Design for Seismic Resilient Cross Laminated Timber (CLT) Structures: A Review of Research, Novel Connections, Challenges and Opportunities

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Abstract

As a sustainable alternative to the steel and concrete, cross laminated timber (CLT) shear wall system is getting increasingly popular in the mid-rise and high-rise construction, and that imposes new challenges in their seismic performance. The conventional connections used in this system, such as steel hold-downs and angle brackets, are however susceptible to brittle failures, thus being inappropriate for using in structures in seismic regions. A series of innovative connections are therefore proposed in the recent years for achieving better seismic behaviours in CLT structures, characterised by adequate capacity, significantly improved ductility and dissipative capacity, as well as more controllable ductile failure modes. This paper first reviews the recent studies of CLT shear wall systems and conventional connections. Connection systems and shear wall reinforcement methods that recently proposed for seismic resilient CLT structures are then introduced, with their design strategies being summarised accordingly. The connections are then discussed comprehensively in terms of structural performance, manufacturability, and constructability, employing similar criteria that previously proposed for steel modular connections. It is found that much improved duclility along with more predictable, ductile, timber damage-free deformation modes are achived in most of the new connections. Some new connectors are deisgned with additional functionalities for optimised seismic performane or easing the construction process, which, however, lead to complex designs that may add difficulties to the mass production. Therefore, comprehensive considereations are needed in connection design and the discussion of this paper aim to assist in the future development of connection systems for seismic resilient multi-storey CLT buildings.

1 Introduction

Cross laminated timber (CLT) is one kind of engineered timber products that is made from layers of timber planks being glued perpendicularly [1]. In comparison to conventional timber materials, the lamination process helps CLT break the size limitation of original timber material and achieve better strength uniformity and dimensional stability [2, 3], making it one of the most used mass timber materials. Due of its superior sustainability, higher prefabrication, efficiency, and strength-to-weight ratio than conventional construction materials [4, 5], CLT is getting increasingly popular in the application of prefabricated low-rise (3-4 stories) and mid-rise structures (5-8 stories) [6] (Figure 1), along with significant opportunities for building high-rise structures.

(a)

(b)

Figure 1.Examples of multi-storey CLT residential buildings (a) Dalston Works, London (Photo: Daniel Shearing) [7] (b) Murray Grove, London [8]

Emerging architectural designs for high-rise CLT buildings, even skyscrapers (Tree Tower Toronto [9], 191-199 College Street [10]), bring great emphasis on the engineering challenges that need to be overcome [11], such as the seismic performance of CLT shear wall systems. The light-weight nature of timber contributes to lower seismic forces, while it also reduces buildings' overturning resistance to lateral load [12], which necessitates the development of high-performing connectors for the CLT shear wall panels or volumetrics.

Seismic-resistant design requires ductile behaviour of certain components in structures, namely steel parts in connections since timber is not a ductile material and prone to brittle tension, bending and shear failures [13]. Ductility can help the structures to: (1) dissipate energy in seismic events without losing the load-bearing capacity significantly, (2) allow for load redistribution within the structures to avoid further collapse, and (3) ensure significant deformation without collapsing to warn the occupants [13]. Appropriate ductility also contributes to structures' robustness, makes them resilient to unforeseen events without total loss of functionality, and potentially capable to rapidly recover their functionalities similar to or even better than the pre-event level [14]. However, the conventional connection system used in CLT construction is limited by insufficient ductility compared to design expectations as well as brittle failure in timber or steel parts. To promote the development of CLT shear wall system, a series of new connection devices with enhanced performance were proposed in the recent literature, while only limited studies [15] have attempted to overview and holistically discuss the performance of these connections. This paper presents a state-of-the-art review of the existing literature on novel CLT connections and their performances, to help researchers and engineers understand the level of research conducted for CLT connections. A systematic approach for summarising connections' structural, constructional and manufacturing performance is presented, providing information for the future development of high-performing CLT connection systems, challenges and opportunities.

