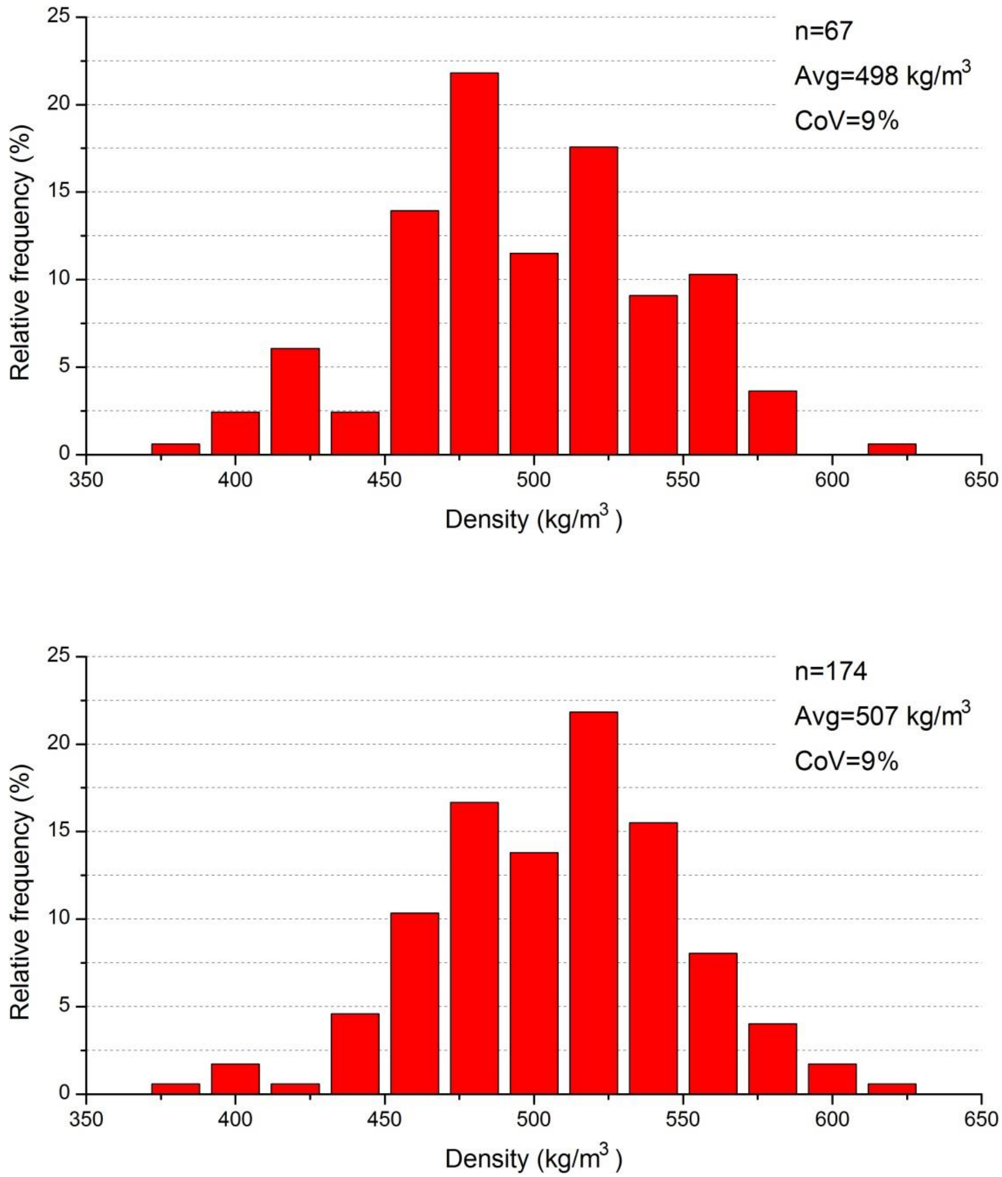
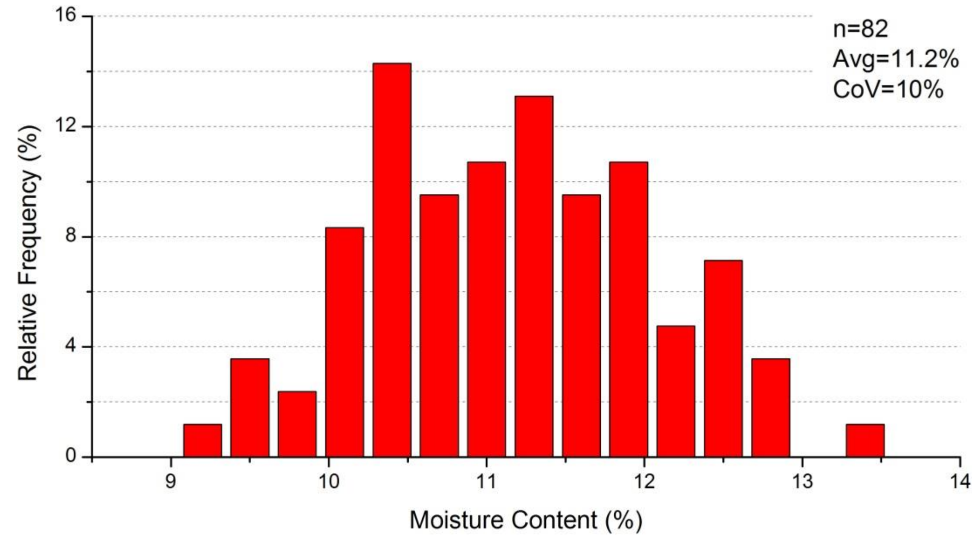


Figure 3-2: Density plots for CLT materials used in fasteners axial load tests (top) and edge-to-edge connection tests (bottom).



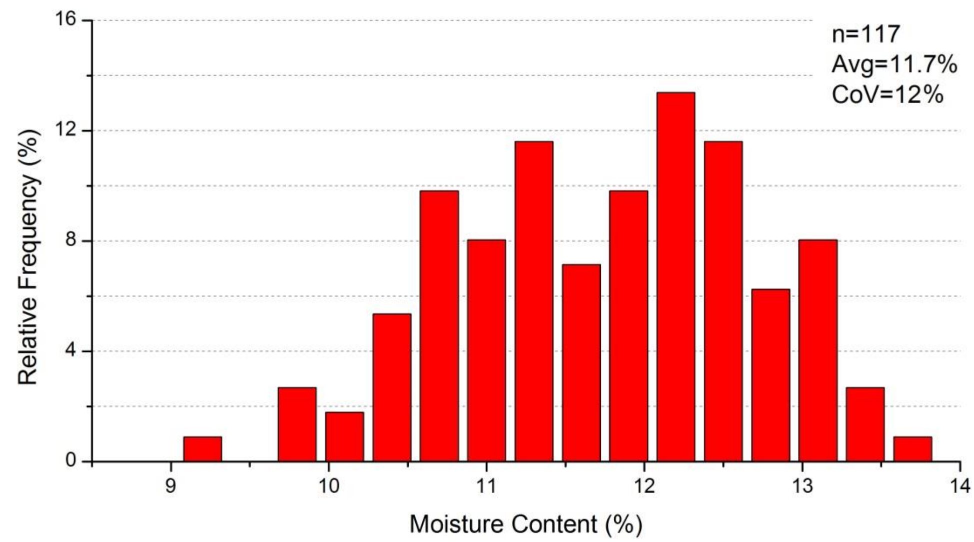


Figure 3-3: Moisture content plots for CLT materials used in fasteners axial load tests (top) and edge-to-edge connection tests (bottom).

3.2.1.2 Plywood

Splice elements used in single-spline connections were Douglas Fir plywood meeting the standards of CSA O121-2013 (CSA, 2009). Thickness of the plywood splines were 18mm or 25mm depend on the connection details and were placed with the face grain oriented parallel to the line of the connections. It is commonly stated that the average density of Douglas-Fir plywood ranges from 500kg/m^3 to 600kg/m^3 and since no measurement of density were made, the median value of 550kg/m^3 selected to use in calculations.

3.2.2 Fastener

3.2.2.1 Screw

There is a wide range of screws to be used in the field of timber construction. However, screws those are suitable to use throughout the field of CLT construction need to meet certain requirements. Self-tapping screws (STS) are widely used for connections in load bearing CLT structures between CLT members or between CLT and steel members due to high strength and no need to predrill for small diameter screws (predrill required for screws with shank diameters larger than 6mm (Eurocode V, 2004). The lack of need for predrilling decreases the construction time and cost. Self-tapping screws are also suitable for connecting the wood-based panels such as plywood or Laminated Veneer Lumber (LVL) to the timber members (Wood-based panels shall only be arranged on the side of the screw head). Self-tapping screws are available in wide range of diameters, lengths, thread length, and head types. The outer thread diameter is ranging from 3mm to14mm and the overall length of the screws is ranging from 18mm to 1000mm (DIBT, 2013).

Wurth ASSY 3 Eco-fast self-tapping screws with 6mm and 8mm diameters were selected based on the edge-to-edge connection geometry to use in the tests (NRC/CNRC, 2013); additional specifications and detailed information are available in Table 3-4 and shown in Figure 3-4.

Table 3-4: Type and dimensions of fasteners used in tests.

Fastener Type	Brand	Thread Diameter (d_{Thread})	Shank Diameter (d_{Shank})	Head Diameter (d_{Head})	Fastener Length (L)	Thread Length (L_{Thread})
Self-tapping Screw	Wurth ASSY3 Eco-fast	6 mm	4.4 mm	12 mm	140 mm	70 mm
		6 mm	4.4 mm	12 mm	160 mm	70 mm
		8 mm	5.8 mm	14.7 mm	140 mm	80 mm
		8 mm	5.8 mm	14.7 mm	160 mm	80 mm

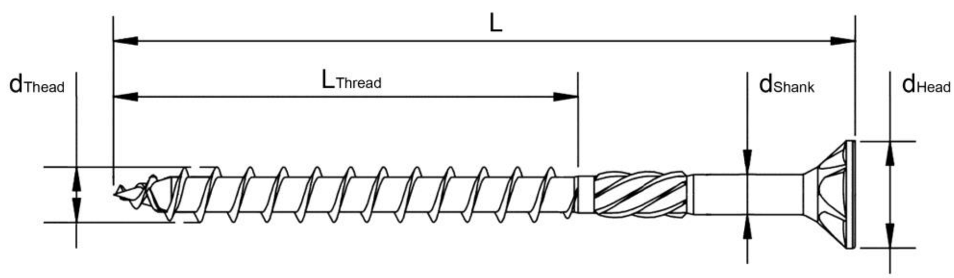


Figure 3-4:Self-tapping screw

For each type of connection (Half-lapped and Single-spline) two screws were used and for each edge-to-edge connection test (shear and tension load resistance tests) two diameters were applied to study the effect of diameters on strength and stiffness of connections. To investigate the difference between withdrawal and head pull-through, axial load tests were carried out with 6mm and 8mm screws on the CLT and Plywood. All self-tapping screws used in the screw axial load and edge-to-edge connection tests were inserted without predrilling.

3.2.2.2 Washer

To study the influence of so-called “rope effect” (axial load in fastener) on the strength and stiffness of studied connections, washers were placed under screw head to provide proper bearing for the screw head in the wood member. Washers used in the tests were 90° steel Cup washers manufactured by Wurth which are accessories to be used with ASSY3 Eco-fast Self-tapping screws. The inner and outer diameters of washers used for 6mm screws were 6.4mm and 18mm and for the 8mm screws were 8.4mm and 25mm respectively. The dimensions and details of the washers are given in Table 3-5 and

Figure 3-5.

Table 3-5: Type and dimensions of washers used in tests.

Fastener	Washer			
	Washer Type	Inner Diameter (d_{Inner})	Outer Diameter (d_{Outer})	Height (h)
6mm Self-tapping Screw	90° Cup washer	6.4 mm	18 mm	4.5 mm
8mm Self-tapping Screw	90° Cup washer	8.4 mm	25 mm	5 mm

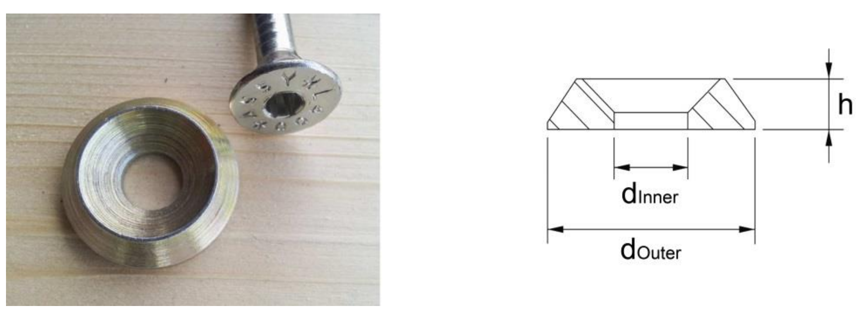


Figure 3-5: Steel cup washer

3.3 Test Specimen Details and Apparatuses

3.3.1 Edge-to-Edge Joints

Throughout this section, the test apparatuses are detailed including specimens, screw arrangement, and test configurations. Two test setups used for the connection tests: shear load test in which the selected connections were loaded in a direction parallel to the joint line; and tension load test in which the connections were loaded in a direction perpendicular to the joint line.

Test specimens were cut from 5-ply 180mm CLT panels having five 36mm thick laminations/plies (180mm thick, 400mm wide, and 600mm long). In these tests the grain in face and middle laminations was orientated parallel to the lines of the edge-to-edge connections. Cross-reinforcing interior laminations were oriented normal to the lines of edge-to-edge connections. The spline elements in single-spline connections were 140mm by 600mm Douglas fir plywood, with the face rain oriented parallel to lines of the connections.

For the single-spline specimens, a notch with a length of 75mm and depth of 18mm or 25mm (based on the plywood thickness used in the connection) was removed from the longer sides to allow the plywood surface to be level with the specimen surface. Through the tests, failed edges of specimens were removed and the opposite edges were used for the next tests. Figure 3-6 shows the details of joint configurations and Table 3-6 and Table 3-7 present the spacing distances.

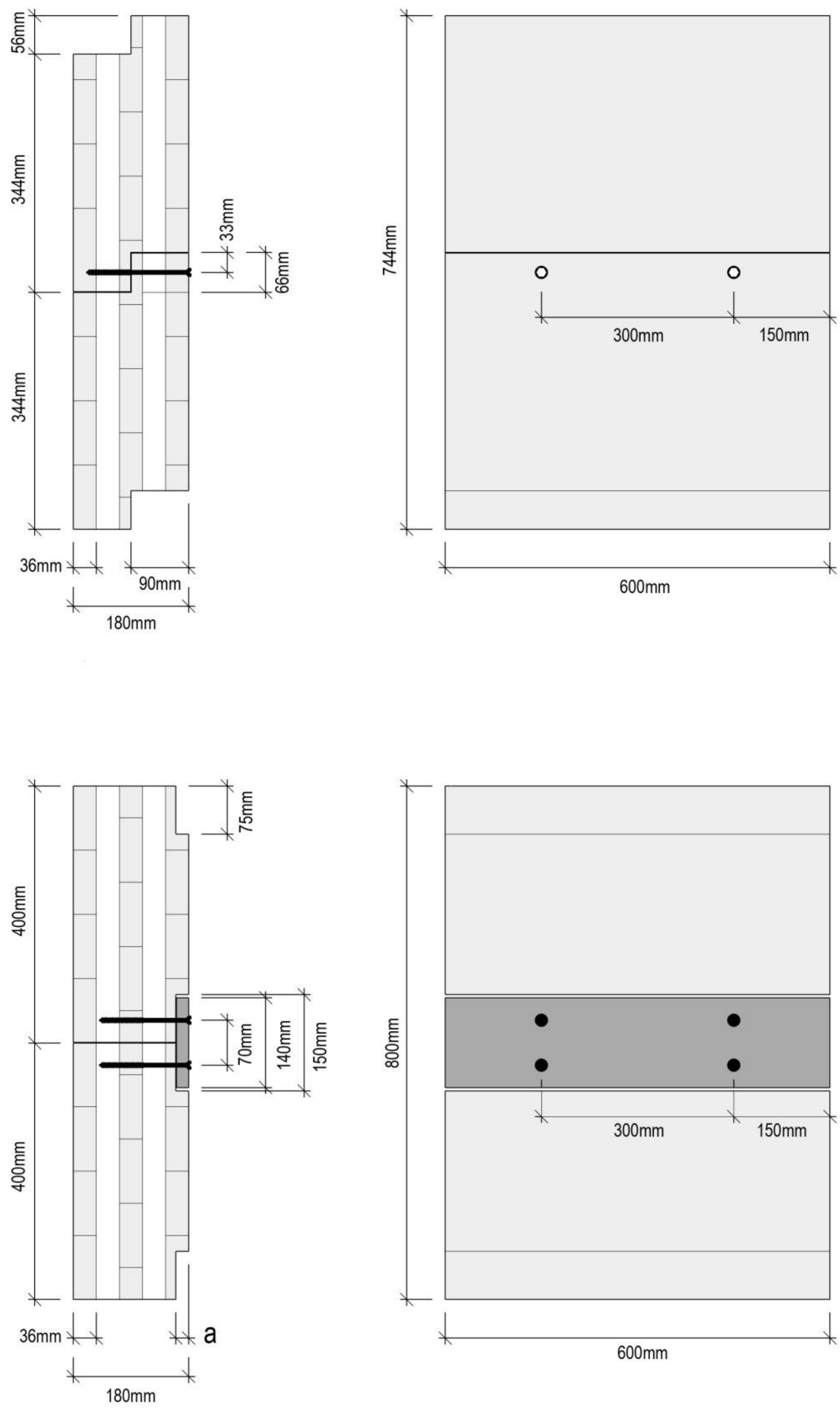


Figure 3-6: Specimen dimensions used in edge-to-edge connection tests: half-lapped connection (top) and single-spline connection (bottom).

Table 3-6: Fasteners spacing distances for edge-to-edge connections under shear loads.

	Screw Diameter		Unloaded Edge (mm)		Unloaded End (mm)		Loaded End (mm)		Spacing in row (mm)	
	Nominal	Shank								
CSA* O86-14	6mm	4.4mm	$1.5d_f$ or $0.5d$	9	$4d_f$ or 50	50	$7d_f$ or 50	50	4df	18
	8mm	5.8mm		12		50		56		24
Half-Lapped	6mm	4.4mm	33		150		150		300	
	8mm	5.8mm	33		150		150		300	
Single-Spline	6mm	4.4mm	35		150		150		300	
	8mm	5.8mm	35		150		150		300	

* CSA O86, 2014, section:12.6.2 Placement of lag screws in connections.

Table 3-7: Fasteners spacing distances for edge-to-edge connections under tension loads.

	Screw Diameter		Unloaded End (mm)		Loaded Edge (mm)		Spacing in Row (mm)	
	Nominal	Shank						
CSA* O86-14	6mm	4.4mm	$1.5d_f$ or 50	50	$4d_f$	17.6	$3d_f$	13.2
	8mm	5.8mm		50		23.2		17.4
Half-Lapped	6mm	4.4mm	150		33		300	
	8mm	5.8mm	150		33		300	
Single-Spline	6mm	4.4mm	150		35		300	
	8mm	5.8mm	150		35		300	

* CSA O86, 2014, section:12.6.2 Placement of lag screws in connections.

Four fasteners were utilized per single-spline connection and two fasteners were used per lap connection in all cases, with only self-tapping screws or with self-tapping screws with washers placed under their heads. CLT was preconditioned to approximately 12% Moisture Content (MC) prior to specimen fabrication. Specimens were stored in a controlled climate chamber set to maintain constant MC of 12% for 24 hours prior to testing. The delay between fabrication and testing was to allow CLT to around screws to relax stress caused by driving screws that would inflate resistance relative to what is achievable under site conditions (Mohammad & Smith, 1997). The material condition corresponded to what is termed dry fabrication and dry loading conditions (CSA O86, 2014). There were six replications per test combination of variables, resulting in a total of 96 edge-to-edge connection tests.

3.3.1.1 Shear Load Resistance Test

Shear load test apparatus was designed to apply shear loads on symmetric lapped joints and non-symmetric spline joints as occur in connections in CLT slabs, Figure 3-7. As shown in the figure, two CLT panels were jointed together by the connection to be tested and the panel element on the left was pushed down relative to the piece on the right, with the apparatus constraining distortions. The specimen on the right was clamped down by 2 rods (1in) to the test frame. The other specimen was attached to the upper mount by 20 lag bolts inserted through two ¾ in steel side plates into the specimen. The length and diameter of lag bolts were 2 ½ in and ¼ in. These lag bolts not only make a very tight connection but also reduce the initial slip between specimen and mount which makes the test setup suitable to perform the cyclic tests as well.

In practice construction of slabs normally results in approximately concentric shear force flows through CLT panels and lapped joints in slabs, resulting in close to pure shear force transfer across joint planes within the lapped joints. Consequently in such situations fasteners are loaded only laterally, or nearly so at small amplitude deformations. When slab connections contain a single-spline joint the arrangement is by default explicitly non-symmetric because joint planes do not lie within the mid-depth planes of slabs.

The resulting eccentricities cause out-of-pane bending, and sometimes also torsional moments. Even if slabs are discretely constrained against out-of-plane deformations by measures like fixing slabs to structural frameworks and walls, eccentricities in internal force flows within slabs will cause some axial forces in fasteners in single splice joints at all displacement amplitudes. Sensitivity of test specimen and real slab structural responses to effects of such eccentricities is proportional to the thickness of the CLT plates being edge-to-edge connected.

As specimens had only two screws attaching any piece of CLT panel to another piece, or to a spline plate, it can be assumed that the lateral force applied to one screw was half the force applied by the loading actuator. Loading was applied monotonically at a displacement rate of 3mm per minute (ASTM D5652, 2007). The maximum resistance/load was reached between 8 and 20 minutes after the commencement of a test. Therefore, the measured responses correspond to what is commonly termed short-term testing duration or monotonic loading conditions.

During test LVDTs (one on each face of a specimen, Figure 3-7) measured joint slip, which corresponds to relative movement of CLT element parallel to the line of the connection. Average LVDT measurements combined with actuator force measurements permitted real-time plotting of load versus deformation relationships. Post testing analysis determined stiffness and strength information in manners consistent with various practices for assigning design properties for connections.