2 CLT Shear Wall System and Conventional Connections

2.1 CLT shear wall system

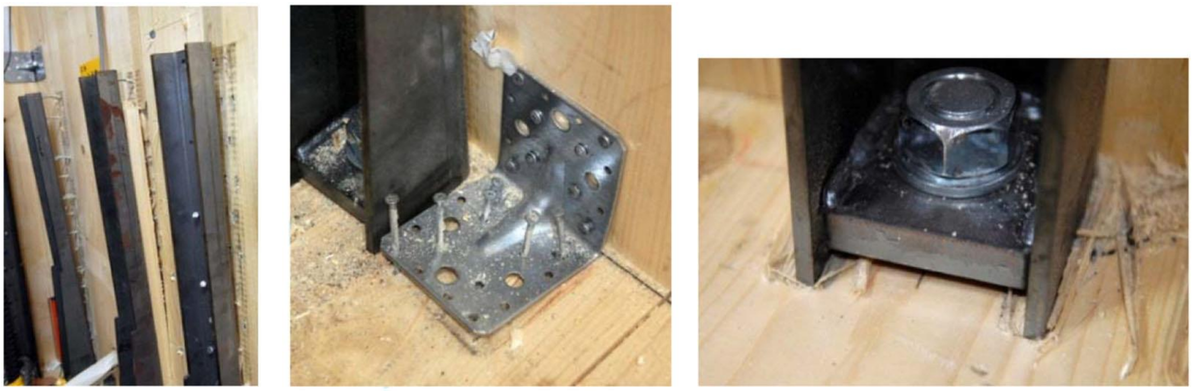
To design multi-storey CLT buildings in earthquake-prone areas, seismic behaviours of CLT systems must be thoroughly investigated. One of the most comprehensive research projects to date is the project 'Sistema Costruttivo Fiemme (SOFIE)', which tested dynamically using shake table experiments on 3-storey and 7-storey full-scale CLT buildings [16-18] (Figure 2).

(a) (b)

Figure 2. (a) The 3-storey [17] and (b) 7-storey CLT buildings [16] tested in SOFIE project

The full-scale tests proved the feasibility of multi-storey CLT construction in seismic regions, as both tested buildings were able to remain standing without significant permanent deformation and damages after experiencing the entire set of shakes, even when the near-collapse state was applied. In the tests with low peak ground acceleration (PGA), the buildings only experienced insignificant damage, as indicated by the reduced natural frequencies measured after each test. When higher PGA was applied, localised damage was recorded in the wall-to-floor connections as shown in Figure 3, and they were consistently observed in the quasi-static monotonic and cyclic loading of one or two storeys CLT buildings [19-21]. Though repairing interventions such as connectors replacements and fasteners tightening were taken after every test, the structural stiffness cannot be fully restored [16].

When the CLT buildings being tested statically in the lateral directions, damages can also be observed in the CLT panels (Figure 4) at the later loading stage under large displacements, including the embedment of wall panels due to the panel rocking and cracking in the corner of the large openings of door and windows due to the in-plane panel deformation [19-21]. It can therefore be concluded that, the potential deformation modes of CLT buildings can be: the in-plane deformation (shear, bending, axial) in the wall panels, the rigid rotation of wall panels, and the deformation in wall-to-wall and wall-to-foundation connections [22]. In common practice, yielding of metal fasteners in the wall-to-floor connections is considered as a favourable ductile failure mode in CLT buildings, as it provides better ductility and has lower risks of sudden strength loss, while it also damages the CLT elements.