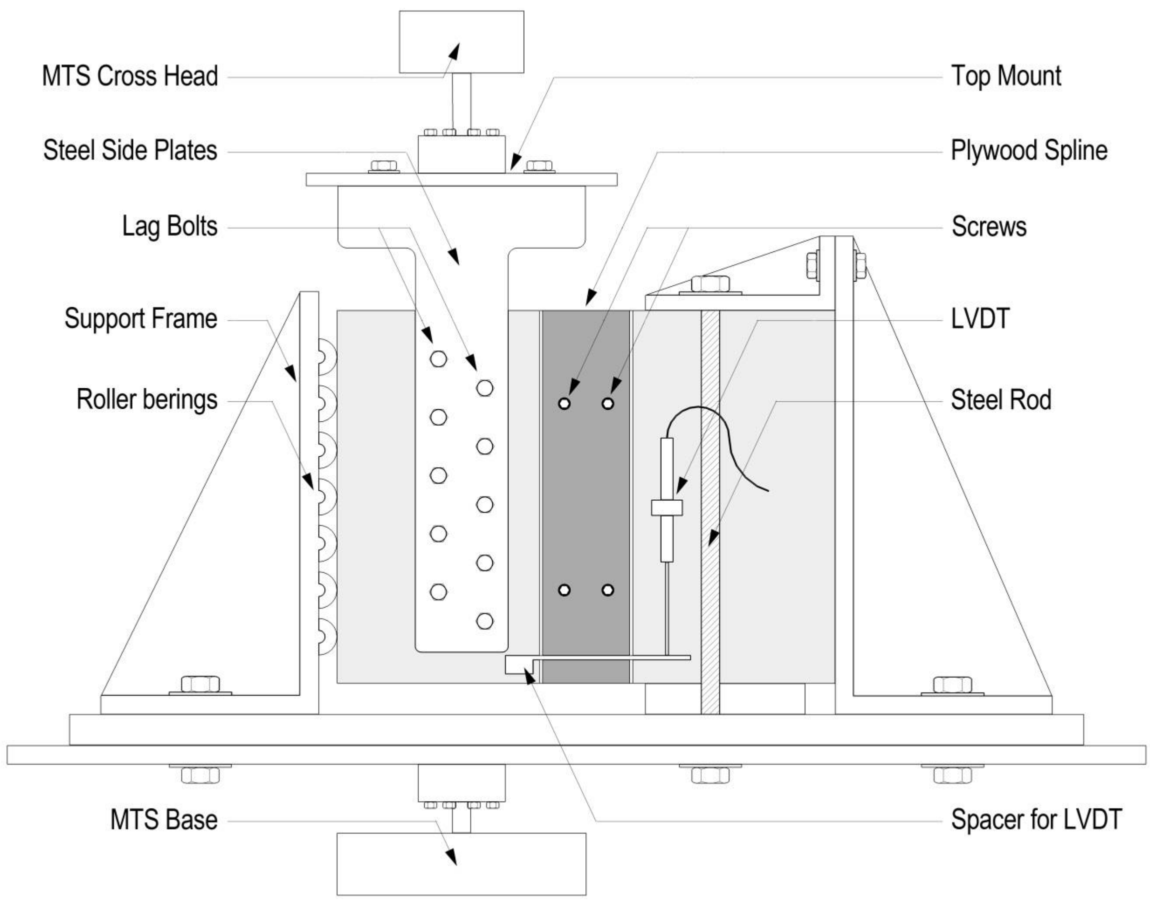


Figure 3-7: Apparatus for shear tests on edge-to-edge connections.

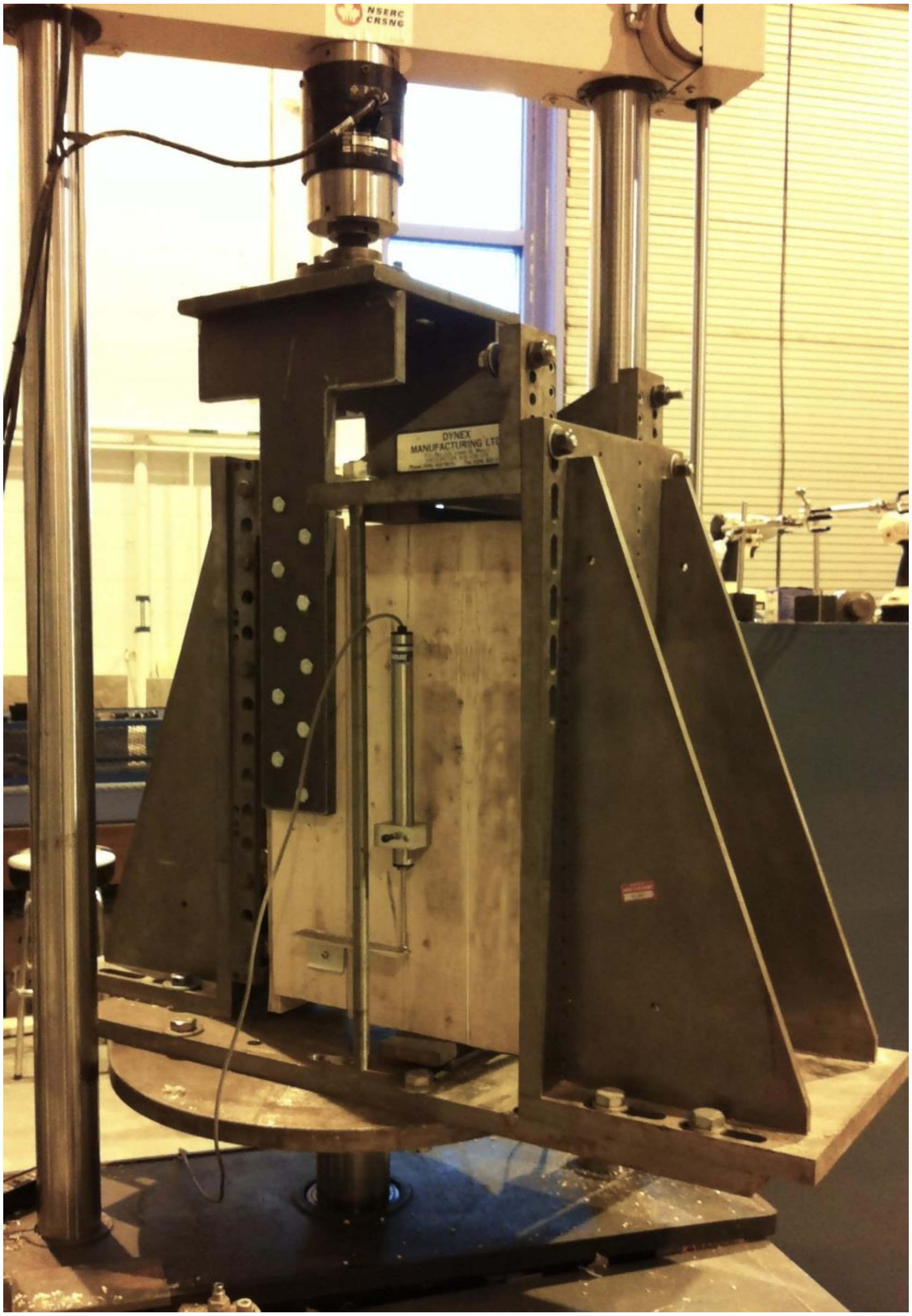


Figure 3-8: Photograph of shear test apparatus used for edge-to-edge connections.

3.3.1.2 Tension Load Resistance Test

Tests were performed using a specially designed apparatus that applied as close as practical pure tension force to the CLT elements, Figure 3-9. CLT specimens were connected to the similar top and bottom mounts by two 30mm bolts through two ¾ in steel side plates. For the cyclic test setup, twenty lag bolts (same as the type used in shear load resistance test) were used in addition to bolts to provide more friction and consequently minimize the slip between side plates and specimen. In doing so, it is possible to bring the specimen to the zero displacement after every load cycle.

As discussed before, because of symmetric configuration of half lapped connection, the applied tension load to CLT plates will be transferred to the fasteners as a lateral loading. However, in case of single-spline connection, the joint involves a splice connecting two discrete CLT plate out of mid-depth. Accordingly, the joint configuration in single-spline connection is eccentric and the applied tension load to the CLT plates may cause out-of-plane bending.

To evaluate the accuracy of the test setup, a number of preliminary tests have been performed and results showed that the out-of-plane displacement is not considerable. Two LVDTs were placed on the sides of specimens to measure the relative displacement Figure 3-10. The average of two slips measured by LVDTs represents the mid-span displacement. Strength, stiffness and other engineering parameters of the studied connections were driven from plotting of load versus displacement. Tension load applied monotonically at a displacement rate of 3mm per minute by the loading actuator (ASTM D5652, 2007). The maximum resistance/load was reached between 6 and 20 minutes after the commencement of a test.

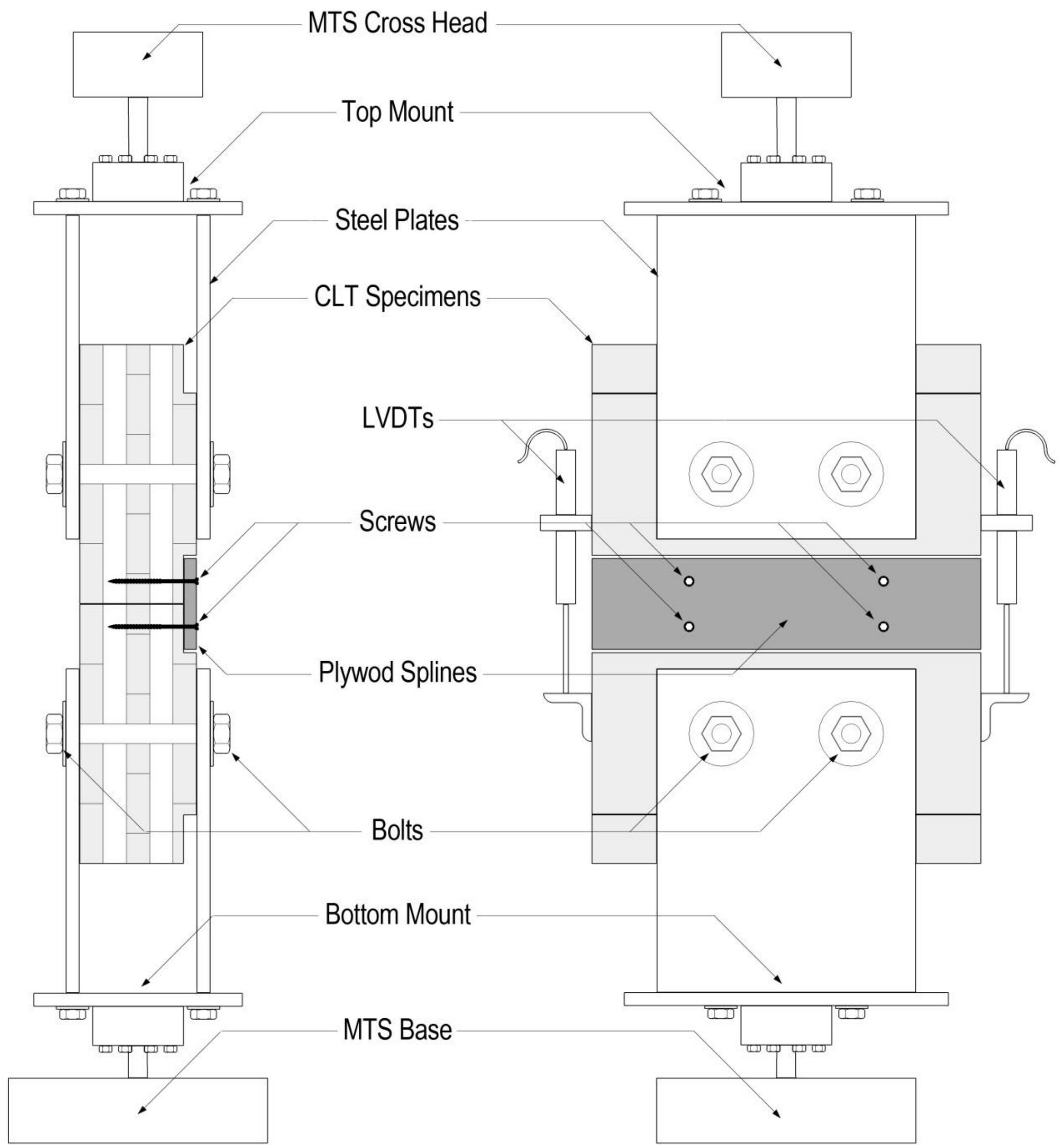


Figure 3-9: Apparatus for tension tests on edge-to-edge connections.

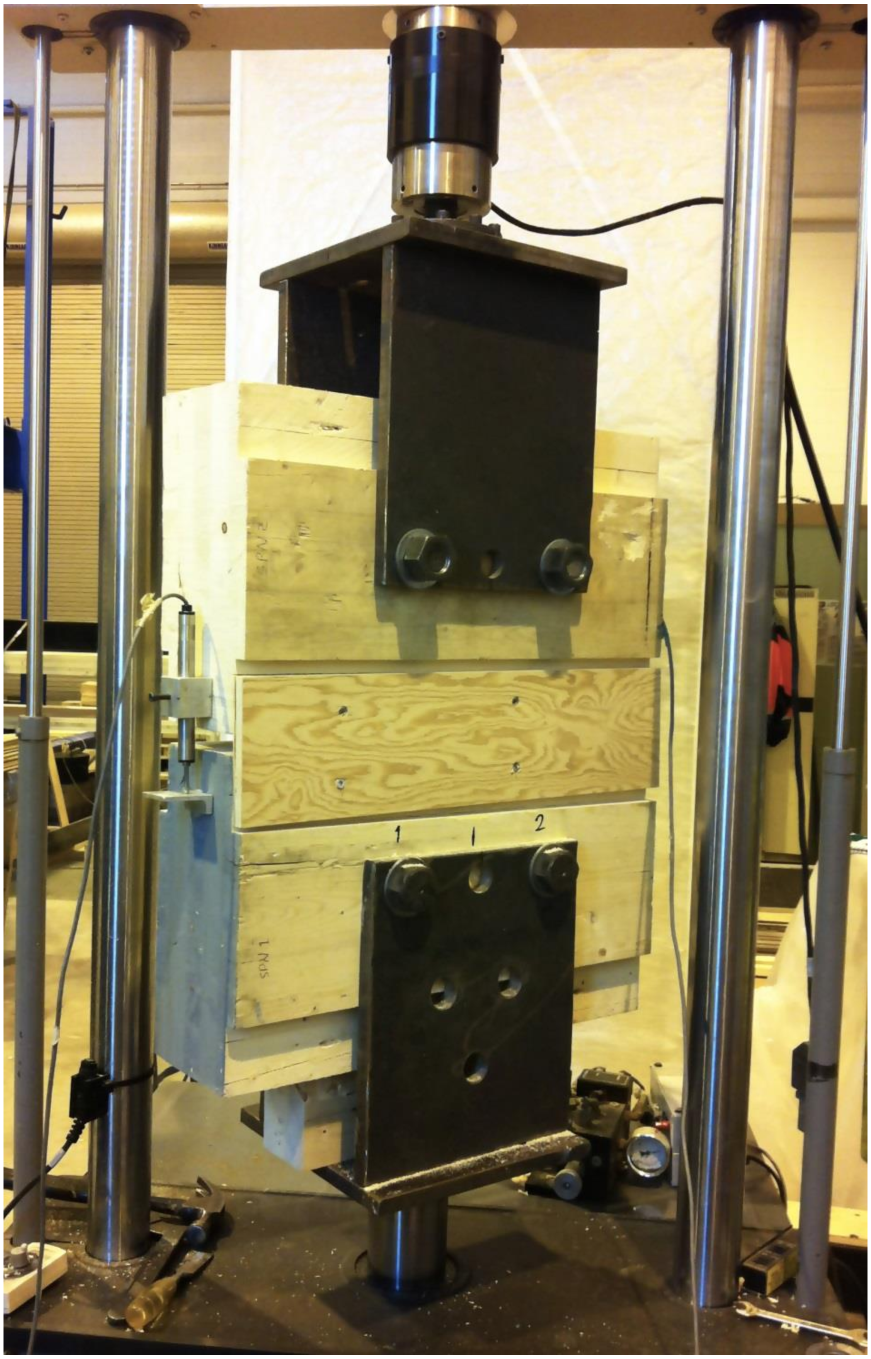


Figure 3-10: Photograph of tension test apparatus used for edge-to-edge connections.

3.3.2 Fasteners Axial Load Test Apparatus

As already discussed, the axial load in the fastener play a key role in the performance of the connections. Figure 3-11 summarizes the scope of axial load tests carried out with intend that they represent behavior of self-tapping screws subjected to longitudinal shearing surface forces similar to those developed due to initial eccentricities or large deformations in joints/connections. Two series of tests have designed to evaluate the applied axial load in fastener including screw thread withdrawal and screw head pull-through tests with and without placing washer under screw head.

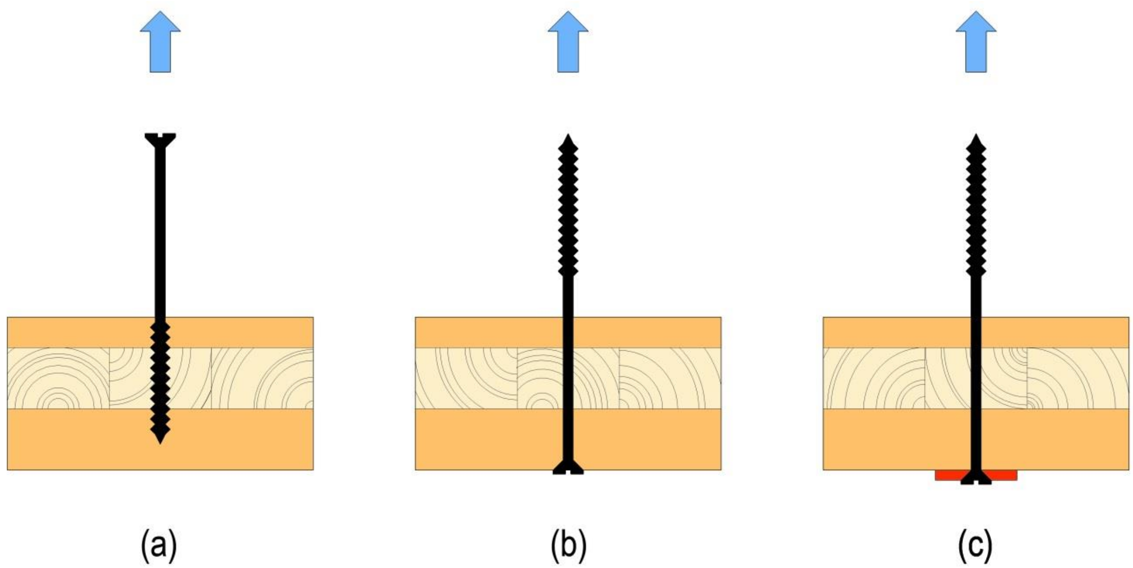


Figure 3-11: Axial load test configurations: withdrawal of screw thread (a); pull-through of screw head (b); and pull-through of screw head with washer (c).

3.3.2.1 Screw Thread Withdrawal Test

Withdrawal tests (Figure 3-12) characterized the behavior of point-side threaded portions of screws being pulled out of CLT. The 6mm self-tapping screws were inserted 70mm and 8mm screws were inserted 80mm into the CLT, meaning that the anchoring resistance was provided along the interaction of the threaded portion of their lengths. Screws were inserted into CLT normal to face plane of a CLT member. The CLT materials used through the withdrawal tests were 3ply CLT (mid-span cut from 5ply CLT) with the length of 180mm, width of 120mm, and height of 90mm (ply thickness: 36mm, 36mm, and 18mm). Each type of test was replicated six times.

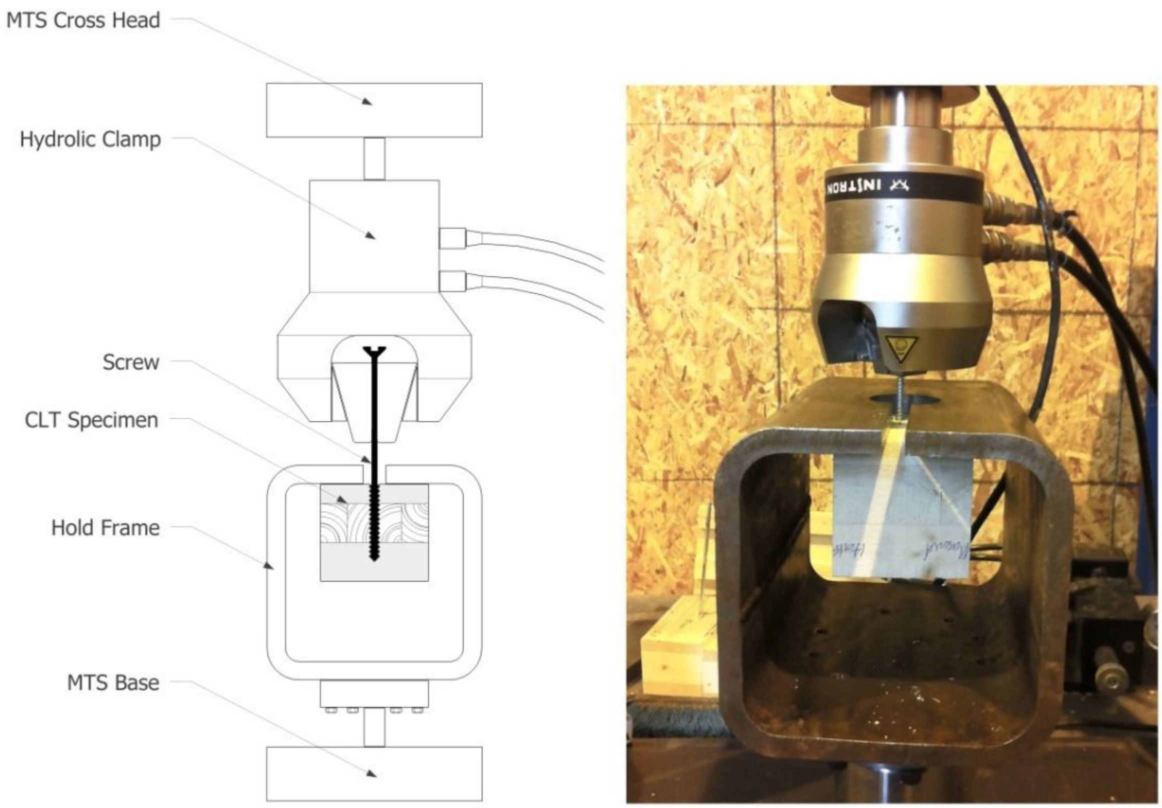


Figure 3-12: Withdrawal test apparatus

Tests performed with a setup designed for the withdrawal and head pull-through tests. The hold frame was a steel square tube (3/4in thick) with an opening in upper side that was connected to the MTS base with an adapter, Figure 3-12. A hydraulic clamp connected to the MTS cross head to grab the screw shank. The MTS internal LVDTs used to measure the slip and there were no external LVDTs.

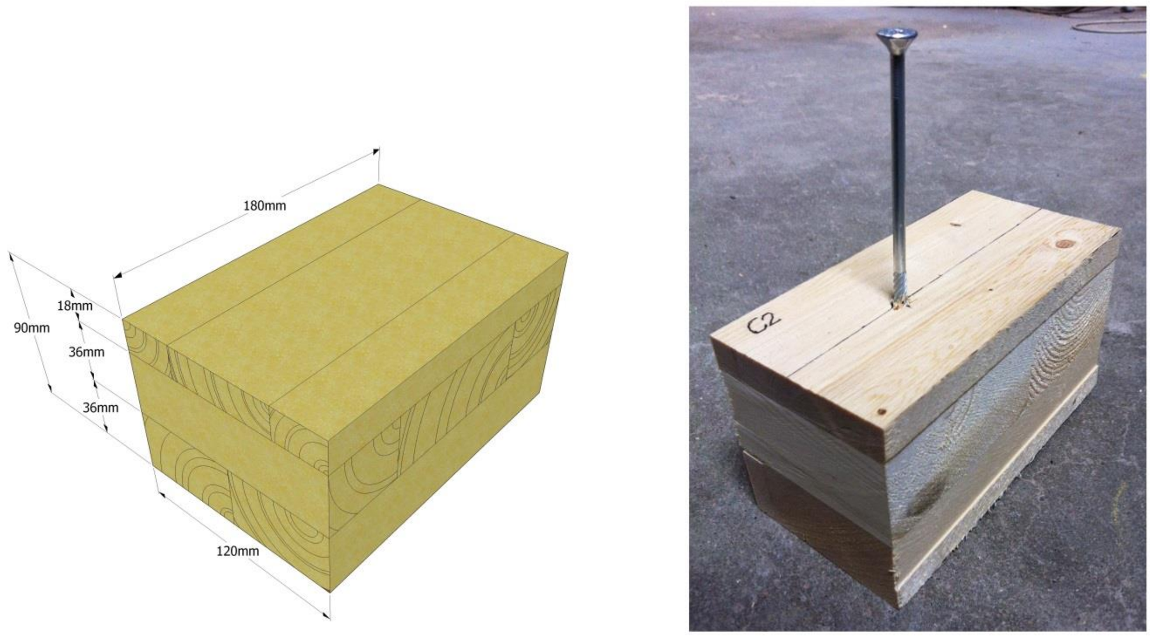


Figure 3-13: CLT specimen for fasteners axial load tests.

The applied rate of loading was 3.5mm per minute, resulting in attainment of peak withdrawal resistance in about 1 minute from commencement of loading. Test samples were fabricated 24 hours before the commencement of tests to relieve the stress caused by driving screws that may affect the test results (Mohammad & Smith, 1997).

3.3.2.2 Screw Head Pull-Through Test

Screw head pull-through tests (Figure 3-14) characterized behaviours of unthreaded portions of screw shanks, with and without a washer under the head, being pulled through CLT or plywood. For pull-through test with CLT, the screws fully penetrated 90mm thickness of CLT, corresponding to a half CLT plate thickness as would occur in a half-lapped edge-to-edge connection. CLT specimens were 180mm length, 120mm width, and 90mm height (ply thickness: 36mm, 36mm, and 18mm), Figure 3-13. Self-tapping screws were 6mm and 8mm with and without cup washers under their head. For each specimen, one self-tapping screw was inserted perpendicular from the thicker ply side into the CLT member.

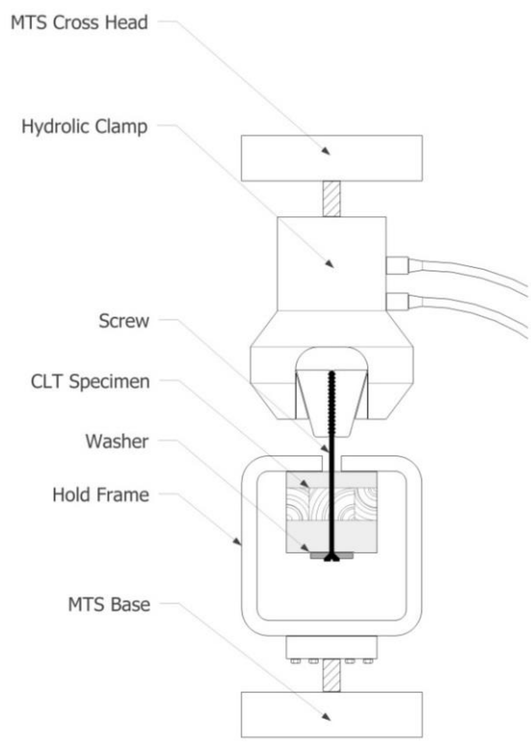


Figure 3-14: Pull-through test apparatus.

In case of pull-through tests with plywood, the screws were fully penetrated 18mm or 25mm plywood (based on the thickness of screws used in the tests), corresponding to a plywood splice used in a single-spline edge-to-edge connection. Plywood specimens used for connections with 6mm screws were 180mm length, 120mm width, and 18mm heights. Accordingly, the length, width, and height of plywood specimens used for tests with 8mm screws were 180mm, 120mm, and 25mm respectively. The specimens are shown in Figure 3-15.

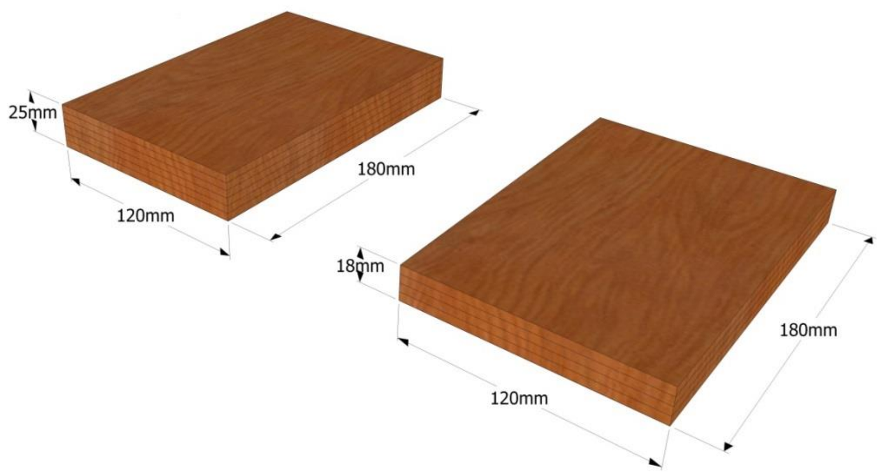


Figure 3-15: Plywood specimens for screw head pull-through tests.

Pull-through test setup was the one described in the withdrawal test, Figure 3-12 and Figure 3-14. A hydraulic clamp was used to grab the thread portion of screw and the cross head pulls it up. Screws were inserted into CLT normal to the face plane of a CLT member. The CLT specimens were the same as in the withdrawal tests and the spline material were 18mm and 25mm thick Douglas Fir Plywood (CSA, 2009). Each type of test was replicated six times.

3.4 Loading Procedures

Two load procedure were used for monotonic and cyclic conditions. These procedure were designed to evaluate the studied edge-to-edge connections under shear and tension forces when subjected to monotonic and cyclic conditions. Tests were performed using MTS Test Machine with a load capacity of 250kN and initial stiffness of 133.78kN/mm when subjected to axial loading up to 30kN (see appendix A).

3.4.1 Monotonic Load Procedure

The monotonic load procedure for edge-to-edge connection tests were carried out according to methods specified in ASTM D5652, (ASTM D5652, 2007) with some modifications. The loading was displacement control with a rating of 3mm/min (0.05mm/s) to reach the maximum load in approximately 10 min (not less than 5min and not more than 20min). The monotonic load procedure for fastener axial load tests was carried out according to test protocol outlined in ASTM D1761, (ASTM D1761, 2007). Loading applied throughout the test under displacement control and at a uniform rate of 3.5mm/min (0.04mm/s). Where the load-displacement curve do not present a clear failure point, it is assumed that failure have occurred when the load was reduced to the 80% of maximum load.

3.4.2 Cyclic Load Procedure

Cyclic loading tests were carried out for edge-to-edge connections according to the methods of EN-12512, (EN-12512, 2002). In case of tension load tests, since it was not possible to go beyond the zero displacement and compress the CLT specimens, the cyclic procedure was non-reverse and just included the positive displacements. Cyclic loading for shear and tension tests is described in Table 3-8 and Figure 3-16. The values of yield points determined from monotonic test results were processed following the methods described in EN-12512, (2002) to calculate the values of forced displacements. The termination of cyclic tests was done when test failure observed or the load reduced to the 50% of the maximum load reached in the test. No cyclic loading tests were performed for screw withdrawal or head pull-through.

Table 3-8: Loading procedure for cyclic tests.

Stage	Percentage of Yield Displacement	Displacement Path *		Number of Cycles
		Tension Tests	Shear Tests	
1	25%	0 : 0.25X : 0	0 : 0.25X : -0.25X : 0	1
2	50%	0 : 0.50X : 0	0 : 0.50X : -0.50X : 0	1
3	75%	0 : 0.75X : 0	0 : 0.75X : -0.75X : 0	3
4	100%	0 : 1X : 0	0 : 1X : -1X : 0	3
5	200%	0 : 2X : 0	0 : 2X : -2X : 0	3
6	400%	0 : 4X : 0	0 : 4X : -4X : 0	3

* X is the average yield slip determined from monotonic tests

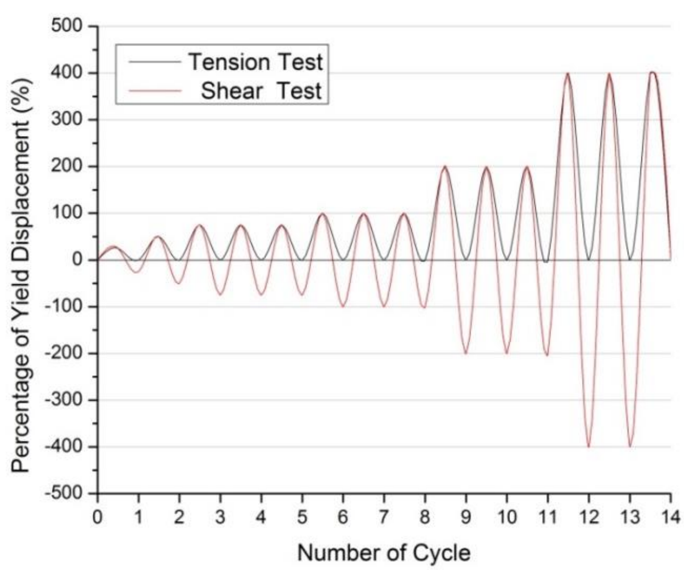


Figure 3-16: Plot of cyclic load procedures.

4 Results and Discussions

Data from edge-to-edge connection and axial load tests were analyzed in the same manner to determine engineering parameters such as stiffness, strength, ductility, and energy absorption characteristics. The chosen range of parameters encompasses those currently employed as the basis of design code resistances, and others that designers might find useful. Analyzed data and results of edge-to-edge connection tests are presented within two sections including: connections without washers under screw heads; and effect of washers under screw heads. Data from axial load tests on screws were analyzed to extract properties that explain connection test results. In the final section of this chapter, connection failure mechanisms are discussed and comparison of connection test results with EYM predictions is made.

4.1 Data Analysis

4.1.1 Load-Displacement Curves

For each test series, collected load data by the load cell was paired with average slip by LVDTs to plot the load-displacement curves. Displacement for connection tests measured by two LVDTs and the average of measured values (which represent the mid-plane slip of connection) used in the calculations and plotting. The comparison between individual paired and average LVDT results showed that the variation was always less than ±4%. The measurement of displacement for axial load tests was made by MTS test machine internal LVDT which represents the slip occurring across the MTS cross head and base. The result of tests implemented on MTS test machine (Appendix A) showed that the initial stiffness of MTS is good enough (133.78kN/mm) does not affect the axial load test results due to displacements occurring in test machine.

The load values measured by load cell are divided by the number of connection unite used per specimen to yield the load value corresponding to each unit of fastener. Number of connection unites for half-lapped connections were taken as the number of screws used in each specimen. However, the number of connection unite for single-spline connections were taken as the number of each pair of screws that together make a connection unit. For axial load tests, the number of connection unite defined as one since there was just one screw driven into each specimen. The number of connection unites for each test design is presented in Table 4-1 and the comparative plots of average monotonic load-displacement curves per connection unit are shown in Figure 4-1Figure 4-4. The load-displacement curves of connection and axial load tests are provided in appendix B and C including individual and average plots of each monotonic and cyclic test series.

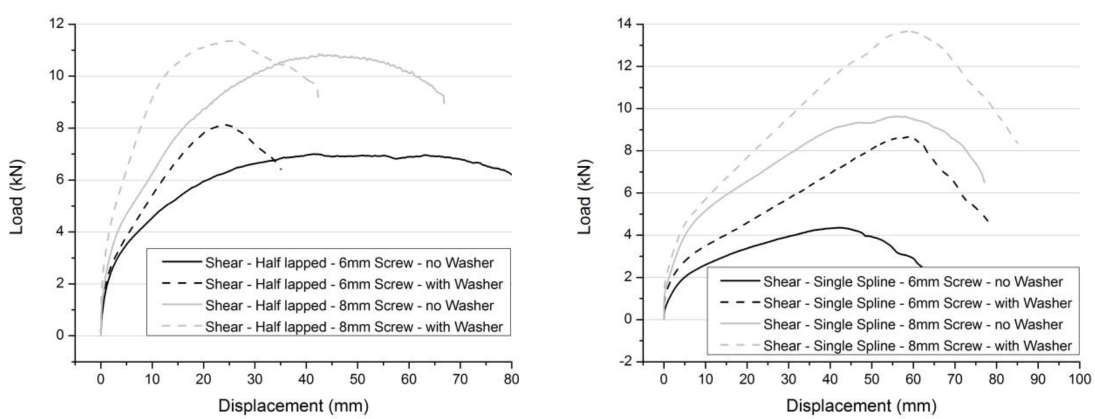


Figure 4-1: Plots of average load-displacement curves for edge-to-edge connections under shear loading.

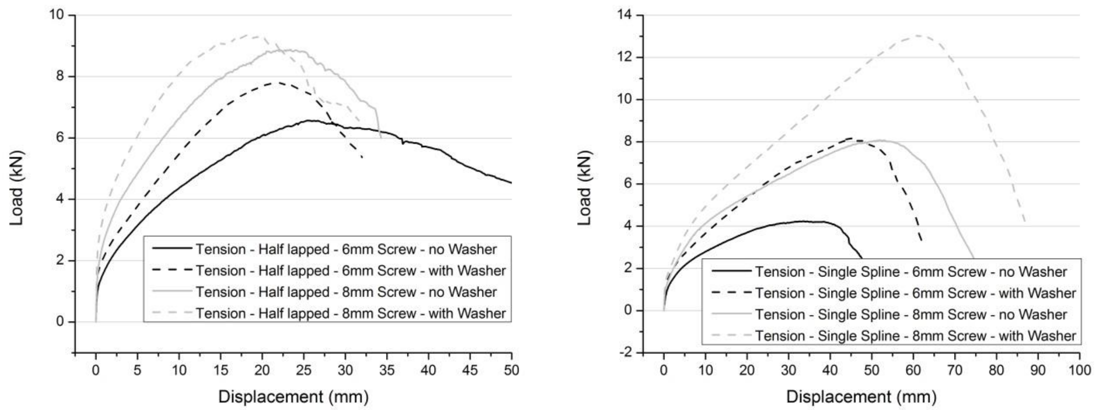


Figure 4-2: Plots of average load-displacement curves for edge-to-edge connections under tension loading.

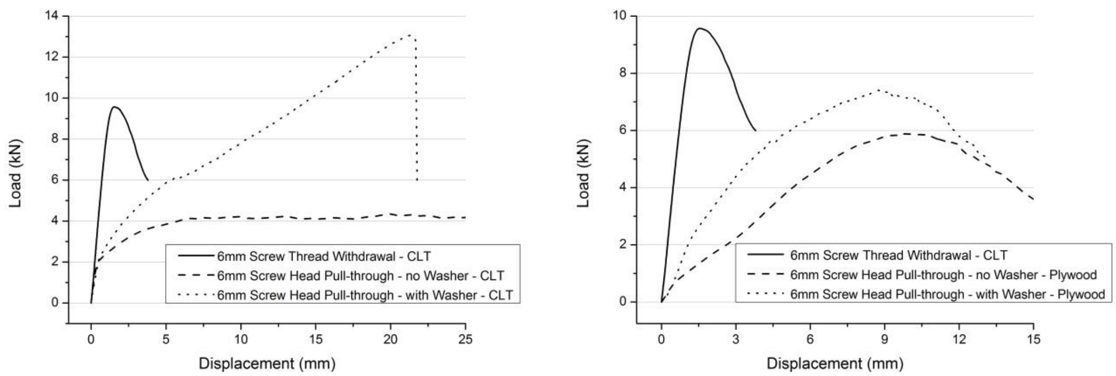


Figure 4-3: Plots of average load-displacement curves for fastener axial load tests using CLT.

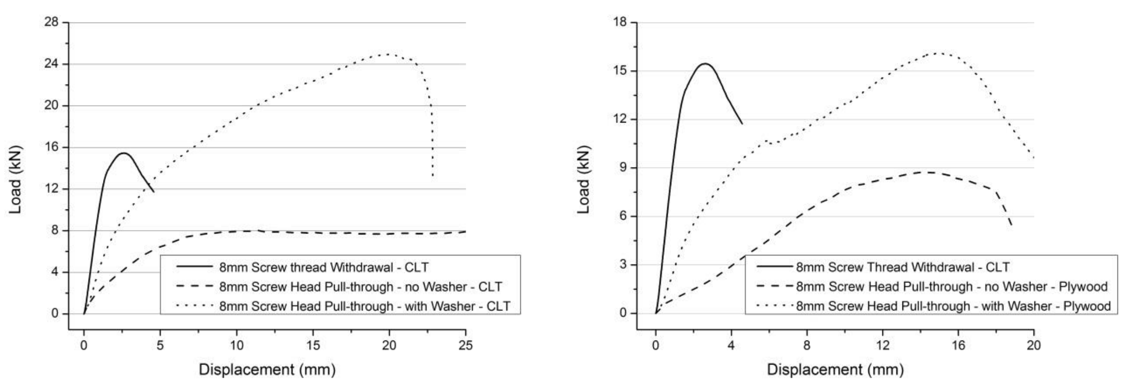


Figure 4-4: Plots of average load-displacement curves for fastener axial load tests using plywood.

Table 4-1: Number of connection unites in each test design.

	Half-Lapped Connection	Single-Spline Connection	Axial Load
Number of Connection Unites	2	2	1

4.1.2 Monotonic Test Data Reduction

The measured displacement paired with corresponding load data were plotted using the software Origin Pro. The engineering and design parameters of studied connections were derived using these plots including yield load (F_{yield}), displacement at yield load (Δ_{yield}), maximum load (F_{max}), displacement at maximum load (Δ_{max}), failure load ($F_{failure}$), displacement at failure load ($\Delta_{failure}$), dissipation energy at 30mm slip (W_{30mm}), dissipation energy at failure point ($W_{failure}$), initial stiffness (K), and ductility ratios. Ductility ratio (D_{max}) is defined as $\Delta_{max}/\Delta_{yield}$, and the failure ductility ratio ($D_{failure}$) as $\Delta_{failure}/\Delta_{yield}$. Plots, tables and values reported in the following sections represent the average value of six replications per test series (individual test data are presented in appendix B.

4.1.2.1 Failure

Failure of the tests was determined as the load corresponding to the failure at the point ($F_{failure}$) where the load capacity of a test specimen started to drop (catastrophic failure) or decreased to the 80% of the maximum load achieved during the test (EN-12512, 2002). The corresponding displacement at the failure load was defined as failure displacement ($\Delta_{failure}$). To establish a clear failure point and study the behavior of the connection at the failure, tests were conducted until the load decreased to the 50% of the maximum load. The mean values for the maximum load, failure, and corresponding displacements are presented in Table 4-2.

Table 4-2: Load properties and corresponding displacement values for edge-to-edge connections per connection unit.