(a) (b) (c)

Figure 3. Failure modes of a 7-storey CLT building in shake table testing: (a) out-of-plane bending of hold-down (b) pulling-out of nails in angle brackets (c) embedment of connector [16]

(a) (b)

Figure 4. Timber panels damage observed in the quasi-static test of CLT buildings under large displacement (a) embedment of wall panels into floor panels that causes the debonding of timber planks (b) cracking in the corner of large opening [19]

In addition to the impact on structural deformability, the connectors were also proved to have significant influence in the kinematic behaviours of CLT shear walls. According to the vertical and horizontal movements of panels measured in quasi-static tests, kinematic behaviours of CLT shear walls in each floor is the combination of sliding and rocking, and the proportions of which are varied according to the arrangement and properties of connectors [19, 23]. It was reported that, when panel rocking dominates the kinematic behaviour, better ductility, energy dissipation and ultimate displacement can be achieved along with self-centring of wall panels under their self-weight, making it superior than the sliding behaviour which resulted in a significant residual lateral displacement [24, 25]. Therefore, to achieve energy-dissipative kinematic behaviour in CLT shear wall system, connections are the essential factors to be considered in design.

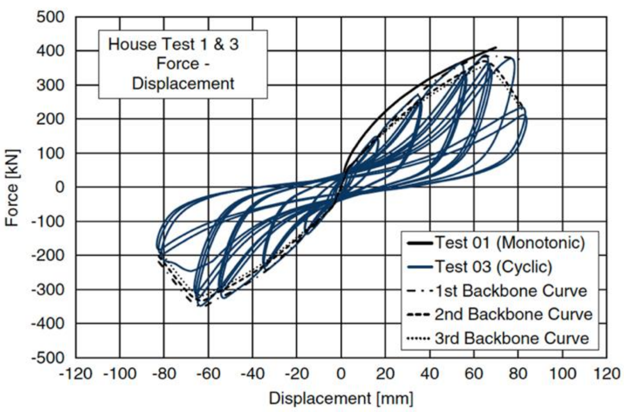
Consequently, both dynamic [16, 18, 26] and static [19-23, 25, 27] tests on CLT panelised systems indicated that structures made of CLT panels generally demonstrated high strength and stiffness with most of the deformation and energy dissipation being developed by the steel connections and the friction between timber panels, proving the feasibility of low-rise CLT construction in earthquake-prone regions. The governing role of steel connections in defining the overall structural performance necessitates the development of high-performing connections for reducing high accelerations of CLT buildings, providing better ductility and enabling rocking and recentering behaviours in the shear wall systems [16].

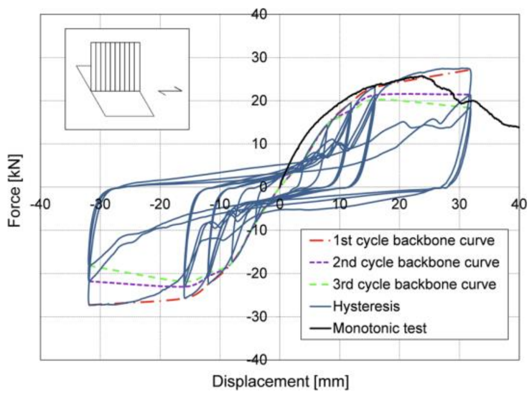
2.2 Conventional CLT connections

In CLT buildings, two kinds of connections are commonly used: splice or nailed and screwed connections in wall-to-wall and floor-to-floor connections [28], and metal plate connectors (hold-downs and angle brackets) with dowel type fasteners in wall-to-floor and wall-to-foundation connections [29]. As prescribed in EC8, the structural elements (timber) in timber buildings should remain elastically, while the dissipative zones should be located in the connections for resisting seismic actions. Therefore, the wall-to-floor and the wall-to-foundation connections are normally designed as energy dissipating devices in CLT structures, while the wall-to-wall and floor-to-floor connections are designed as non-ductile and should be overstrengthed. The metal plate connectors used in CLT structures are then the primary source of ductility and mechanical performance that govern the delivery of secured structures [30].

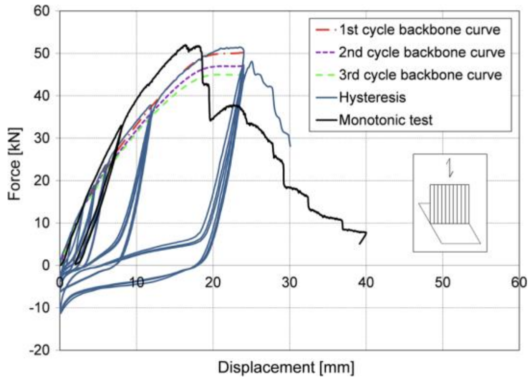
2.2.1 Experimental studies

The mechanical behaviours of hold-downs and angle brackets have been widely studied, with some drawbacks being commonly recognised despite their wide application in today's CLT construction. The typical behaviour of metal plate connectors is the "strong plate-weak fastener" behaviour [31], and one of their unique characteristics is the permanent damage fasteners introduced in timber. The deformed fasteners crush timber and create permanent cavities around them, which can lead to degraded stiffness and strength at load reversals, as well as reduced resistance and delayed attainment of maximum strength during the cyclic process (Figure 5. (b)&(c)). These features make the conventional connectors unpredictable and unrepairablem, while reduce structure's capacity and energy dissipation during the seismic event, meanwhile leave great residual displacements that reduce the structure's resistance to aftershocks [16, 28, 32, 33]. In addition, similar features can also be observed in the hysteresis loops of full-scale buildings (Figure 5. (a)), which further demonstrate the impact of connection properties to the overall buildings' performance.





(b)



(a) (c)

Figure 5. Hysteresis loops and monotonic curve for (a) a 2-storey full-scale CLT building [19] and the (b) angle brackets and (c) hold-downs that used in the building [24]

In addition to timber damage, both angle brackets and hold-downs are characterised by high stiffness but insufficient ductility [24, 34], belonging to L-low ductility class (2<μ<4) or M-medium ductility class (4<μ<6) as prescribed in EC8 [35] in their primary directions. As dissipative timber connections are required to achieve ductility class M-medium or H-high (6<μ), increasing the number of connectors and using small-diameter fasteners are the recommended methods of designing ductile timber structures with conventional connections [35, 36]. The large amount of connectors and fasteners can lead to time-consuming on-site fastening work with hard-to-verify assembly quality [37], and also limit the potential of fully reusing timber components, as the removal of nails and screws can be labour-intensive and further damage the structural material [38]. Also, small-diameter fasteners can introduce high stress in timber and pinch through the fibres before the capacity of timber is fully developed, causing brittle failure with sudden reduction in connection strength and large residual displacement even after the removal of the external loading.

2.2.2 Analytical models and design rules

As a new structural material, specific design code or guidance for CLT have not yet developed [39]. The general rules for timber buildings in EC5 and EC8 or information in relavent literature are applied when designing CLT structures, though they are not fully applicable. Previous comparative studies between analytical and experiment results [24, 34, 36] indicated the conservative approach for strength prediction (lower than 80% of the tested results) and the significant stiffness overestimation (up to 9 times higher) of the existing analytical models of timber connections [24, 40].

The prediction errors can be attributed to several factors of timber connections. The bearing capacity of conventional timber connections is defined by the combinations of the embedment strength, the sensitivity to splitting, the connection configurations as well as the variation of fasteners types in connections [41]. Due to its heterogeneity, timber behaves differently in differently directions and may have inherent defects such as large knots, resin pockets, bark inclusions [3]. Therefore, making the capacity dependent on the timber with dispersive properties as a natural material [42] may lead to unpredictable connection behaviours as well as considerable variations between specimens [36], expeccailly when the damage progression machannism within timber is not well understood, which also limits the development of accurate modelling methods.