Connection Type	Load Direction	Fastener Type: Screw	Fastener Type: Washer	Test series	F_{max} (kN)	Δ_{max} (mm)	$F_{failure}$ (kN)	$\Delta_{failure}$ (mm)
Half-Lapped	Shear	6mm	None	SHL6N	7.59 (3)	62.31(31)	6.07 (3)	84.07(15)
			18mm	SHL6W	8.42 (6)	25.04 (9)	6.74 (6)	35.82 (7)
		8mm	None	SHL8N	10.99(3)	44.09 (9)	8.81 (3)	75.91(13)
			25mm	SHL8W	11.52(7)	24.99(16)	9.22 (7)	46.16(13)
	Tension	6mm	None	THL6N	6.71 (3)	29.25(17)	5.37 (3)	42.71 (8)
			18mm	THL6W	8.06 (6)	22.43(15)	6.44 (6)	30.04(10)
		8mm	None	THL8N	9.08 (7)	22.83(10)	7.26 (7)	32.53 (5)
			25mm	THL8W	9.49 (5)	18.65 (9)	7.59 (5)	26.61 (7)
Single-Spline	Shear	6mm	None	SSS6N	4.41 (5)	43.61(10)	3.53 (5)	54.87 (8)
			18mm	SSS6W	8.74 (2)	57.75 (4)	6.99 (2)	67.84 (4)
		8mm	None	SSS8N	9.88 (6)	54.55(13)	7.91 (6)	73.21 (5)
			25mm	SSS8W	13.96(6)	58.39 (8)	11.17 (6)	74.71 (6)
	Tension	6mm	None	TSS6N	4.35 (5)	36.89(10)	3.48 (5)	45.18 (4)
			18mm	TSS6W	8.45 (5)	47.51 (8)	6.76 (5)	54.05 (4)
		8mm	None	TSS8N	8.18 (4)	51.21 (6)	6.54 (4)	64.43 (5)
			25mm	TSS8W	13.18(3)	63.02 (5)	10.55 (3)	74.45 (7)

CoV (%) in paranthesis

CoV values in Table 4-2 indicate that for edge-to-edge connections variability in design strength related parameters (F_{max} , $F_{failure}$) is low and variability in displacement related paramters (Δ_{max} , $\Delta_{failure}$) is relatively high, especially in the case of lapped joints. Many past investigations support the finding that displacement related parameters are more variable than strength related parameters (Smith et al., 1998). EYM analysis (versions of CSA O86-14 and Eurocode V) that predict the failure mechanism of connections depend on the fasteners yielding to form plastic hinges and fastener embedment in to the CLT members. The observed failure mechanisms for connections without washers under screw heads were in agreement with those predicted prior to testing with minor defects. However, the prediction of failure modes for connections with washers under screw heads was questionable. In case of half-lapped connections, presence of washers increased the embedding resistance of screw head and consequently the axial load applied to fastener increased. This phenomenon leads to increase in lateral strengths due to the so called rope effect.

In case of single-spline connections, the rotation of screw head in the splines was predicted (plastic hinge deformation). The corresponding EYM failure anticipated as mode III (Figure 2-6) due to using thin plywood splines. However, presence of washers under screw heads not only increased the axial load in fasteners (rope effect) but also restricted the screw head rotation. It was observed that the washer placed under screw head did not allow the screw head to rotate into the splines. Therefore, the corresponding EYM failure mode was mode IV (Section 4-4).

4.1.2.2 Yield point

In general, yielding of materials is defined as a change in the behavior of materials in which the material begins to deform from ideal elastic to a plastic or pseudo-plastic phase. Knowledge of yielding is vital in structural engineering. Stress beyond the yielding may not cause an ultimate or catastrophic failure but causes some deformation which is permanent and nonreversible. The yield point can be defined from load-displacement curves as the point at which the plastic deformation begins to occur. However, it is often difficult to accurately define yielding of timber connection due to absence of clear and distinct change in stiffness. To date, there are several possible ways to define yielding of timber connections. The study performed by Munoz et al., (2008) compared six commonly used methods in the estimation of yield point (Figure 4-5).

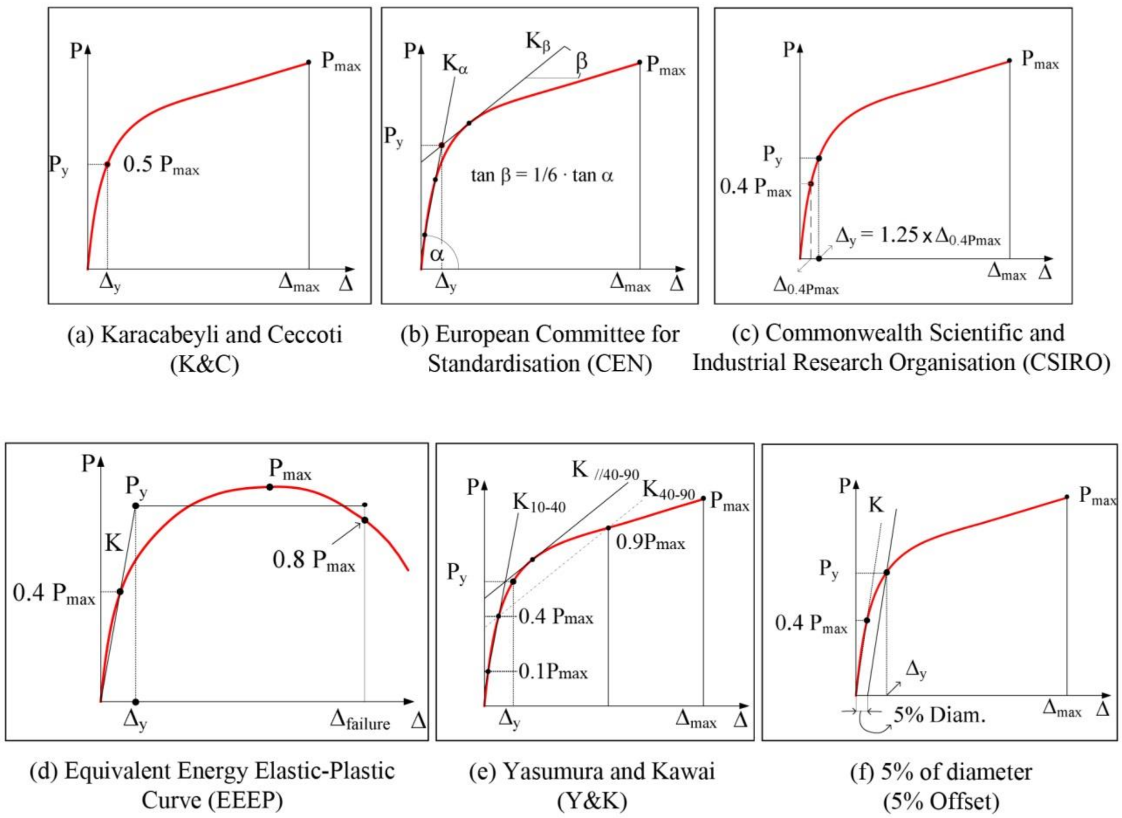


Figure 4-5: Methods for determination of yield point used by Munoz et al. (2008).

Karacabeyli and Ceccotti (K&C) and Commonwealth Scientific and Industrial Research Organization (CSIRO) are generally taken as the methods that define the yield points regardless of load-displacement curve shape. K&C method defines the yielding as the load corresponding to 50% of the maximum load and CSIRO method defines the yield point and its relative displacement by multiplying the value of displacement at 40% maximum load by a factor of 1.25. Study by Munoz et al. (2008) has shown that neither K&C nor CSIRO produced realistic values for timber connections.

The Equivalent Energy Elastic-Plastic Curve (EEEP) method defines the yield point based on bilinear curve that represents an ideal elastic-plastic behavior (Figure 2-5). This method estimates relatively high yield loads which are always off the load-displacement curves.

Yasumura and Kawai (Y&K) and European Committee for Standardization (CEN) methods define yielding based on the nature of load-displacement response. Both methods produce reasonable values for yielding. However, CEN approach may estimate unrealistic values for yield points due to the yield point’s location off the load-displacement curves.

The last studied approach by Munoz et al. (2008), 5% of diameter (5% Offset) method, defines the yield point as the intersection of a parallel line to the initial stiffness which is offset by 5% of fastener diameter and the load-displacement curve. Results of the current study showed that based on the load-displacement curve shapes, this method would be a proper approach to define the yielding especially in the case of connections with washers.

Applying the above studied methods by Muñoz et al on the load-displacement response curves of connection tests (Figure 4-1 and Figure 4-2), particularly the curves corresponding to connections using washers, have shown that the 5% offset method (ASTM D5652, 2007) provides relatively reasonable yield values. The estimated values of yielding by 5% offset method form the base of discussion in the following sections. Table 4-3 presents the yield load and displacement values estimated by CEN and 5% offset methods.

Table 4-3: Yield data per connection unit for edge-to-edge connections.

Joint Type	Load Direction	Fastener Type		Test series	$F_{yield\ (CEN)}$ (kN)	$\Delta_{yield\ (CEN)}$ (mm)	$F_{yield\ (5\%)}$ (kN)	$\Delta_{yield\ (5\%)}$ (mm)
		Screw	Washer					
Half-Lapped	Shear	6mm	None	SHL6N	4.43 (20)	6.62 (1)	3.25 (3)	4.38 (34)
			18mm	SHL6W	5.52 (47)	10.61(61)	3.45(11)	4.41 (56)
		8mm	None	SHL8N	7.78 (13)	9.72 (40)	4.63 (4)	5.35 (26)
			25mm	SHL8W	8.31 (12)	5.05 (37)	5.12 (5)	3.09 (24)
	Tension	6mm	None	THL6N	4.96 (13)	7.67 (37)	3.39(15)	4.54 (25)
			18mm	THL6W	6.46 (14)	8.37 (43)	3.71 (5)	4.01 (31)
		8mm	None	THL8N	5.24 (12)	4.38 (28)	3.98 (5)	2.99 (14)
			25mm	THL8W	5.97 (17)	2.56 (50)	4.26 (4)	1.88 (24)
Single-Spline	Shear	6mm	None	SSS6N	2.55 (12)	5.91 (25)	1.88 (4)	4.31 (15)
			18mm	SSS6W	6.91 (5)	16.22(26)	3.55 (2)	10.49 (4)
		8mm	None	SSS8N	5.81 (6)	8.11 (14)	4.21 (5)	5.71 (9)
			25mm	SSS8W	11.19(11)	21.84(10)	5.73 (6)	10.12(23)
	Tension	6mm	None	TSS6N	2.54 (15)	4.84 (34)	1.87 (5)	3.49 (22)
			18mm	TSS6W	7.05 (5)	20.21 (6)	3.46 (5)	8.91 (3)
		8mm	None	TSS8N	5.53 (12)	11.57 (29)	3.51 (4)	6.89 (18)
			25mm	TSS8W	11.29 (3)	28.85 (9)	5.42 (3)	12.38 (8)

CoV (%) in parenthesis

CoV values in Table 4-3 indicate that variability for yield values estimated by the CEN method is higher than thoes estimated by 5% offset method. It is also indicated that variability in yield displacement (Δ_{yield}) is relatively high, particularly in the case of lapped connections. The yielding data of CEN and 5% offset methods presented in Table 4-3 exhibit great differences in values, particularly in case of connections with washers placed under screw heads. CEN method defines the initial secant as a straight line that cuts the curve in 10% and 40% of maximum load while the 5% offset method spans the secant between 0% and 40% of the maximum load. This also explains the differences of the initial stiffness values presented in Table 4-4. The over estimation of yield values by CEN method could be caused by the approach that defines the lower intersection points of initial secants and location of the intersection of scants which is always above the curves.

4.1.2.3 Stiffness

Initial stiffness is subjected to the rigidity of the connection in its elastic range to resist the deformation corresponding to the applied tension or shear forces. The values of two initial stiffness defined by CEN and 5% offset methods are presented in Table 4-4.

Table 4-4: Initial stiffness properties per connection unit for edge-to-edge connections.

Connection Type	Load Direction	Fastener Type		Test series	$K_{(CEN)}$ (kN/mm)	$K_{(5\%)}$ (kN/mm)
		Screw	Washer			
Half-Lapped	Shear	6mm	None	SHL6N	0.72 (39)	0.82 (33)
			18mm	SHL6W	0.97 (74)	1.11 (65)
		8mm	None	SHL8N	0.81 (37)	0.93 (34)
			25mm	SHL8W	1.56 (29)	1.74 (25)
	Tension	6mm	None	THL6N	0.69 (22)	0.82 (67)
			18mm	THL6W	0.85 (28)	0.94 (25)
		8mm	None	THL8N	1.41 (15)	1.35 (12)
			25mm	THL8W	2.94 (33)	2.39 (24)
Single-Spline	Shear	6mm	None	SSS6N	0.38 (11)	0.44 (11)
			18mm	SSS6W	0.27 (16)	0.34 (15)
		8mm	None	SSS8N	0.61 (9)	0.74 (9)
			25mm	SSS8W	0.47 (18)	0.59 (18)
	Tension	6mm	None	TSS6N	0.55 (17)	0.55 (16)
			18mm	TSS6W	0.35 (4)	0.39 (4)
		8mm	None	TSS8N	0.51 (17)	0.52 (15)
			25mm	TSS8W	0.39 (8)	0.44 (9)

CoV (%) in parenthesis.

CEN method defines the initial stiffness ($K_{(CEN)}$) as per EN 12512, (2002) as the slope of the chord initial secant line that spanned between points on load-displacement curve corresponding to 10% and 40% of the maximum load. The 5% offset method defines the initial stiffness ($K_{(5\%)}$) as per ASTM D5652, (2007) as the slope of the line that spanned between origin and the yield point. Stiffness values estimated by CEN are in more than 80% agreement with the ones estimated by 5% offset method, respectively. A very high variability observed in parameters related to stiffness values of half-lapped connections. This could be the result of using a single slender screw per connection unit rather than using pairs of screws. Particularly, in case of half-lapped connections with washers, it is also observed that in some instances failure was catastrophic which caused a very high CoV values.

4.1.2.4 Ductility

Ductility is defined as the ability of connection to deform under the action of a shear or tension loads. Timber materials are inherently brittle and presence of mechanical fasteners in timber joints provides ductility (Haller, 1999). Different definitions of the ductility ratio are discussed by Jorissen et al., (2010), Brühl et al., (2011), and Jorissen & Fragiacomo, (2010). Two measurement of ductility, D_{max} and $D_{failure}$, were selected to evaluate the ductility ratio with in this research relative on displacement at maximum load (Δ_{max}) and displacement at failure ($\Delta_{failure}$). Based on discussion by Munoz et al. (2008) in section 4.1.2.2, yield displacement value (Δ_{yield}) was determined by CEN and 5% offset methods and used in the ductility ratio calculations. D_{max} is measured by the ratio of the maximum displacement and yield displacement as EN 12512, (2002).

$$\boldsymbol{D_{max}} = \boldsymbol{\Delta_{max}} / \boldsymbol{\Delta_{yield}} \qquad (4\text{-}1)$$

$D_{failure}$ is defined as the ratio between failure displacement and yield displacement.

$$D_{failure} = \Delta_{failure} / \Delta_{yield} \qquad (4\text{-}2)$$

D_{max} and $D_{failure}$ values are shown in Table 4-6. Smith et al., (2006) presented an approach to classify the timber connections based on D_{max} values (Table 4-5). However, ductility ratio is based on either maximum displacement or failure displacement (Smith et al., 2006). There are considerable differences in ductility parameters shown in Table 4-6 due to using two distinct methods to estimate yield displacement and results did not show meaningful differences in the ductility ratio between half-lapped and single-spline connections. In general, in spite of some exceptions, placing washers beneath screw heads decreased the ductility of studied connections. However, the post yield deformation still remains significant enough not to create a non-ductile behavior. Explanation of the observed effects lies in how addition of washers changed the deformation and failure mechanisms and consequantly, the post-yeild displacements.

Table 4-5: Classification of ductility classes (Smith et al., 2006).

Classification	Ductility Ratio
Brittle	$D_{max} \leq 2$
Low-Ductility	$2 < D_{max} \leq 4$
Moderate Ductility	$4 < D_{max} \leq 6$
High-Ductility	$6 < D_{max}$

Table 4-6: Ductility measures per connection unit for edge-to-edge connections.

Connection Type	Load Direction	Fastener Type: Screw	Fastener Type: Washer	Test series	$D_{max\ (CEN)}$	$D_{failure\ (CEN)}$	$D_{max\ (5\%)}$	$D_{failure\ (5\%)}$	Ductility * Classification
Half-Lapped	Shear	6mm	None	SHL6N	12.49 (63)	16.19 (48)	15.46 (44)	20.53 (27)	high-high
			18mm	SHL6W	5.04 (72)	7.34 (68)	7.93 (65)	11.57 (68)	medium-high
		8mm	None	SHL8N	5.51 (54)	9.88 (67)	8.79 (30)	15.49 (42)	medium-high
			25mm	SHL8W	5.55 (43)	10.44 (44)	8.45 (28)	15.86 (31)	medium-high
	Tension	6mm	None	THL6N	4.22 (40)	6.23 (36)	6.72 (25)	9.98 (30)	medium-high
			18mm	THL6W	2.99 (30)	4.09 (35)	5.87 (20)	7.98 (25)	low-medium
		8mm	None	THL8N	5.51 (26)	7.85 (24)	7.73 (14)	11.05 (13)	medium-high
			25mm	THL8W	11.22 (50)	16.37 (55)	10.46 (27)	15.05 (30)	high-high
Single-Spline	Shear	6mm	None	SSS6N	7.64 (19)	9.64 (20)	10.23 (11)	12.93 (12)	high-high
			18mm	SSS6W	3.77 (27)	4.45 (29)	5.61 (14)	6.62 (18)	low-medium
		8mm	None	SSS8N	6.87 (22)	9.18 (16)	9.58 (14)	12.87 (8)	high-high
			25mm	SSS8W	2.83 (22)	3.68 (31)	5.95 (15)	7.73 (24)	low-medium
	Tension	6mm	None	TSS6N	8.25 (30)	10.07 (27)	10.93 (21)	13.34 (16)	high-high
			18mm	TSS6W	2.36 (11)	2.68 (7)	5.33 (7)	6.07 (4)	low-medium
		8mm	None	TSS8N	4.71 (26)	5.92 (26)	7.59 (15)	9.56 (16)	medium-high
			25mm	TSS8W	2.19 (6)	2.61 (11)	5.11 (5)	6.04 (9)	low-medium

* High: $D>6$; Medium: $4<D\leq 6$; Low: $2<D\leq 4$; Brittle: $D<2$ (Smith et al., 2006).
CoV (%) in parenthesis.

4.1.2.5 Energy Dissipation

This section presents the energy dissipation characteristics of half-lapped and single-spline connections obtained from monotonic shear and tension load resistance tests. The energy calculation was made on the load-displacement curves obtained from the experimental data in which the area under the each curve was calculated.

This section reports two energy dissipation characteristics named dissipation energy at 30mm displacement (W_{30mm}) and dissipation energy at failure point ($W_{failure}$). The parameters $W_{30\mathrm{mm}}$ and $W_{failure}$ are ones that can be used to subjectively estimate relative merits of particular joints/fasteners in terms of ability to absorb energy under high amplitude deformation, or as the basis of energy-based structural design calculations (Smith & Frangi, 2008).

Dissipation of energy at 30mm displacement (W_{30mm}) corresponds to the area under load-displacement curve from commencement of test to 30mm displacement. Such a limitation is suggested by EN 12512, (2002) which defines the ultimate load value as the maximum load recorded by 30mm or less slip. Dissipation energy at failure point ($W_{failure}$) corresponds to the area under load-displacement curve from commencement of test to the failure point. The energy dissipation values are presented in Table 4-7.

In general, the dissipated energy values of half-lapped connections are higher than those values of single-spline connections by up to 177%. Such a difference lies in the higher loadings and wider post-yield displacements provided by half-lapped connections.

Table 4-7: Dissipation Energy per connection unit for edge-to-edge connections.

Connection Type	Load Direction	Fastener Type: Screw	Fastener Type: Washer	Test series	W_{30mm} (kNxmm)	$W_{failure}$ (kNxmm)
Half-Lapped	Shear	6mm	None	SHL6N	149 (7)	522 (14)
			18mm	SHL6W	186 (11)	230 (16)
		8mm	None	SHL8N	215 (6)	584 (51)
			25mm	SHL8W	279 (5)	443 (15)
	Tension	6mm	None	THL6N	147 (3)	224 (8)
			18mm	THL6W	178 (5)	180 (13)
		8mm	None	THL8N	211 (5)	230 (3)
			25mm	THL8W	204 (9) *	204 (9)
Single-Spline	Shear	6mm	None	SSS6N	85 (4)	188 (8)
			18mm	SSS6W	118 (5)	404 (8)
		8mm	None	SSS8N	168 (3)	559 (8)
			25mm	SSS8W	195 (6)	743 (9)
	Tension	6mm	None	TSS6N	93 (4)	155 (8)
			18mm	TSS6W	132 (4)	316 (8)
		8mm	None	TSS8N	136 (4)	395 (8)
			25mm	TSS8W	169 (5)	678 (9)

*Failure occurred before 30mm displacement.
CoV (%) in parenthesis.

Placing washers under screw heads decreased the energy dissipation properties for half-lapped by up to 25% while it increased the corresponding values for single-spline connections by up to 115%. Explanations for such contrast effects lies in how placing washers under screw heads alters the failure mechanisms and consequently loadings and post-yield displacements (Section 4.2.2).

4.1.3 Cyclic Connection Test Data Reduction

In this section, test data are analyzed to determine the impairment of strength and equivalent viscous damping ratio of half-lapped and single-spline connections under cyclic loading procedures. The derived parameters are important to the design of structures. Duration of tests was short-term which refers to low cycle fatigue testing corresponding to such a loadings caused by seismic events. The load-displacement curves and their back-bone graphs derived from cyclic connection tests accompanied by average monotonic load-displacement curves are presented in Appendix C. The back-bone graphs were plotted by connecting points of maximum load achieved in each cycle to the next level's points.

4.1.3.1 Impairment of Strength

Impairment of strength (ΔF) refers to reduction of a load when attaining a certain displacement (EN-12512, 2002). Impairment of strength was measured as the differentiation between maximum load achieved in the first cycle and maximum load achieved in the third cycle of same amplitude (Figure 4-6).

$$\Delta F = |F_{1st} - F_{3rd}| \tag{4-3}$$

For comparison reasons, the percentage of reduction in strength capacity from first cycle to second and third cycles at displacements corresponding to 100%, 200%, 400% and 800% of yield load (these percentages refers to the loading procedure that described in cyclic test protocol) from monotonic tests are presented in Table 4-8. Load reduction percentage at or next to yield displacement was minor and increased with displacement amplitude. In general, differences for shear load directions were greater than differences for tension load directions particularly in case of half-lapped connections. Placing washers under screw heads decreased the strength reduction of studied connections considerably.

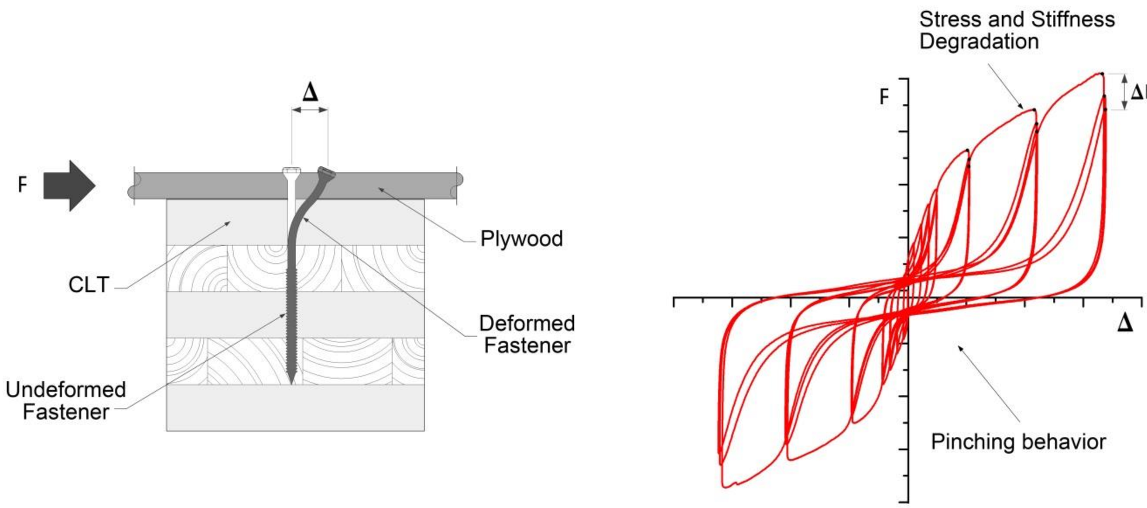


Figure 4-6: Plotting of cyclic edge-to-edge connection test.

4.1.3.2 Equivalent Viscous Damping

Dissipation of energy during cyclic loading is quantified by the equivalent viscous damping ratio (v_{eq}). This non-dimensional factor demonstrates the hysteresis damping properties of connections under a specified loading regime and is determined by the methods specified in EN 12512, (2002) as the ratio between dissipated energy (E_d) of a half cycle and the relevant available potential energy (E_p) multiplied by 2π (Figure 4-7), equation 4-4.

Table 4-8: Reduction in load capacity per connection unit for edge-to-edge connections.

Connection Type	Load Direction	Fastener Type		Test series	100% Yield Slip		200% Yield Slip		400% Yield Slip		800%yield Slip	
		Screw	Washer		2nd	3rd	2nd	3rd	2nd	3rd	2nd	3rd
Half-Lapped	Shear	6mm	None	SHL6N	4.2%	5.2%	3.9%	6.0%	15.6%	24.4%	27.9%	49.3%
			18mm	SHL6W	2.4%	2.8%	3.3%	4.7%	14.5%	23.3%	19.9%	56.3%
		8mm	None	SHL8N	5.1%	7.8%	5.5%	8.0%	22.0%	32.0%	37.9%	70.4%
			25mm	SHL8W	2.9%	3.7%	2.6%	3.7%	8.9%	12.0%	49.2%	99.5%
	Tansion	6mm	None	THL6N	4.7%	5%	2.0%	5.3%	3.8%	6.3%	7.4%	9.4%
			18mm	THL6W	1.9%	2.6%	2.2%	3.1%	3.1%	4.9%	7.4%	11.1%
		8mm	None	THL8N	1.1%	6.4%	1.4%	5.5%	0.8%	5.5%	7.0%	7.4%
			25mm	THL8W	2.0%	3.0%	0.4%	1.6%	3.3%	7.3%	12.0%	13.1%
Single-Spline	Shear	6mm	None	SSS6N	2.8%	3.6%	3.0%	4.5%	6.7%	10.0%	11.2%	16.3%
			18mm	SSS6W	3.5%	4.8%	3.6%	5.8%	7.4%	10.8%	15.7%	22.6%
		8mm	None	SSS8N	5.2%	7.8%	5.2%	7.2%	6.4%	10.6%	6.8%	10.8%
			25mm	SSS8W	3.9%	5.7%	3.0%	5.0%	4.5%	7.1%	6.0%	9.6%
	Tension	6mm	None	TSS6N	3.4%	3.7%	0.8%	4.2%	7.4%	8.3%	6.1%	8.3%
			18mm	TSS6W	2.9%	3.9%	2.6%	4.2%	5.3%	8.0%	7.1%	9.7%
		8mm	None	TSS8N	4.0%	6.0%	4.8%	7.3%	7.1%	12.1%	8.4%	12.55
			25mm	TSS8W	4.7%	5.9%	3.9%	6.3%	5.0%	8.0%	6.7%	10.7%

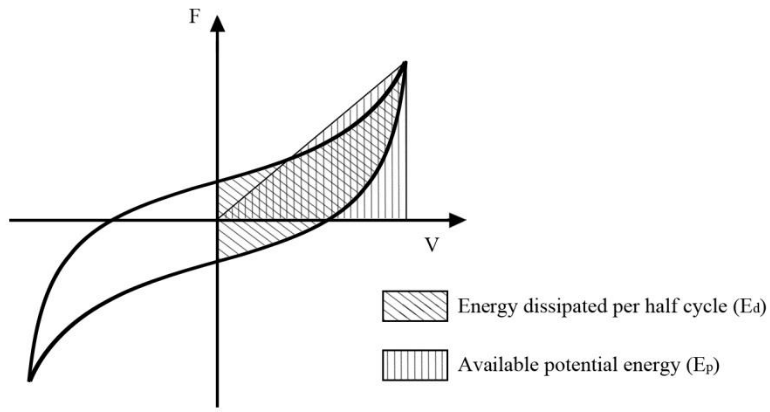


Figure 4-7: dissipation energy and available potential energy definitions (DIN, 2002).

The equivalent viscous damping ratio (ν_{eq}) is defined as:

$$\nu_{eq} = E_d / 2\pi E_p \qquad (4\text{-}4)$$

Dissipated energy (E_d) was defined as the area of each half cycle and available potential energy (E_p) was defined as a triangular area defined by origin, point on the curve corresponding to maximum load, and the maximum load displacement (Figure 4-7).

Table 4-9 presents the equivalent viscous damping ratios for the first and third cycles at 100%, 200%, and 400% of the average yielding displacement. Embedment of fastener shank into timber specimens would cause permanent damages to the wood fibers around the shank area. This phenomenon would cause the so called “pinching effect” due to reduction in embedment resistance under a cyclic loading procedure (Figure 4-6). Pinching causes damping at displacements equal or greater than ones at yielding.

Table 4-9: Equivalent viscous damping ratios per connection unit for edge-to-edge connections.

Connection Type	Load D rectio n	Fastener Type		Test series	100% Yield Slip		200% Yield Slip		400% Yield Slip	
		Screw	Washer		1st	3rd	1st	3rd	1st	3rd
Half-Lapped	Shear	6mm	None	SHL6N	0.11	0.07	0.15	0.07	0.22	0.06
			18mm	SHL6W	0.13	0.10	0.16	0.10	0.19	0.08
		8mm	None	SHL8N	0.12	0.09	0.22	0.08	0.17	0.07
			25mm	SHL8W	0.14	0.11	0.20	0.09	0.19	0.10
	Tension	6mm	None	THL6N	0.18	0.12	0.19	0.10	0.23	0.08
			18mm	THL6W	0.15	0.16	0.17	0.13	0.20	0.09
		8mm	None	THL8N	0.19	0.14	0.21	0.12	0.18	0.08
			25mm	THL8W	0.17	0.16	0.19	0.14	0.21	0.12
Single-Spline	Shear	6mm	None	SSS6N	0.11	0.08	0.20	0.09	0.20	0.08
			18mm	SSS6W	0.11	0.10	0.16	0.10	0.19	0.10
		8mm	None	SSS8N	0.13	0.07	0.19	0.08	0.20	0.09
			25mm	SSS8W	0.14	0.08	0.18	0.09	0.21	0.11
	Tension	6mm	None	TSS6N	0.14	0.09	0.21	0.11	0.19	0.07
			18mm	TSS6W	0.13	0.10	0.17	0.10	0.20	0.11
		8mm	None	TSS8N	0.11	0.07	0.16	0.09	0.22	0.06
			25mm	TSS8W	0.12	0.09	0.19	0.08	0.21	0.07

4.1.4 Fasteners Axial Load Test Reduction

The axial load in the fastener plays a key role in the performance of connections and their failure modes. Results from axial load tests on fastener including screw thread withdrawal and screw head pull-through tests with and without a washer under screw head are analyzed to determine maximum load (F_{max}), displacement at maximum load (Δ_{max}), Failure load ($F_{failure}$), displacement at failure load ($\Delta_{failure}$), yield load (F_{yield}), displacement at yield load (Δ_{yield}), and stiffness (K). The method used to determine the yield point was 5% offset method as ASTM D1761, (2007). Load-displacement curves and their derived parameters are presented in Appendix B.

4.1.4.1 Screw Thread Withdrawal

In both studied edge-to-edge connections, half-lapped and single-spline, the self-tapping screws were inserted into the CLT normal to face plane of a CLT member, meaning that the anchoring resistance was provided along the interfaces of the threaded portion of their lengths. The CLT materials used through the withdrawal tests were 3ply CLT (ply thickness: 36mm, 36mm, and 18mm) which represented the edge of CLT panels where screws are inserted. Screw thread withdrawal test data was analyzed to investigate the behavior of point-side threaded portions of screws being pulled out of CLT. Table 4-10 presents the parameters derived from load-displacement curves of screw thread withdrawal tests.

4.1.4.2 Screw Head Pull-Through

Screw head pull-through tests characterized behaviors of unthreaded portions of screw shanks, with and without a washer under the head, being pulled through in CLT or plywood. Test data was analyzed with intent to define the parameters which are related to embedding strength of screw heads. For pull-through test with CLT, the screws fully penetrated normal to the thicker ply side into the CLT member, corresponding to a half CLT plate thickness as would occur in a half-lapped edge-to-edge connection. In the case of pull-through tests with plywood, the screws were fully inserted into the plywood,

Table 4-10: Test data for fastener axial load tests.

Type of Test	Wood Material	Fastener Type: Screw	Fastener Type: Washer	Test series	F_{max} (kN)	Δ_{max} (mm)	$F_{failure}$ (kN)	$\Delta_{failure}$ (mm)	F_{yield} (kN)	Δ_{yield} (mm)	K (kN/mm)	D_{max}	$D_{failure}$
Withdrawal	CLT	6mm	None	TC6	9.62 (3)	1.59 (7)	7.69 (3)	2.91 (4)	8.94 (2)	1.03 (5)	8.86 (4)	1.55 (6)	2.83 (5)
		8mm	None	TC8	15.71 (9)	2.53 (15)	12.57 (9)	4.12 (6)	13.74 (6)	1.28 (6)	10.75 (5)	1.98 (14)	3.23 (8)
Pull-through	CLT	6mm	None	HC6N	5.64 (11)	64.74 (19)	4.51 (11)	80.52 (4)	2.55 (19)	1.05 (63)	3.21 (47)	86.14 (63)	112.44 (62)
			18mm	HC6W	13.14 (1)	21.52 (2)	10.51 (1)	22.36 (3)	10.91 (8)	9.55 (28)	1.21 (20)	2.41 (28)	2.51 (27)
		8mm	None	HC8N	9.09 (11)	27.76 (59)	7.27 (11)	45.68 (3)	6.94 (11)	4.45 (34)	1.65 (20)	7.11 (68)	11.11 (27)
			25mm	HC8W	25.92 (8)	23.02 (11)	20.73 (8)	22.82 (6)	18.06 (17)	5.71 (36)	3.39 (22)	4.55 (38)	4.54 (40)
	Plywood	6mm	None	HP6N	5.99 (8)	9.99 (7)	4.79 (8)	13.28 (8)	6.66 (32)	9.78 (26)	0.68 (11)	1.06 (20)	1.43 (23)
			18mm	HP6W	7.53 (4)	9.11 (7)	6.02 (4)	11.57 (7)	6.21 (6)	3.86 (17)	1.64 (16)	2.42 (19)	3.11 (26)
		8mm	None	HP8N	8.88 (5)	14.37 (8)	7.11 (5)	19.03 (8)	8.62 (7)	11.9 (8)	0.71 (4)	1.22 (15)	1.62 (16)
			25mm	HP8W	16.13 (3)	15.37 (5)	12.91 (3)	18.19 (3)	11.86 (8)	4.61 (15)	2.59 (7)	3.39 (15)	4.02 (16)

corresponding to a plywood splice used in a single-spline connection. Results from load-displacement curves are presented in Table 4-10.

In general, washers under screw heads altered the yield and post yield values considerably. Maximum load values increased significantly by up to 185% while yield load values increased by up to 325%. The increase in the relevant displacement values was even greater. Consequently, placing washers under screw heads decreased the stiffness values.

4.2 Discussion of Edge-to-Edge Connection Results

4.2.1 Connections without Washers under Screw Heads

4.2.1.1 Half-Lapped Connection

Average load versus deformation responses of half-lapped connections using 6mm and 8mm self-tapping screws without washers inserted under screw heads under shear and tension loads are shown in Figure 4-8.

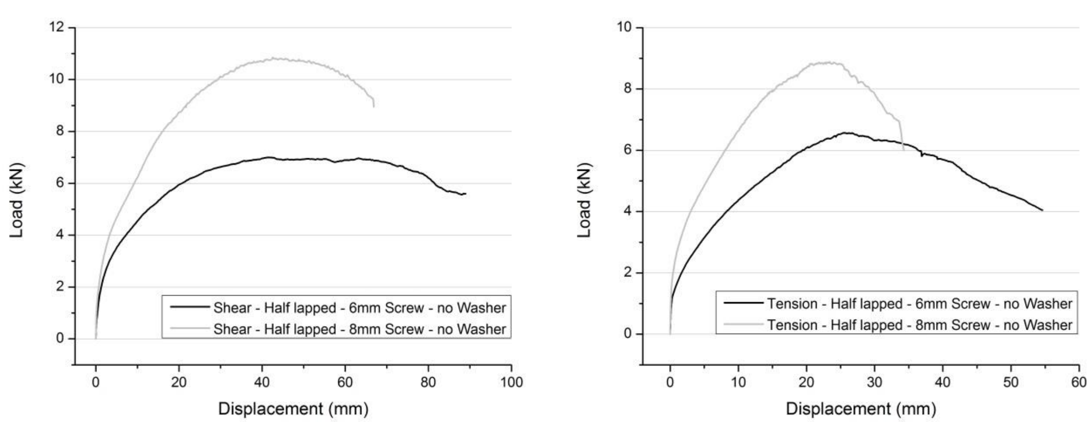


Figure 4-8: Average load-displacement curves of half-lapped connections without washers under shear loads (left) and tension loads (right).

Derived engineering parameters from test data showed that the maximum load capacity and yield load values of half-lapped connections under shear loads using 8mm screws are 45% and 42% higher than those using 6mm screws. The corresponding ratios in case of tension loads are 35% and 17% respectively (Table 4-2 and Table 4-3). This increase in loading values was due to higher fastener bending strength and embedment strength of CLT member provided by 8mm screws.

The comparison of maximum and yield loads also showed that the values for half-lapped connections using 6mm screws under shear loads are 13% and 4% higher than those under tension loads. The corresponding value in case of connections using 8mm screws are 21% and 17% respectively (Table 4-2 and Table 4-3). The explanation lies in the effects of wood grain direction of outer plies which is perpendicular to the tension load direction and CLT member thickness at load direction which is smaller where tension loads applied. The results also showed that initial stiffness of connections under shear loads using 8mm screws are relatively higher than those using 6mm screws. The initial stiffness values for connections using 6mm screws were constant regardless of applied loading directions while the corresponding values for connection using 8mm screws under tension loading were 45% higher than those under shear loadings (Table 4-4).

In general, half-lapped connections exhibited relatively ductile behavior. However, ductility ratios of connections under shear loads were higher due to the higher post yield deformations (Table 4-6). There was no considerable difference between the values of dissipating energy at 30mm displacement (W_{30mm}) of connections under shear and tension loadings (Table 4-7). In contrast with W_{30mm}, the values of dissipating energy at failure ($W_{failure}$) of connections under shear loads were almost 100% higher than those values for connections under tension loads (Table 4-7). This is a consequence of having higher failure displacement for connections under shear loads.

The results also demonstrated that there is no meaningful deference of energy dissipation value at failure ($W_{failure}$) between connections using 6mm and 8mm screws regardless of applied load direction. However, connections using 8mm screws are able to dissipate 44% more energy than connections using 6mm screws at 30mm displacement (W_{30mm}), Table 4-7.

Figure 4-9: Observed failure for half-lapped connections without washers under shear loads (left) and tension loads (right).

Observations of the failure of half-lapped connections under both shear and tension loadings showed that the screws deform on either sides of joint interfaces to form two hinge like deformations (Figure 4-9) which refers to failure mode IV (Figure 2-6) as predicted by EYM (Johansen, 1949).

4.2.1.2 Single-Spline Connection

Average load-displacement curves of single-spline connections using 6mm and 8mm self-tapping screws without washers inserted under screw heads under shear and tension loads are shown in Figure 4-10.

Calculated engineering parameters from test data showed that the maximum load capacity and yield load values of single-spline connections under shear loads using 8mm screws are 125% higher than those using 6mm screws. The corresponding ratio in case of tension loads is 88% (Table 4-2 and Table 4-3). These increases in loading values of connections using 8mm screws were due to not only higher fastener bending strength and embedment strength of CLT members but also thicker plywood splines used in the connections. The comparison of maximum and yield loads also showed that the values for single-spline connections using 8mm screws under shear loads are 21% and 20% higher than those under tension loads. Results did not show any change in the corresponding value in case of connections using 6mm screws (Table 4-2 and Table 4-3).

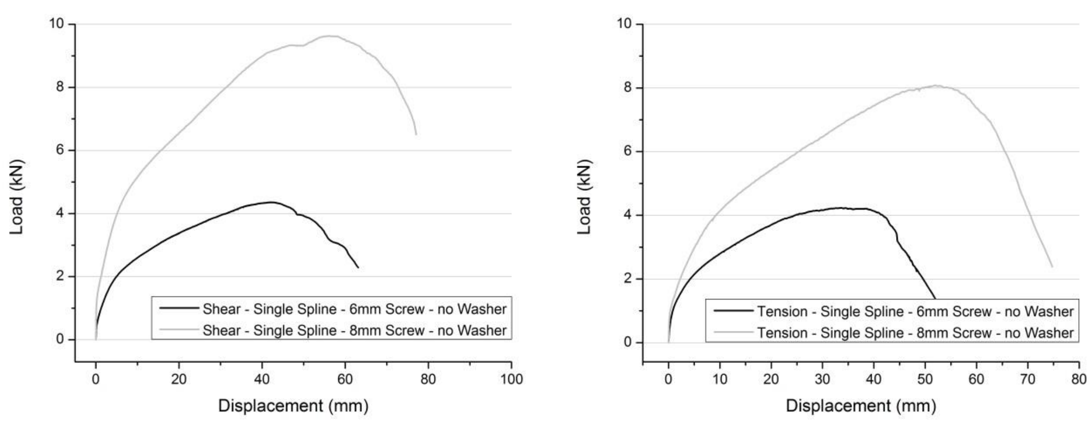


Figure 4-10: Average load-displacement curves of single-spline connections without washers under shear loads (left) and tension loads (right).

In general, the spline connections exhibited relatively low initial stiffness and high ductility. No meaningful change in initial stiffness and ductility ratios were observed for studied spline connections (Table 4-4 and Table 4-6).

No special trend was observed related to the values of energy dissipation of connections under shear and tension loadings. However, energy dissipation values at 30mm displacement and failure for connections using 8mm screws are respectively up to 95% and 200% higher than connections using 6mm screws (Table 4-7).

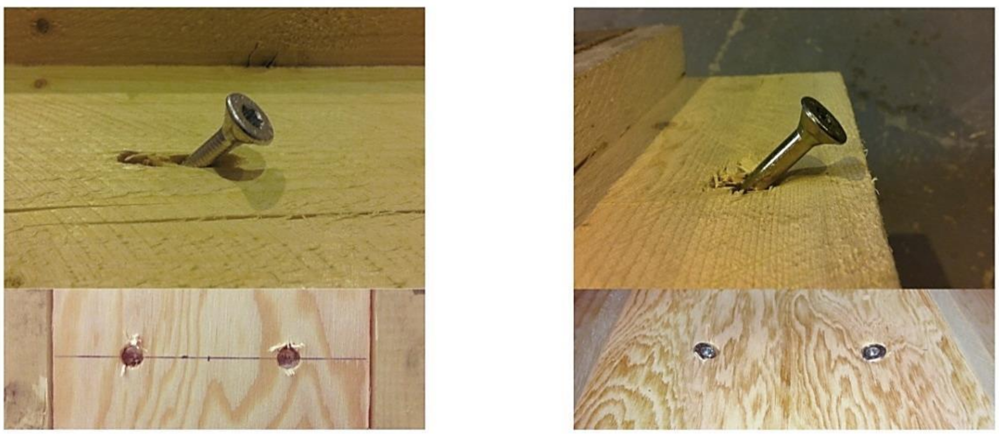


Figure 4-11: Observed failure for single-spline connections without washers under shear loads (left) and tension loads (right). Plywood has been removed to show the plastically deformed screws.

Observations of the failure of single-spline connections under both shear and tension loadings showed that the screws deform to form a hinge in which the screw head rotates and turns in the plywood spline (

Figure 4-11). This failure mechanism refers to failure mode III (Figure 2-6) considered under EYM models (Johansen, 1949).

4.2.1.3 Comparison of Half-Lapped and Single-Spline Connections

Average load-displacement curves of half-lapped and single-spline connections without washers under screw heads are shown in Figure 4-12.