To ensure the full activation of all ductile elements and avoid plasticisation in non-ductile zones [43], as required in EC8 [35], the overstrength method that developed by Jorissen and Fragiacomo (Eq.1) [13] is widely used on both building and connection levels in timber structure design. This can also lead to errors in the analytical predictions. At building level, all timber elements and connections in non-dissipative zones (e.g., wall-to-wall and floor-to-floor connections) are strengthened to avoid plasticisation. At connection level, timber elements are strengthened to ensure the development of cyclic yielding in fasteners [44]. In this method, the introduction of the overstrength factor γ_{Rd} in the design strength of brittle elements ($R_{d,brittle}$) is for eliminating the impacts of all possible factors that may lead to unexpected stronger capacity in ductile elements ($R_{d,ductile}$).

$$\gamma_{Rd} R_{d,ductile} \leq R_{d,brittle} \qquad (1)$$

However, the embedment strength calculated with Johansen's theory in EC5 [45] can be significantly inaccurate due to the greater scattering of timber material properties than the steel material [46], and specific overstrength factors for different connections are not yet in standards [39]. The estimated overstrength factor could therefore be insufficient and limit the attainment of the overstrength effect. Thus, in addition to the overstrength method, common strategies in EC5 of avoiding brittle failure in timber connection are introducing prescriptive safeguards in connection configuration design, such as minimum spacings, minimum number, slenderness ratios and edge distances of fasteners, and the effective number of fasteners [36]. However, the conventional steel connectors may experience brittle failure even with these safeguarding factors being properly applied, as recorded in an experimental study [47].

Furthermore, the capacity of brittle elements (timber) and ductile elements (fasteners) are considered independently in the overstrength method, which however is unrealistic, because of the simultaneous deformation in timber, steel plate and fasteners in conventional plate connections. Desirable fasteners yielding (ductile behaviour) normally appears along with other failure modes such as timber crushing or splitting (brittle behaviour), steel plate fracture (brittle behaviour) or bending (ductile behaviour), as well as nail breakage and pulling-out (brittle behaviour) [29, 48-51] (Figure 6). The primary failure modes varied according to different connection factors, such as fastener types, arrangements and geometry, timber properties, loading directions, connection locations, as well as connector configurations. The interaction between these factors is still unknown, making it difficult to predict the primary failure mode of connections using existing analytical models, in which only timber crushing and fastener yielding are considered along with the assumption of rigid steel plates. The ignorance of the composite effect and the rigid plate assumption taken in current analytical models could lead to significant estimation errors, especially for connections with small steel plate thicknesses, as they overlook the deformation contribution of steel elements [24, 34]. For example, it is suggested in EC5 that, the stiffness calculated for steel-to-timber connections should be doubled up to account for the strengthening of steel plate, which was proved to lead to greatly higher connections stiffness [40, 52]. The inaccurate representation of connection stiffness, which is especially crucial to the global stiffness of CLT shear wall system as discussed above, can lead to significant errors in the estimation of the principal elastic vibration period in seismic design, as proved in a numerical parametric study [53]. When having all brittle failure modes considered, some newly proposed analytical models [54-56] showed better agreement with the test results and provided clearer identifications of the related failure modes [36, 57], indicating the need of further improving the design guideline of the conventional metal plate connections.

(a) (b) (c)

Figure 6. Different kinds of failure modes in timber plate connections: (a) cutting-through of fasteners in timber (b) breakage in metal connector (c) pulling-out of fasteners [34] [52]

2.3 Overview conclusion

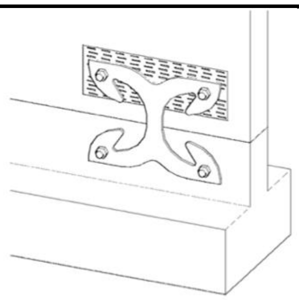
Despite the wide application, the local- and macro-scale testing on conventional timber connections revealed the insufficient mechanical performance, the risk of brittle failure and performance stability of them to be applied in large CLT construction. The comparison studies between experimental and analytical results proved that,the performance of timber connections is not yet fully understood and standardised, which can lead to risks of unforeseeable connection behaviours and difficulties in structural design. Furthermore, the lack of design guidance, in particular for the identification of suitable, ductile failure mechanisms, further increases the difficulties of designing ductile timber connections, which is an important issue in seismic design. This is the main barrier for the slow adoption of timber structures in the construction sector and the general hesitance perceived despite the desire of architects and engineers to use this bio-material more widely.