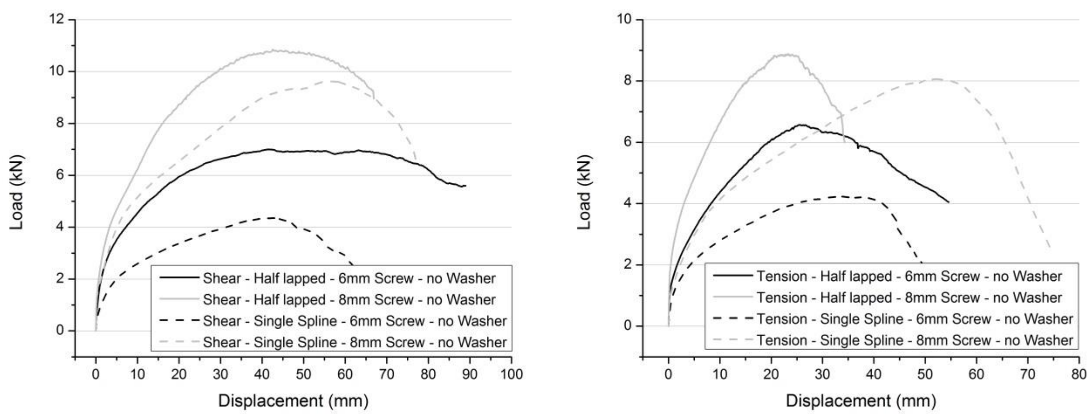


Figure 4-12: Average load-displacement curves for edge-to-edge connections under shear loads (left) and tension loads (right).

Results showed that the maximum load capacity and yield load values of half-lapped connections using 6mm screws are 63% and 76% higher than single spline connections using 6mm screws respectively regardless of applied loading directions. The corresponding ratios in case of connections using 8mm screws are 11% and 13% respectively (Table 4-2 and Table 4-3). The results also showed that initial stiffness of half-lapped connections using 6mm and 8mm screws are 68% and 26% higher than single-spline connections respectively (Table 4-4).

The half-lapped connections are able to dissipate 50% more energy than single-spline connections at 30mm displacement regardless of screw diameter and applied load direction. In case of dissipation energy at failure, half-lapped connections were superior but no special trends were observed (Figure 4-7).

In general, as the Figure 4-12 shows, half-lapped connections are superior in all respects (i.e. initial stiffness, strength, ductility, ability to absorb energy) to single-splice joints. In rough terms it is appropriate to think for the joint types investigated, that using of half-lapped CLT plate edge-to-edge connections is 50% superior to using of single-spline edge-to-edge connections to resist shear and tension flows in diaphragm slabs. The difference is attributed to combined effects of using relatively thin plywood as the head-side member and eccentricities that complicate force flows in single-spline connections. Examination of plastically deformed screws from failed specimens revealed that half-lapped and single-spline joints failed by type IV and type III mechanisms respectively, based on the classification shown in Figure 2-6. This agreed with mechanisms predicted to govern by EYM equations. However, this does not mean that type of design level model accurately predicts observed joint capacities.

CoV values of derived engineering parameters from tests indicate that for joints that do not have washers placed under screw heads variability in design strength related parameters (F_{yield}, F_{max}, $F_{failure}$) is low. Therfore it is arguably reasonable to base design capacities of shear connections in diaphragms (which usually will have many screws) on the average strength per screw. However, variability in displacement related paramters (Δ_{yield}, Δ_{max}, Δ_{filure}, D_{max}, $D_{failure}$) is relatively high, especially in the case of half-lapped joints. Variability in parameters related to energy absorption capabilities (W_{30}, W_f) is intermediate to variability in strength and displacement related parameters; which is to be expected as they are derived by integration of load-displacent relationships. Many past investigations support the finding that displacemet related parameters are more variable than strength related parameters, e.g. Smith et al. (1998).

4.2.2 Effect of Washers under Screw Heads

4.2.2.1 Half-Lapped Connection

Figure 4-13 compares average load-displacement responses for half-lapped connections with and without washers placed under the heads of screws. From that comparison it is clear that addition of washers has slight effect on initial stiffness of a joint (*K*), increases strength (F_{yield}, F_{max}, $F_{failure}$) moderately, and decreases the post-yield point deformation (i.e. reduces Δ_{max}, $\Delta_{failure}$, D_{max}, $D_{failure}$, W_{30mm}, $W_{failure}$). In terms of decreaced post-yield deformation it is important however to recognise that the result of adding washers does not create a non-ductile response, because inelastic deformations remain significant. Explanation of the observed effects lies in how addition of washers changed the deformation and failure mechanisms after the response exceeded the small deformation regime.

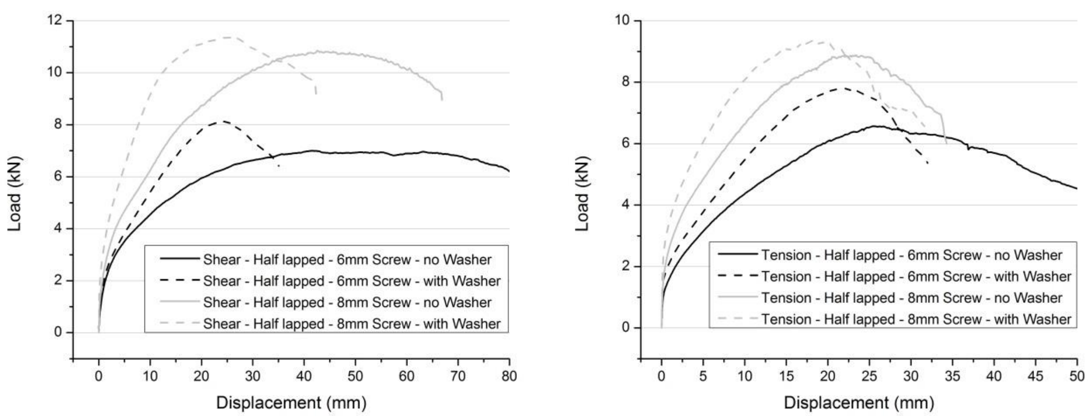


Figure 4-13: Effect of washers on average load-displacement responses of half-lapped connections.

Figure 4-14 shows tyical post-failure residual deformations in half-lapped connection speciments with and without washers placed under screw heads. In both instances the failure mechanism involved plastic bending deformation of the screw on either side of the joint plane. The greatest bending distortion occured in either instance on the side of the joint where the screws were most effectively anchored into the CLT. When there were no washers the anchoring was most effective on the point-side of the joint, and therefore development of axial forces in screws was controlled by pull-through resistance of the head-side portions of screws. By contrast, when there were washers the screws were anchored most effectivey on the head-side of the joint, with development of axial forces in screws controlled by withdrwal resistance of threaded portions of screws. As shown in Figure 4-14, this is entirely consistent with results of axial load tests on screws.

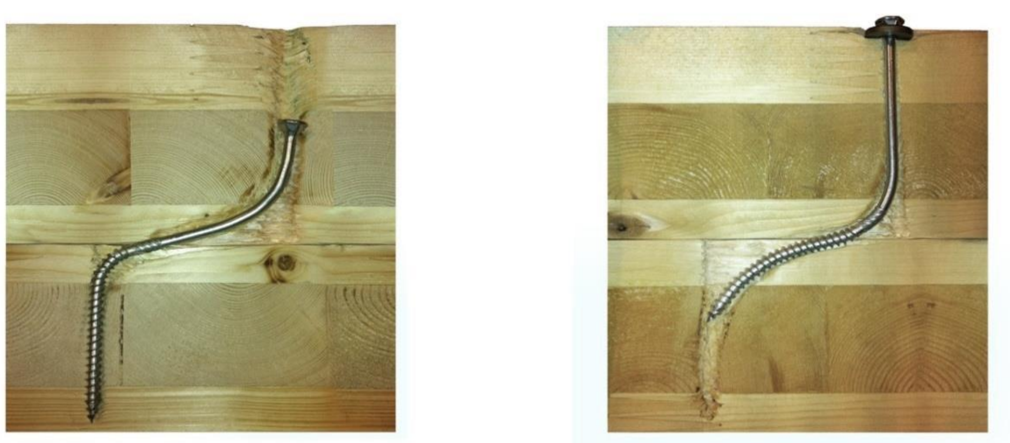


Figure 4-14: Residual deformations in half-lapped connections: without washer (left) and with washer (right).

4.2.2.2 Single-Spline Connection

Figure 4-15 compares average load-displacement responses for single-spline connections with and without washers placed under the heads of screws. It is obvious that the effect of adding washers is more accentuated than for half-lapped joints.

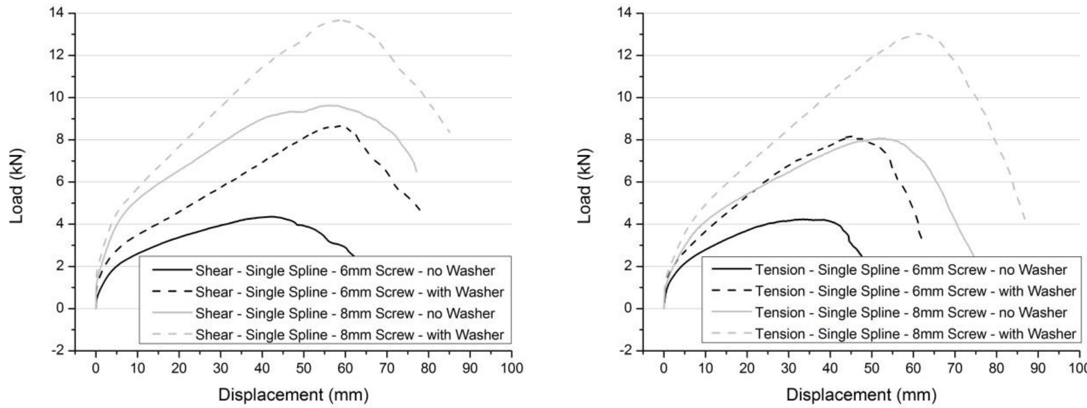


Figure 4-15: Effect of washers on average load-displacement responses of single-spline connections.

Again relative anchoring characteristics of screws in head-side and point-side members were important. With single-spline joints incorporating washers significantly increases the rotational restraint of screw at their heads, which altered the bending deformations in screws. Post-testing examination of plastic deformation of screws from connections with washers indicated that the behavior approached that associated with an EYM mechanism IV failure (Figure 2-6).

For single-spline connections, addition of washers had slight effect on initial stiffness (*K*), but altered all other engineering parameters significantly (i.e. strength, ductility, ability to absorb energy). When washers were present, post-yield deformation was strongly influenced by large deformation effects and resulting developmemt of axial forces in screws. Because screws are well anchored on the point side of the joint plane and were resistant to pull-through failure on the head side of the joint plane, the rope effect played a strong role in determining the maximum resistance. On average F_{max} increased by nearly 80% because of the addition of washers.

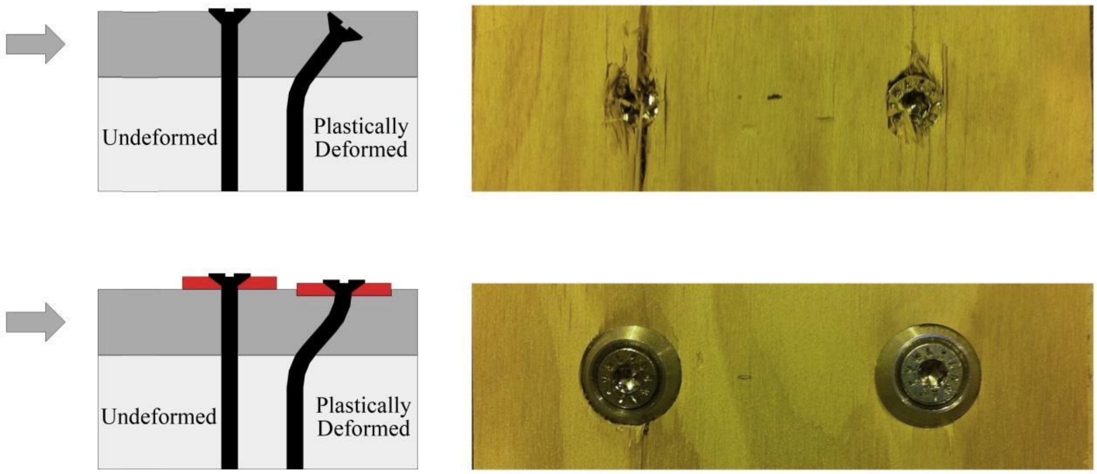


Figure 4-16: Residual indentation of screws into head-side members of single-spline connections: without washers (top), with washers (bottom).

Figure 4-16 illustrates how the increased bearing contact area on the outer surface of the plywood spline (head-side member) prevented pull-through failure. Attainment of F_{max} corresponded to reaching the withdrawal resistance of threaded portions of screws. Again this was fully consistent with results of axial load tests on screws.

4.3 Fasteners with Axial Load

Table 4-10 and Figure 4-17 and Figure 4-18 summarize results of axial load tests on screws in CLT and plywood. As those results show, it took more force to withdraw a self-tapping screw inserted along its threaded portion into CLT than to pull an unthreaded screw shank and screw head through CLT or plywood. However, it took more force to pull an unthreaded shank and a washer beneath a screw head through CLT or plywood than to withdraw a threaded self-tapping screw inserted into CLT, except for HP6W series. This matches the findings from connection shear and tension tests (Section 4.2). The quite sudden drop off in residual capacity of screws in withdrawal after attainment of peak resistance at a relatively small Δ_{max} (Δ_{max} equaled 1.6mm for 6mm screws and 2.5mm for 8mm screws), and associate low values of D_{max} (D_{max} equaled 1.6 for 6mm screws and 2.0 for 8mm screws), and $D_{failure}$ ($D_{failure}$ equaled 2.8 for 6mm screws and 3.2 for 8mm screws) imply desirability of conservative sizing of screw point-side penetrations into CLT. If that were done it would make joints with laterally loaded screws more likely to fail benignly by a combination of EYM bending and head pull-through mechanisms.

In general the variability in derived engineering parameters (Table 4-10) was small or negligible. This implies that axially loaded screws within joints and connections exhibit consistent and therefore predictable performances.

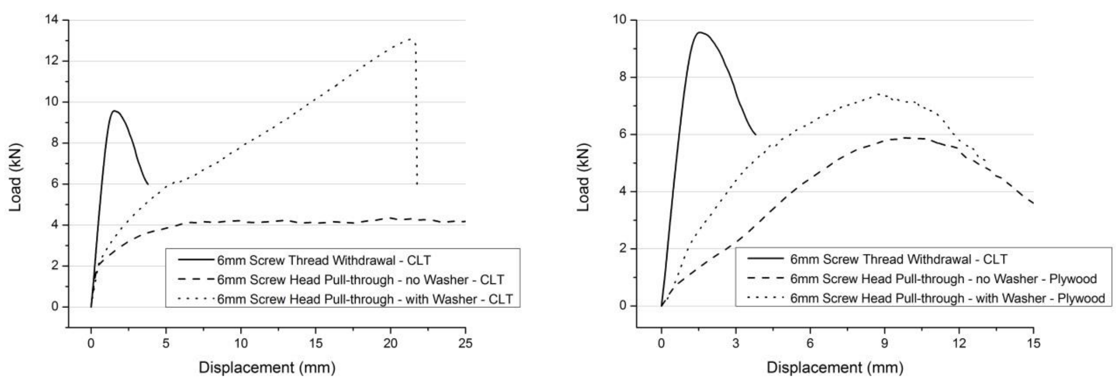


Figure 4-17: Average load-displacement responses of axially loaded 6mm screws.

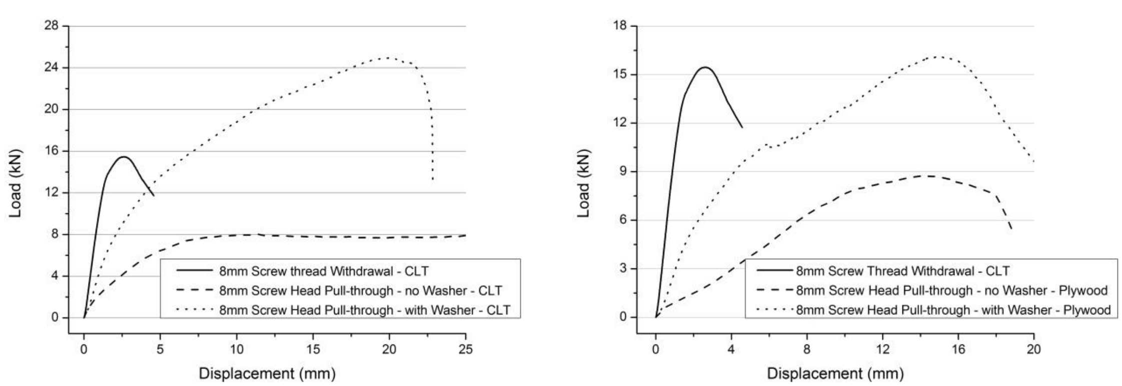


Figure 4-18: Average load-displacement responses of axially loaded 8mm screws.

4.4 Comparison of Test Results and Design Code Calculations

For the studied CLT edge-to-edge connections made using simple fasteners, lateral-load capacities are commonly addressed by simple design methods like the rigid-plastic beam analysis (commonly called the European Yield Model or EYM). In the EYM the embedment strengths of wood members and fastener yield moment capacity are used in combination with member thickness and fastener diameter to estimate the type of failure and the capacity (Johansen, 1949). The shear and tension load resisting values of CLT edge-to-edge connection tests were compared with calculated resisting values using EYM model predictions including CSA O86, (2014) and Eurocode V, (2004) in conjunction with screw embedment strength estimated from density of the CLT, and manufacturer suggested yield moments of screws (DIBT, 2013). Eurocode V design provisions of wood screws and CSA O86-14 equations for wood screws and lag screws were used to calculate the yielding resistance values of 6mm and 8mm self-tapping screws. The characteristic embedment strength of screws in CLT connections were determined using the equations proposed by Uibel and Blass (2006), equation 4-5.

$$f_{h,k} = \frac{0.031(1-0.015d)\rho_k^{1.16}}{1.1sin^2\alpha+cos^2\alpha} \qquad \textbf{Equation 4-5}$$

Where, d is screw diameter, ρ_k is characteristic density of main member, and α is the angel between the load and outer layer grain direction. The characteristic density values for CLT were the values determined from tests (Section 3.2.1.1). The characteristic fastener yield moment (M_{yRk} in Eurocode V) and screw yield strength (f_y in CSA O86-14) were adopted from the technical data published by fastener manufacturer (DIBT, 2013).

Table 4-11: EYM predictions of yield and maximum load capacities of half-lapped connections with and without washers.

Calculation Method			Predicted Strength (kN)							
			6mm Screw				8mm Screw			
			No Washer		With Washer		No Washer		With Washer	
			F_{yield} (kN)	F_{max} (kN)	F_{yield} (kN)	F_{max} (kN)	F_{yield} (kN)	F_{max} (kN)	F_{yield} (kN)	F_{max} (kN)
Experimental Measurement		Shear	3.25	7.59	3.45	8.42	4.63	10.99	5.12	11.52
		Tension	3.39	6.71	3.71	8.06	3.98	9.08	4.26	9.49
Design Prediction	CSA O86-14	Shear	2.62 (0.80)	-	2.62 (0.75)	-	4.58 (0.98)	-	4.58 (0.89)	-
		Tension	2.49 (0.73)	-	2.49 (0.66)	-	4.37 (1.08)	-	4.37 (1.03)	-
	Eurocode V	Shear	2.33 (0.72)	3.74 (0.49)	2.33 (0.67)	4.73 (0.56)	3.84 (0.83)	6.11 (0.56)	3.84 (0.75)	7.76 (0.67)
		Tension	2.22 (0.65)	3.63 (0.54)	2.22 (0.60)	4.63 (0.57)	3.66 (0.92)	5.93 (0.65)	3.66 (0.86)	7.59 (0.80)

Values in parenthesis are the ration between the design predictions and experimental measurements.
F_{yield} values of experimental measurements were determined using 5% offset method (section 4.1.2.2).

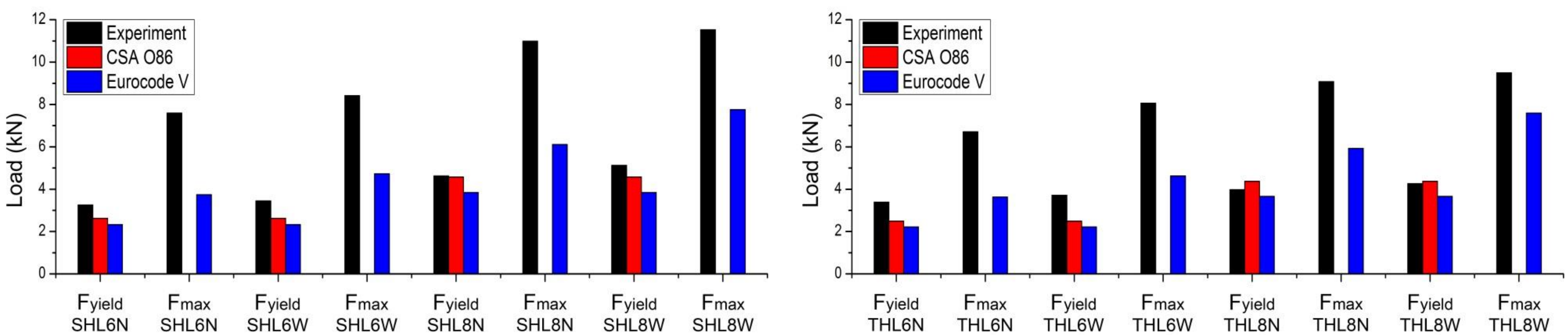


Figure 4-19: Comparison of the Maximum Load (F_{max}) and Yield Load (F_{yield}) values of half-lapped connections from experiments and those calculated following CSA O86, Eurocode V: (left) shear load direction; (right) tension load direction.

Table 4-12: EYM predictions of yield and maximum load capacities of single-spline connections with and without washers.

Calculation Method			Predicted Strength (kN)							
			6mm Screw				8mm Screw			
			No Washer		With Washer		No Washer		With Washer	
			F_{yield} (kN)	F_{max} (kN)	F_{yield} (kN)	F_{max} (kN)	F_{yield} (kN)	F_{max} (kN)	F_{yield} (kN)	F_{maxv}(kN)
Experimental Measurement		Shear	1.88	4.41	3.55	8.74	4.21	9.88	5.73	13.96
		Tension	1.87	4.35	3.46	8.47	3.51	8.18	5.42	13.18
Design Prediction	CSA O86-14	Shear	2.08 (1.11)	-	2.48 (0.69)	-	4.00 (0.95)	-	5.01 (0.87)	-
		Tension	1.97 (1.05)	-	2.41 (0.70)	-	3.79 (1.08)	-	4.86 (0.90)	-
	Eurocode V	Shear	1.96 (1.04)	3.45 (0.78)	2.28 (0.64)	4.17 (0.48)	3.40 (0.81)	5.61 (0.57)	3.77 (0.66)	7.69 (0.55)
		Tension	1.91 (1.02)	3.41 (0.78)	2.22 (0.64)	4.10 (0.48)	3.33 (0.95)	5.55 (0.68)	3.66 (0.68)	7.58 (0.58)

Values in parenthesis are the ration between the design predictions and experimental measurements.

F_{yield} values of experimental measurements were determined using 5% offset method (section 4.1.2.2).

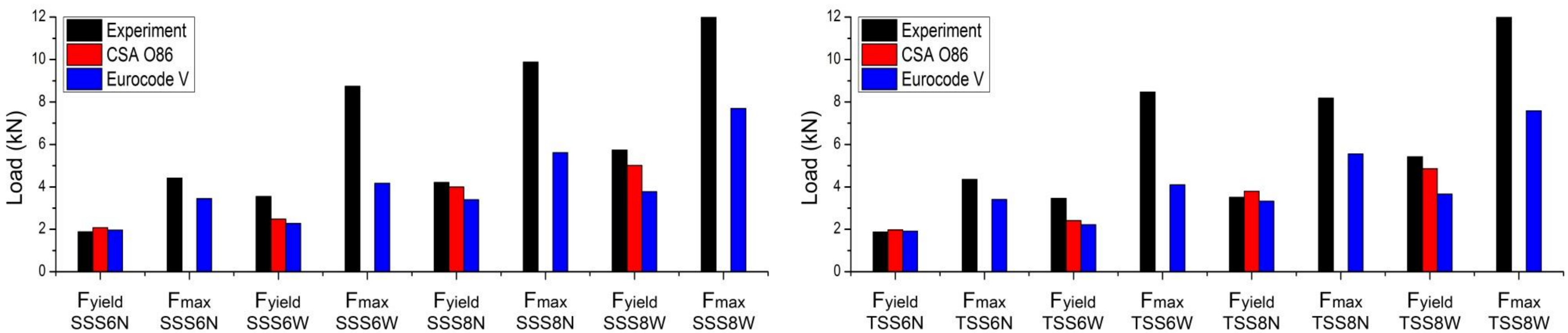


Figure 4-20: Comparison of the Maximum Load (F_{max}) and Yield Load (F_{yield}) values of single-spline connections from experiments and those calculated following CSA O86, Eurocode V: (left) shear load direction; (right) tension load direction.

The load capacity values from EYM models are calculated following the equations corresponding to the failure mode observed in the experiments. Table 4-13 shows the observed EYM failure modes of the studied edge-to-edge connections and Table 4-11Table 4-12 show EYM model predictions of F_{yield} and F_{max} and their ratios to values estimated from test data.

Table 4-13: EYM failure modes of the studied edge-to-edge connections.

	Observed Failure Mode			
	6mm Screw		8mm Screw	
	No Washer	With Washer	No Washer	With Washer
Half-Lapped Connection	IV	IV	IV	IV
Single-Spline Connection	III	IV *	III	IV *

* Design code prediction was failure mode III

Magnitudes and inconsistencies of ratios of EYM predicted values to experimental measured values in Table 4-11 and Table 4-12 suggest need to more deeply examine how to estimate design resistances of types of connections like those discussed here. Relative to EYM assumptions, it is to be noted that post-yielding distrotions in screws approximated but did not fully attain the antisymmetric shape consistant with mechanism IV failures (Figure 2-6). To note is that the F_{yield} values of EYM model predictions do not include any allowance for the rope effect enhancement of capacities at large deformation. Estimates of F_{max} of Eurocode V do include rope effects. The rope effect reflects the strength available after yielding due to a necessary large displacement to achieve its benefits. According to the Eurocode V methods the rope effect contribution to F_{max} can be taken to be 0.25 times the characteristic axial withdrawal capacity of a fastener, but not exceeding F_{yield}. However, as in axial load tests (Section 4.3), the head-side pull-through capacity for a screw was less than the point-side withdrawal resistance.

The rope effect calculations in Table 4-11 and Table 4-12 are based on measured head pull-through resistance.

Comparison of the measured values with the estimates using CSA O86-14 and Eurocode V showed that the design provisions do not estimate the lateral resistance of connections properly. In rough term, the calculated lateral resistance following CSA O86-14 and Eurocode V were in 85% and 65% agreement with measured values respectively. In some instances, CSA O86-14 overestimated the load capacity of connections. However, Eurocode V underestimated the connections' load capacity, except F_{yield} of SSS6N and TSS6N. The allowed rope effect term in Eurocode V approach increased the estimated values. However, the predicted values remain low at approximately 60% of the measured maximum load. Test data from Table 4-11 and Table 4-12 demonstrate that the prediction of load values by EYM approaches for connections without washers were more accurate than those corresponding to connections with washers. This is due to the complication provided by placing washer beneath screw head and how this alters the connection behavior. Post testing examination of plastic deformation in screws from single-spline connections with washers indicated that the behavior approached that associated with an EYM mechanism IV. EYM calculations according to Eurocode V imply that transition from a mechanism III failure when there are no washers to a mechanism IV failure when there are washers will increase F_{yield} by up to 14% and F_{max} by up to 37%. Corresponding actual observed increases in capacities due to presence of washers were 89% for F_{yield} and 98% for F_{max} (based on Table 4-12). Again findings indicate some limitations in applicability of current generation EYM calculation methods for types of connections investigated.

5 Conclusions

The primary focus of this thesis was investigation and characterization of commonly used edge-to-edge connections in CLT assemblies and diaphragms. Results presented here indicate that half-lapped connections using self-tapping joints are superior to single-spline connections in term of strength and stiffness when acting as plate edge-to-edge in-plane shear and tension connections. Results also demonstrate that placing washers in under heads of self-tapping screws can significantly increase the load capacities of either half-lapped or single-spline shear joints in CLT slabs. It should be noted that, it is important to consider eccentricities that affect the behavior of edge-to-edge connections in CLT assemblies, as can occur for example when single-spline connections are employed.

Results proved that half-lapped joints can create effective edge-to-edge connections in CLT slabs. However, it also needed to be acknowledged that such connections have been found to perform poorly in terms of out-of-plane behavior of CLT slabs (Sadeghi et al., 2015). Specifically presence of half-lapped connections can cause clustering of out-of-plane modal frequencies that amplifies motions to an extent that adversely affects dynamic serviceability of CLT floor slabs (Ussher et al., 2014). This indicates need to consider functionality of slab connection methods from broad perspectives associated with performance of superstructure systems, and not to simply focus on an isolated question like the in-plane shear and tension strength or stiffness of connections. Further research is strongly needed on the out-of-plane requirements of CLT edge-to-edge connections.

Although not initially intended as a primary purpose of what was done, the study in this thesis has highlighted need to address adequacy of contemporary EYM type connection design methods. In particular there is need to investigate further: influences that eccentricities in structural arrangements have on flows of forces through connections and connections within CLT slabs and adequacy of simplified approaches for estimating rope effect contributions toward ultimate design capacities of joints with laterally loaded self-tapping screws.

Comparison of test data with EYM predictions indicated that current generation models can fail to capture true ultimate load performances of commonly employed types of connections. Tests on axially load screws and lateral load tests on half-lapped and single-spline connections all indicated that contemporary practices for accounting for rope effect contributions to joint capacities are unreliable and too simplistic. Further research is required to investigate how to improve design level calculations models.

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Appendix A

Determination of Test Machine Stiffness

A-1 MTS Stiffness during Axial Loading

The MTS test machine used was not very much stiffer than undamaged connection specimens. Therefore cross-head displacement did not match connection slip well during initial stages of loading specimens. This appendix gives a simple method used to determine value of the stiffness of test machine during axial loading tests.

All the experiments throughout this project were conducted using an MTS 810 material test system (load frame model: 318.25) with the maximum load capacity of 250kN. The majority of tests were conducted using external LVDTs to measure the relative slip at the connections. However, axial load test series were conducted using internal LVDTs of the MTS. In doing so, the frame deformation or slip at the apparatus members could affect the measured slip displacement.

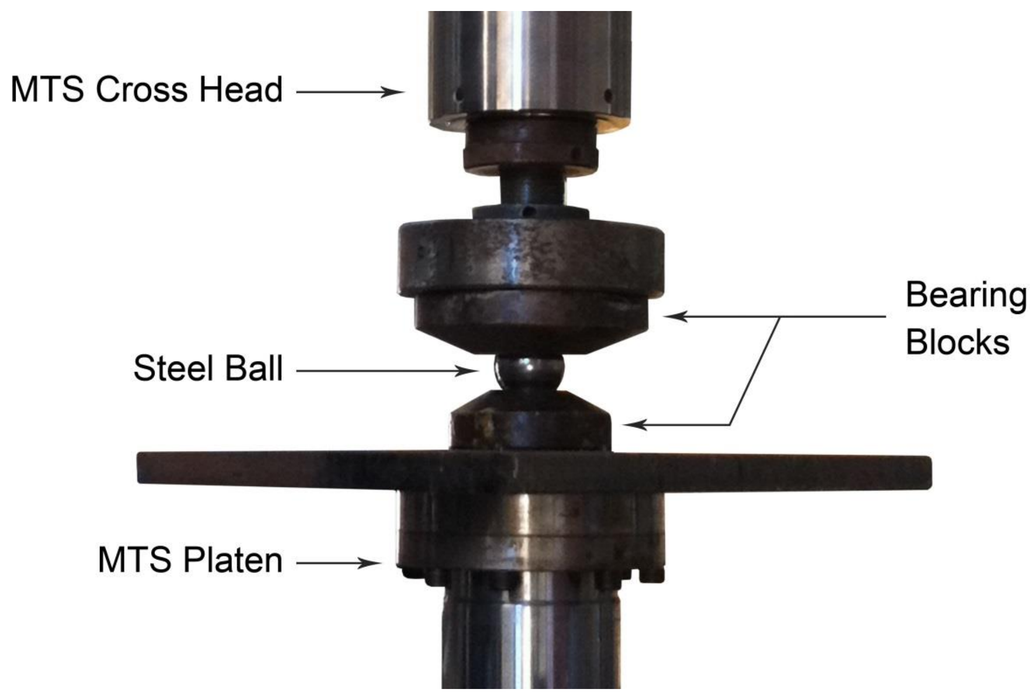


Figure A-1: MTS axial load tests apparatus

A subsidiary series of tests were performed to measure the stiffness of MTS Test Machine in axial compression. The test apparatus is shown in Figure A. Two steel bearing blocks and a 1 ½ inch diameter steel ball were inserted between the MTS cross head and platen. The steel ball was placed tightly into the spherical depressions of bearing block so that there was negligible deformation at that position in the setup. Tests were replicated for 6 times with load control procedure with an increasing rate of 100N/min. Since the applied loads to specimens in the edge-to-edge connection and fasteners axial load tests in all cases were less than 30kN, the MTS axial compression tests conducted until the load reached to 30kN. The axial compression stiffness of MTS machine was estimated by the slope of load-displacement curves (defined by the origin and the point that load reaches to 30kN). This parameter shows how much the measured displacement affected by the slip occurs in MTS Test Machine. The calculated average value for the axial compression stiffness was 133.78kN/mm which means that the slip occurs in MTS for loading up to 30kN is about 0.2mm (Figure A-2).

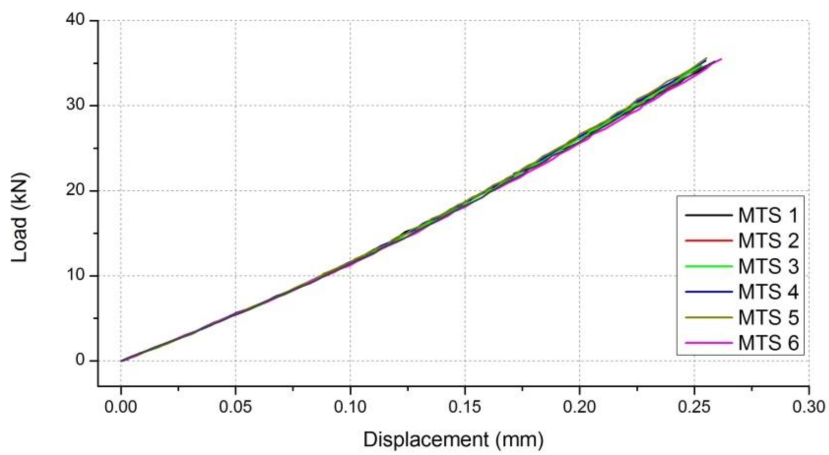
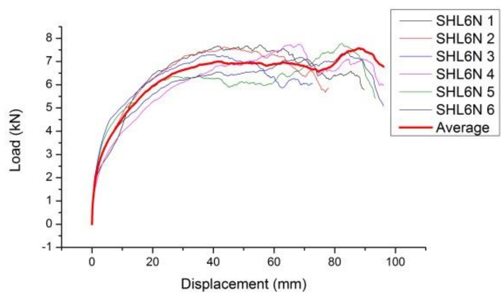


Figure A-2: Load-Displacement curves of MTS axial load tests

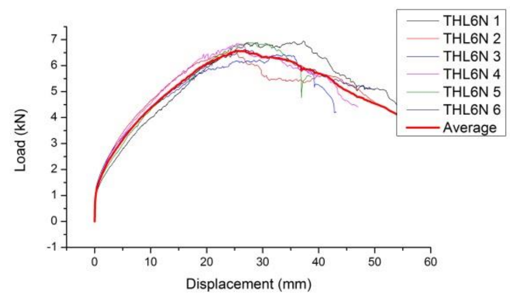
Appendix B

Monotonic Load-Displacement Curves

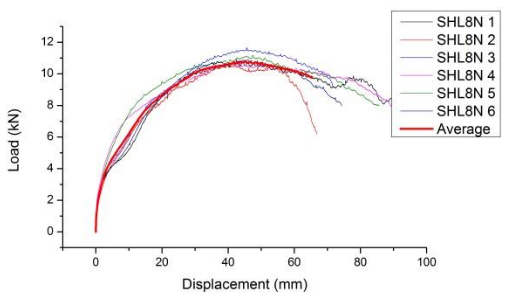
B-1 Edge-to-Edge Connection Tests without Washers



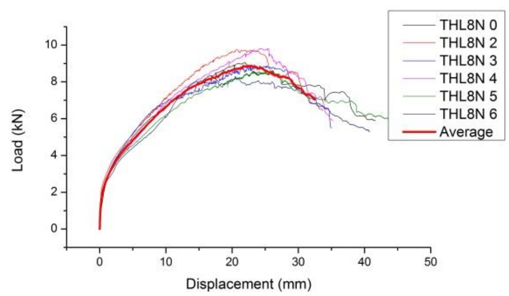
(a): SHL6N



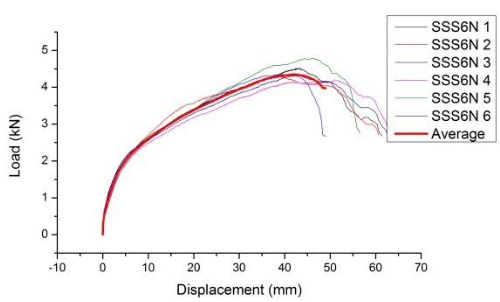
(b): THL6N



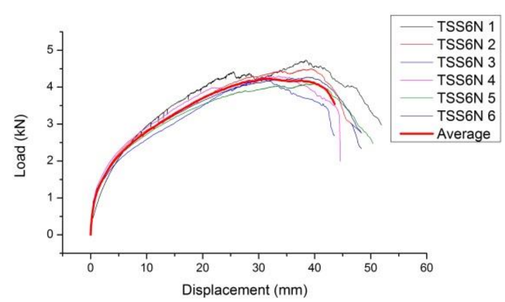
(c): SHL8N



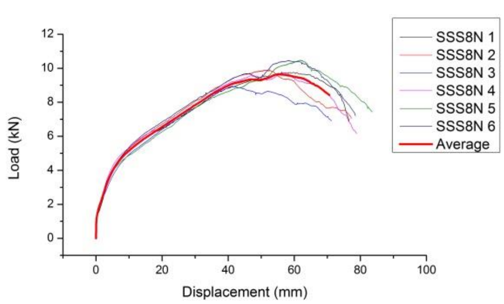
(d): THL8N



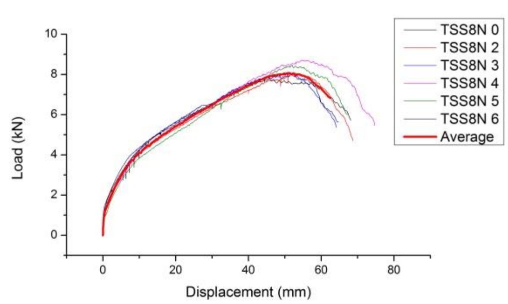
(e): SSS6N



(f): TSS6N

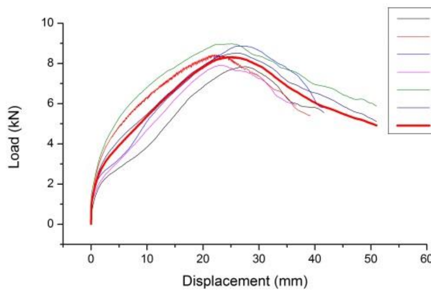


(g): SSS8N

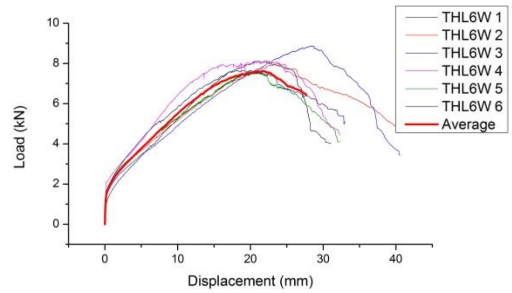


(h): TSS8N

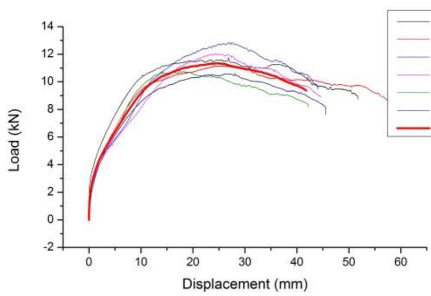
B-2 Edge-to-Edge Connection Tests with Washers



(a): SHL6W



(b): THL6W



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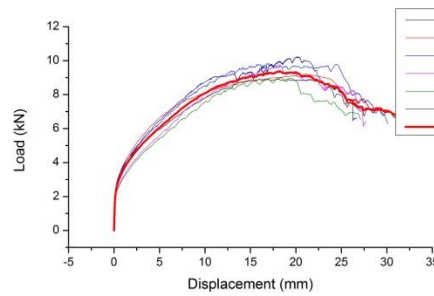

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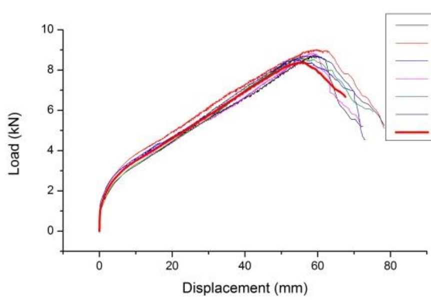

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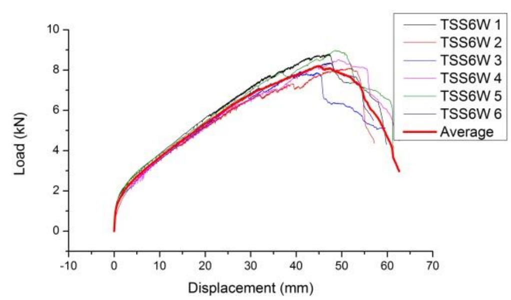
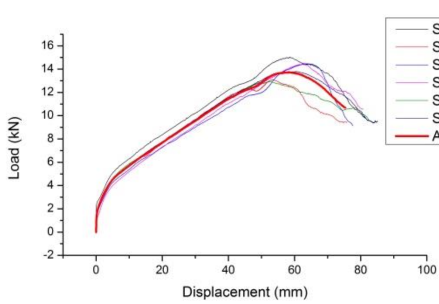
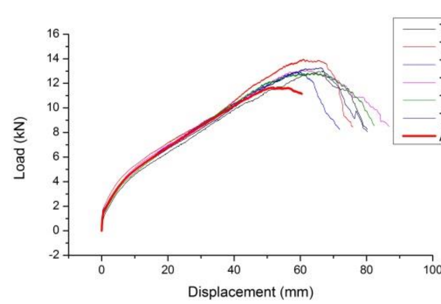


(f): TSS6W

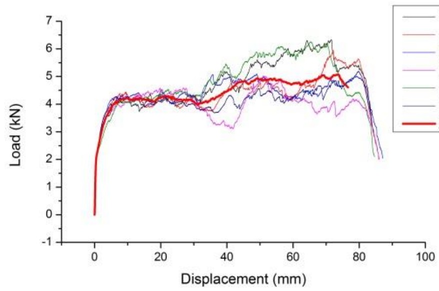


(g): SSS8W

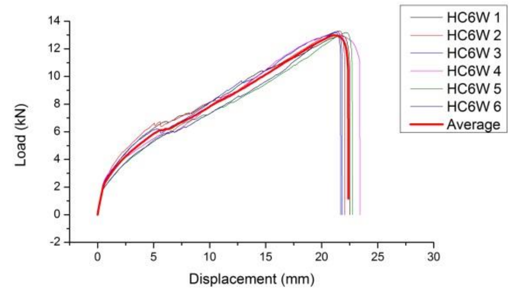


(h): TSS8W

B-3 Fasteners Axial Load Tests – Screw Head Pull-Through



(a): HC6N



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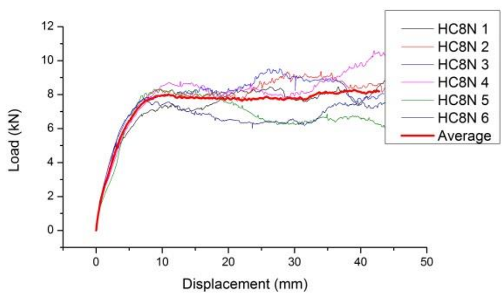
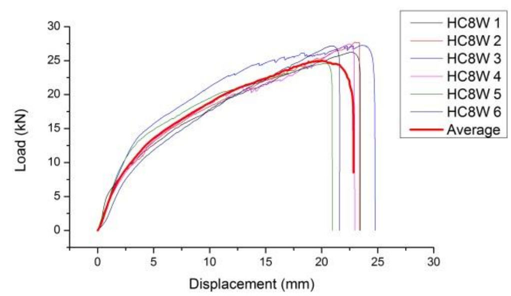