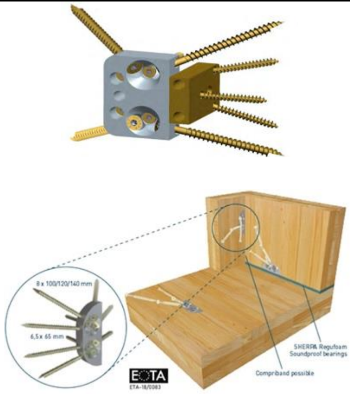
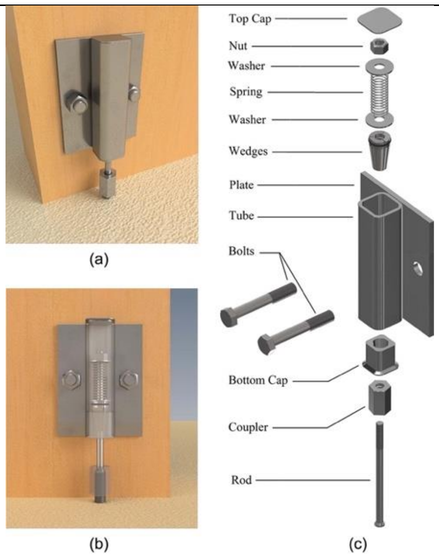
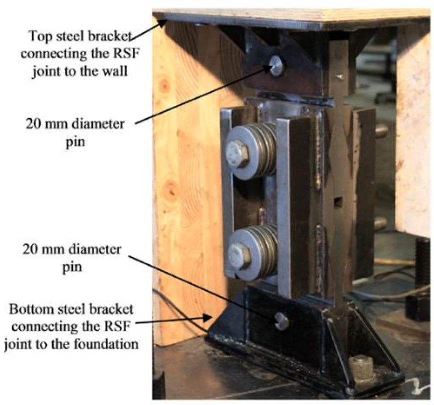
3 Innovative Connections for CLT Shear Walls

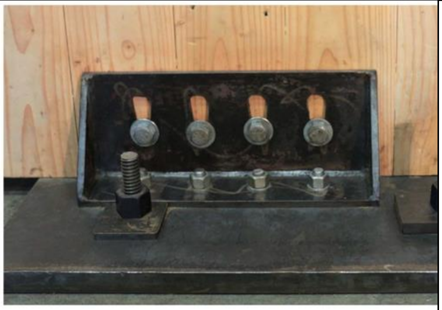
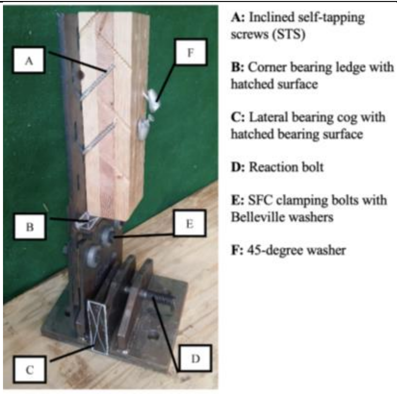
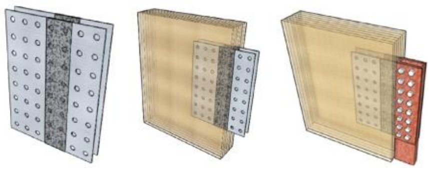
3.1 Innovative connections for CLT shear wall systems

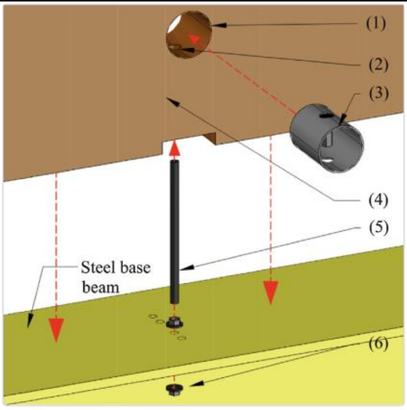
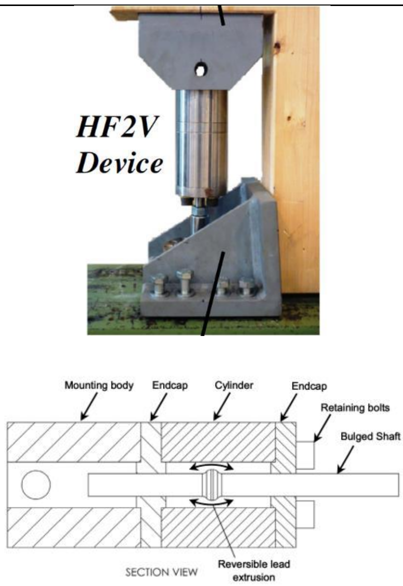
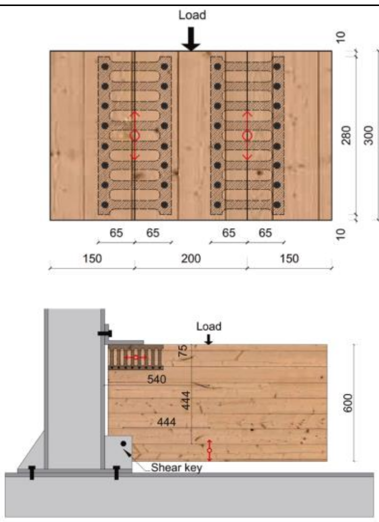
To improve the seismic behaviours of CLT structures and address the identified limitations in conventional timber connections, a series of new connectors have been recently proposed and summarised here for the ease of comparison and discussion.

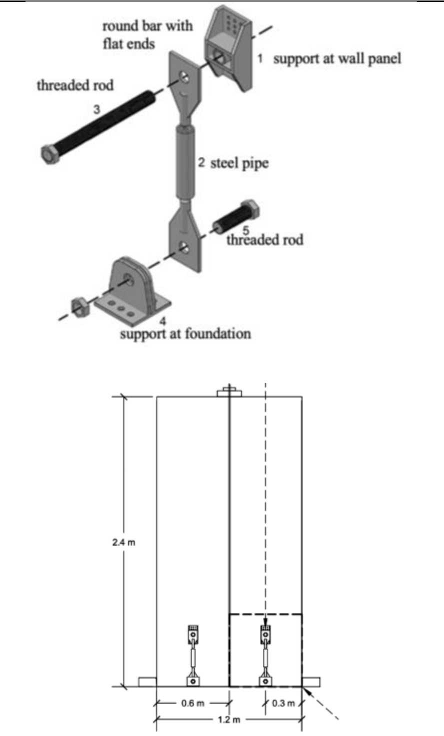
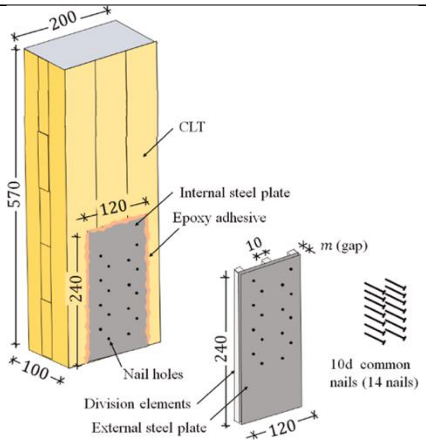
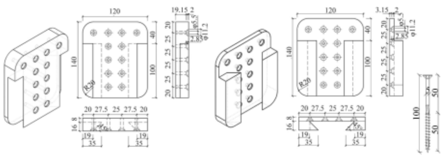
Table 1. Innovative connectors for CLT shear wall system