(c): HC8N



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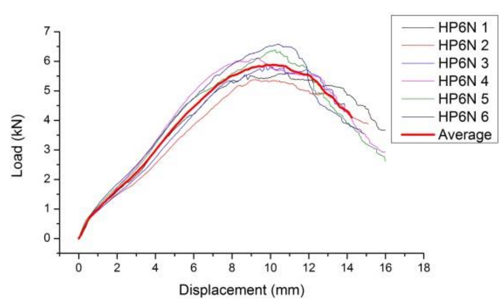
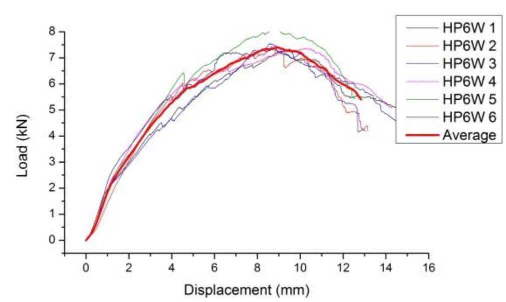


(e): HP6N



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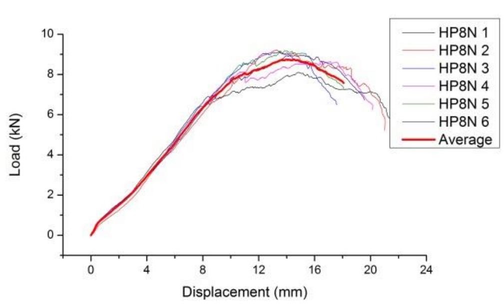
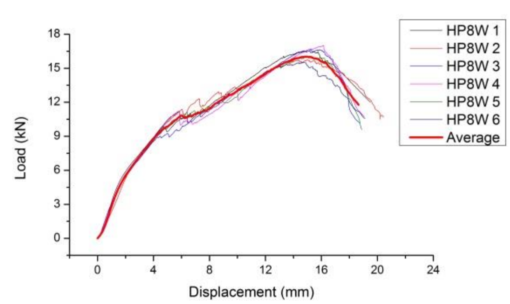
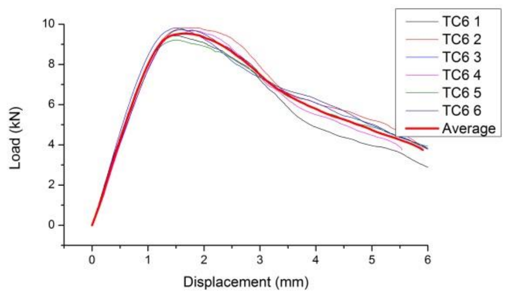


(g): HP8N

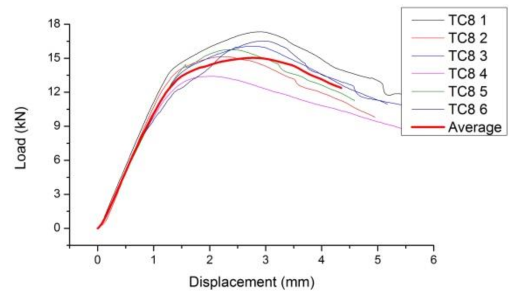


(h): HP8W

B-4 Fasteners Axial Load Tests – Screw Thread Withdrawal



(a): TC6

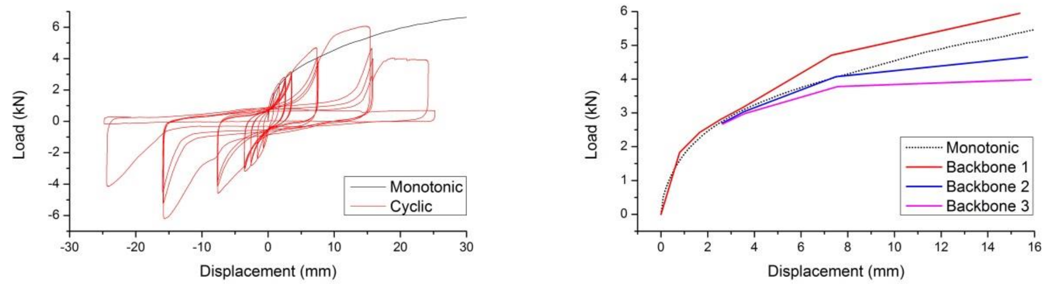


(b): TC8

Appendix C

Cyclic Load-Displacement and Backbone Curves

C-1 Half-Lapped Connection Tests – Shear Load Direction



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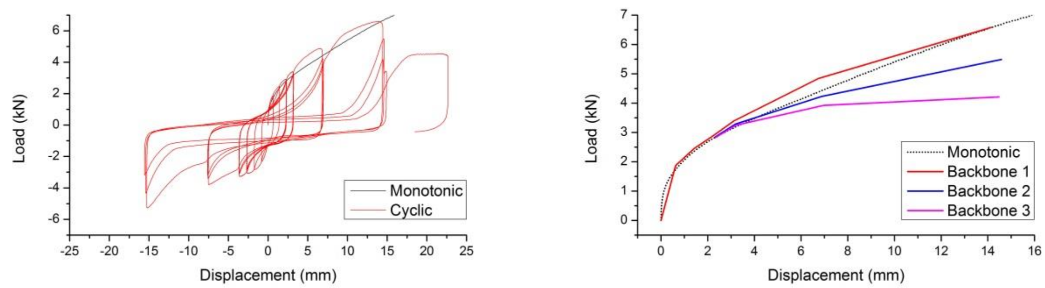

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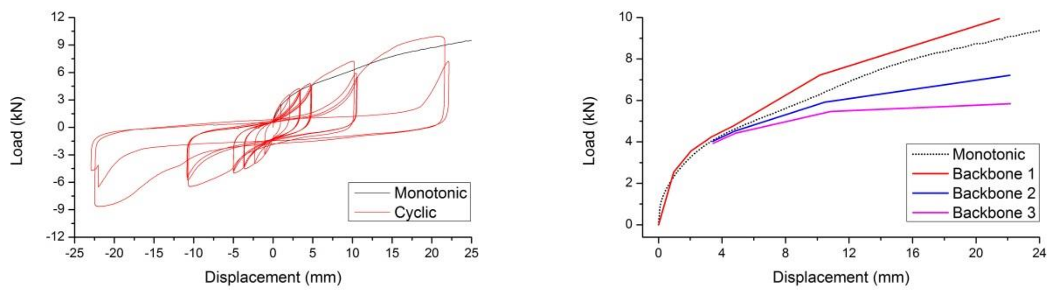
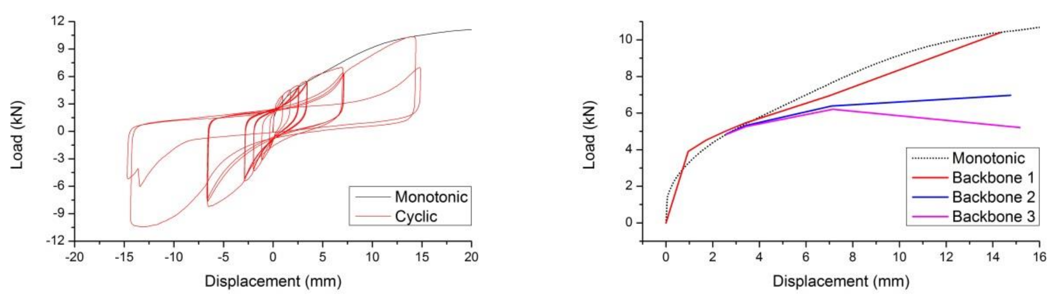
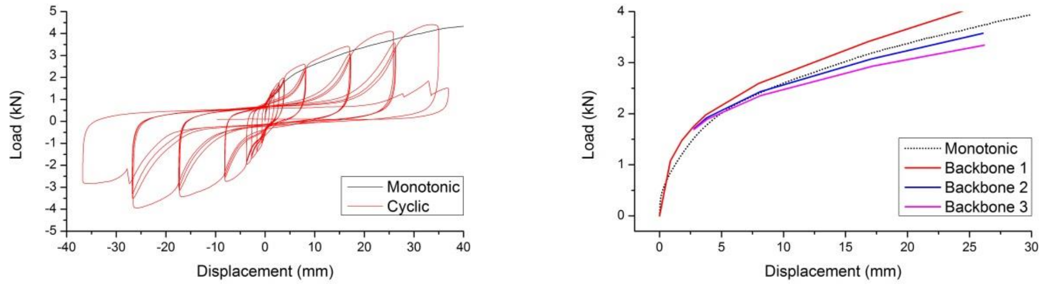


(c): SHL8N



(d): SHL8W

C-2 Single-Spline Connection Tests – Shear Load Direction



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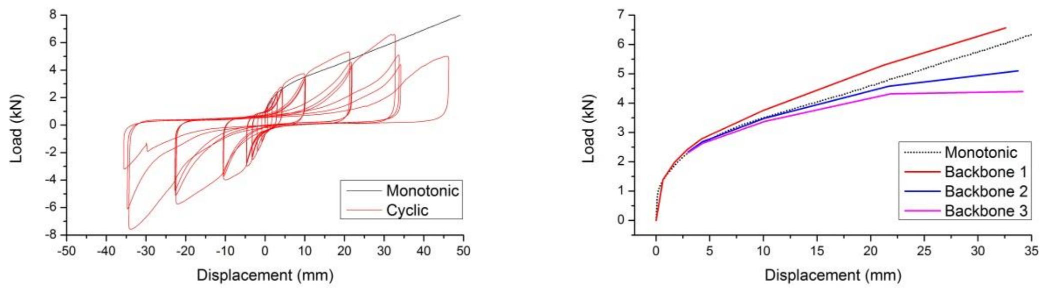

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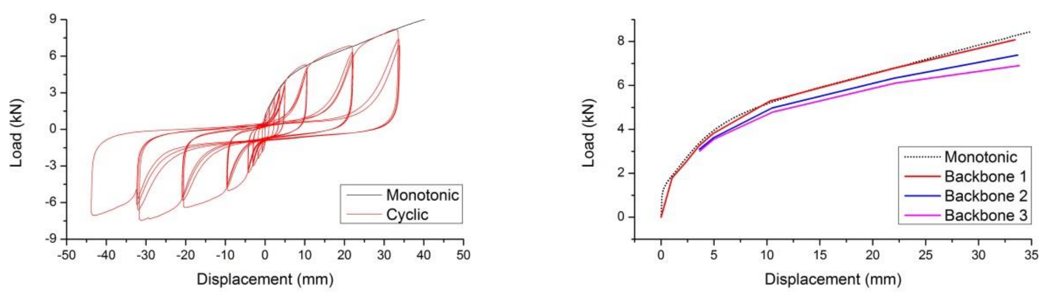
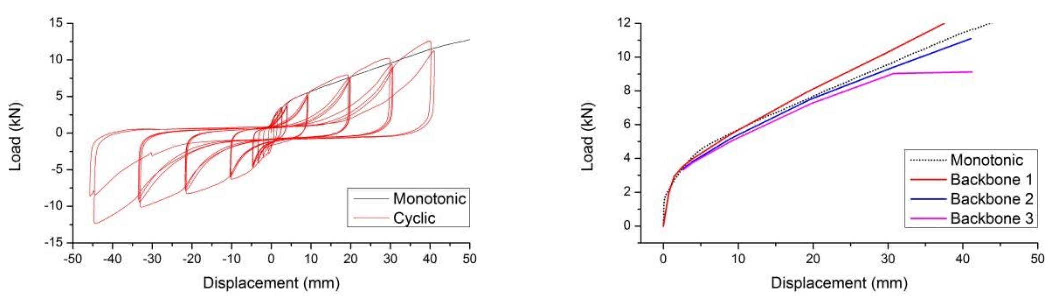
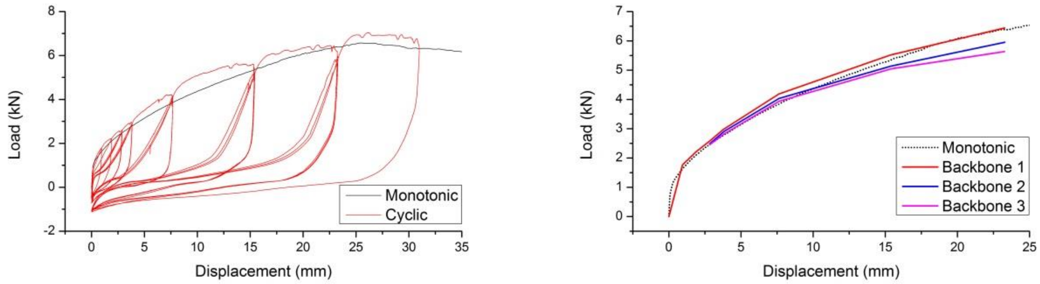


(c): SSS8N

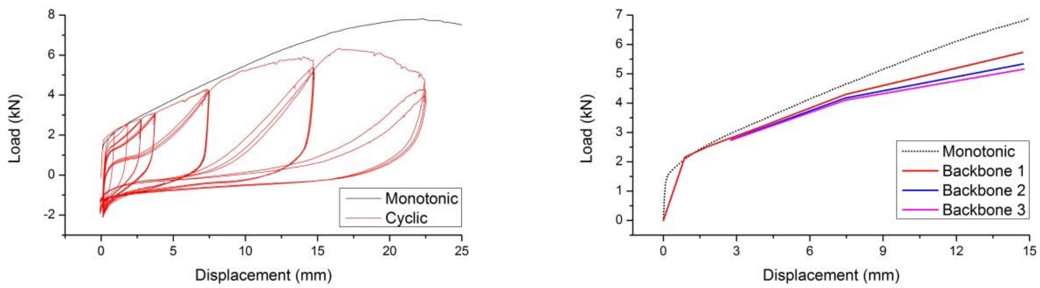


(d): SSS8W

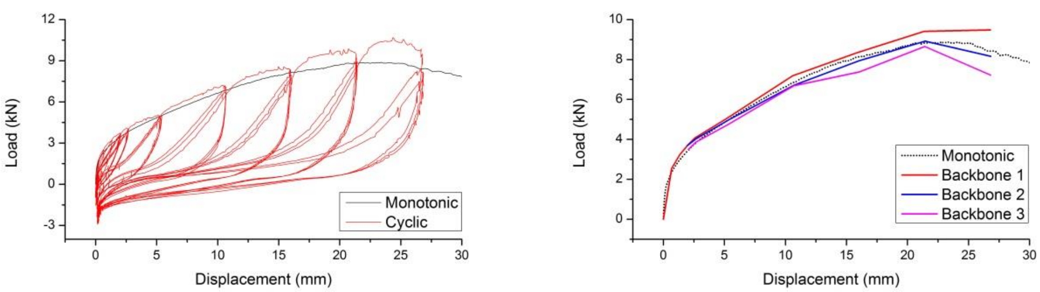
C-3 Half-Lapped Connection Tests – Tension Load Direction



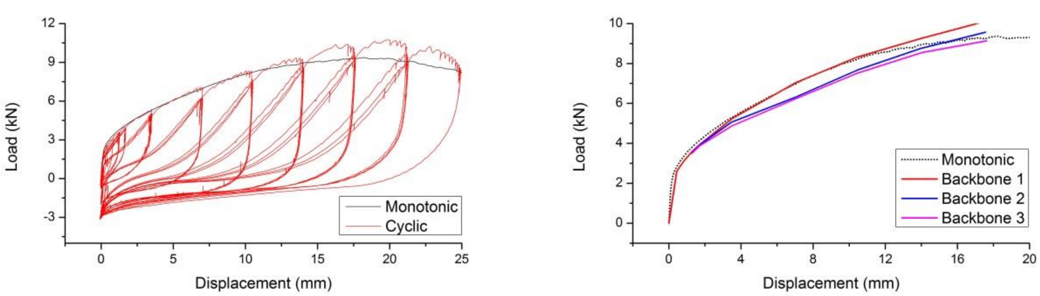
(a): THL6N



(b): THL6W

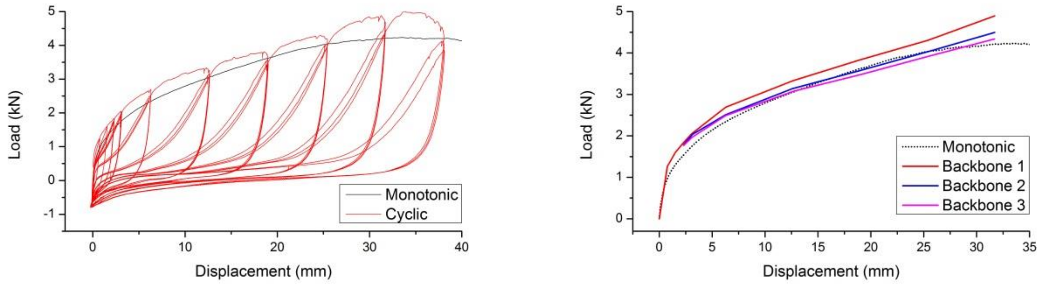


(c): THL8N

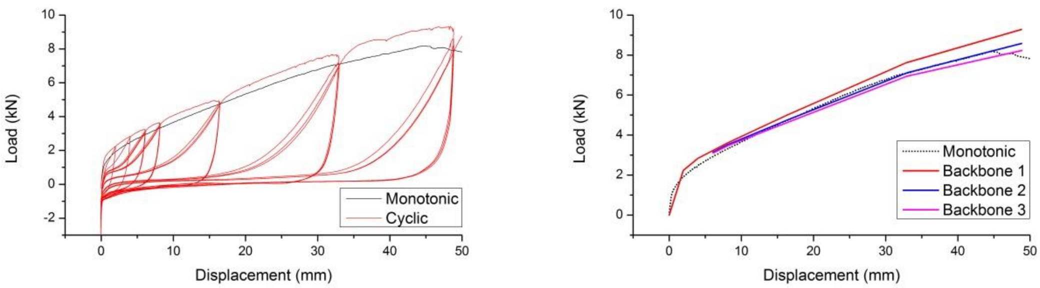


(d): THL8W

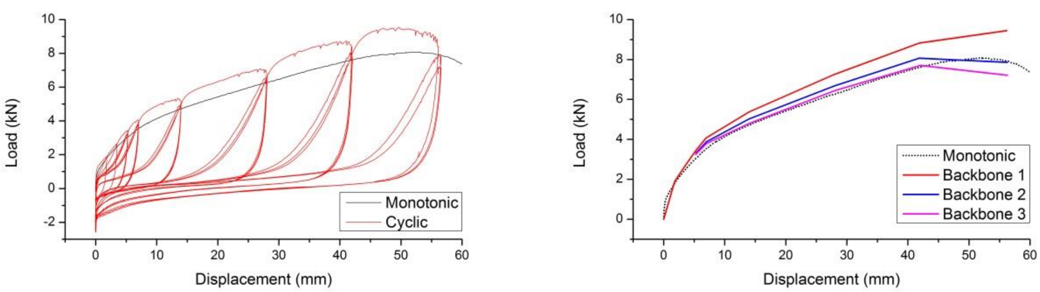
C-4 Single-Spline Connection Tests – Tension Load Direction



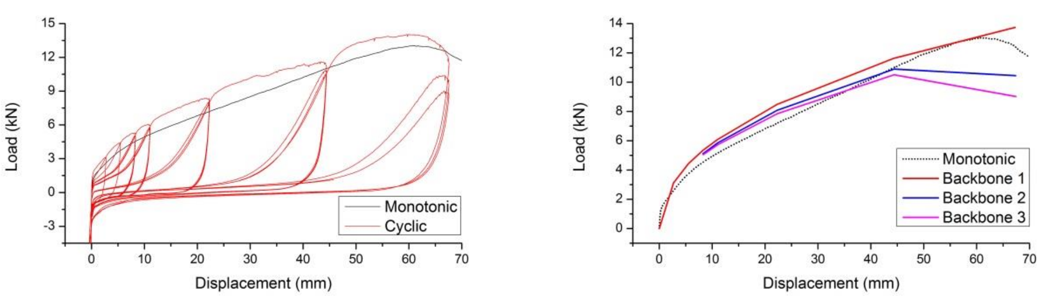
(a): TSS6N



(b): TSS6W



(c): TSS8N



(d): TSS8W

Curriculum Vitae

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Publications:

Sadeghi, M., Ballerini, M., Smith, I., Pedrotti, E. 2015. Bending Properties of Connections in Cross Laminated Timber, International Association for Bridge and Structural Engineering (IABSE) Conference 2015, May 13-15, Nara, Japan.

Sadeghi, M., Smith, I. 2014. Edge Connections for CLT Plates: In-Plane Shear Tests on Half-Lapped and Single-Spline Joints, World Conference on Timber Engineering (WCTE) 2014, August 10-14, Quebec City, Canada.

Ussher, E., Sadeghi, M., Weckendorf, J., Smith I. 2014. Vibration Serviceability Design Analysis of Cross-Laminated-Timber Floor Systems, World Conference on Timber Engineering (WCTE) 2014, August 10-14, Quebec City, Canada.

Conference Presentations:

Sadeghi, M. "Bending Properties of Connections in Cross Laminated Timber." International Association for Bridge and Structural Engineering (IABSE) Conference 2015, Nara, Japan, 14 May 2015.

Sadeghi, M. "Edge Connections for CLT Plates: In-Plane Shear Tests on Half-Lapped and Single-Spline Joints." World Conference on Timber Engineering (WCTE) 2014, Quebec City, Canada, 13 August 2014.

Sadeghi, M. "Continuity Connections for CLT Plates in Hybrid Superstructures." NEWBuildS Annual Workshop 2014, Vancouver, Canada, 7 May 2014.