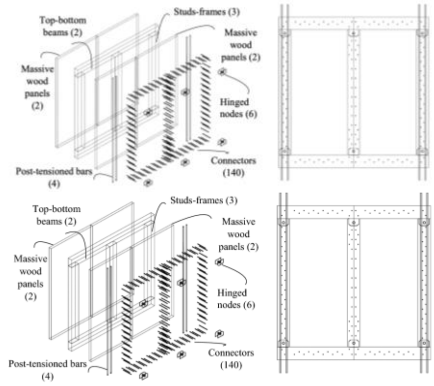
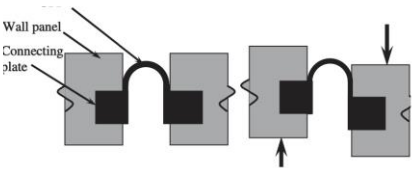
Index	Name	Connection Figures	Descriptions	Ref
	Connector For CLT panels (CLT-C)			
CLT-C1	X-bracket		The X-bracket is a novel steel bracket designed for providing CLT buildings with improved ductility and energy dissipative capacity in both shear and tensile direction, as well as for reducing permanent damage in timber, strength degredation and pinching effect.	[46, 50, 58]

CLT-C2	The X-RAD from Rothoblaas Ltd.		The X-RAD is a multi-directional point-to-point connection that links wall and floor CLT panels, which is easy to assemble and disassemble but requires precise profiling and fitting. With the inclined screws and the linking metal panels, this connector is characterised by high strength and stiffness with adequate ductility.	[37, 59, 60]
CLT-C3	SHERPA-CLT-connector		The SHERPA-CLT-connector is a coupling element that can be used in the angle joint, t-joint and longitudinal joint of CLT panels. It is designed for safe and high-precision assembly without the need of any scaffolding, as the connectors are placed in the interior of buildings.	[61, 62]
CLT-C4	Pinch-free Connector (PFC)		The PFC is a novel tensile connector, which is designed to overcome the pinched effect in conventional timber connections with improved reload stiffness and better hysteresis performance. The equipped preloaded spring ensure the permanent contact between timber and connector, therefore eliminating the crushing-induced slack through a ratcheting mechanism.	[32]
CLT-C5	Slip-friction connector (Tectonus)		The Tectonus is a friction tensile connector, which allows rocking and fully self-centring behaviours in CLT shear walls. It can dissipate energy via friction and effectively eliminate the slip between the connected elements. This system is recently commercialised and applied in the newly built 'Fast+Epp' building in Vancouver [15].	[63-66]

CLT-C6	Shear key with slots		This is a novel type of shear transferring device that designed along with CLT-C5 for the rocking shear wall behaviour. It behaves similarly to angle bracket connections when working in shear, while the slots with special shape allow for uplifting during the rocking of CLT panels.	[63-66]
CLT-C7	Slip-friction connector (Slotted-bolted connection)		This slip-friction connector (SFC) is a vertical connector that is made with steel plates clamping together with slotted bolt holes and fixed to timber with inclined self-tapping screws. Certain degree of linear movement is allowed in this connector to achieve great energy dissipative performance with limited strength degradation.	[67, 68]
CLT-C8	XL-stubs		The XL-stubs are modified hold downs with hourglass steel plates to replace the original rectangular steel plates. The reduced area at the middle of the hourglass steel plate can help trigger deformation during loading and reduce plastic deformation in timber, thus achiving improved energy dissipation capacity.	[31, 69]
CLT-C9	Holz-Stahl-Komposit (HSK) System		Holz-Stahl-Komposit (HSK) System is a shear connector formed by steel plates that are inserted into timber and bonded with chemical adhesive. Duct-tape is used with this connector to prevent the formation of adhesive bond in specific areas, creating a ’weak zone’ that can act as a yielding fuse.	[12, 70]

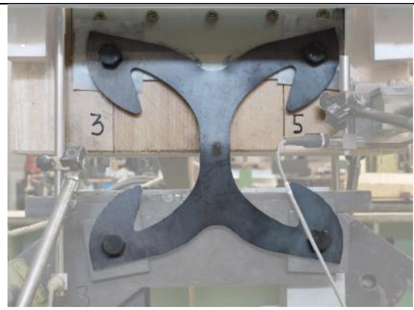
CLT-C10	Novel tube connector		This tube connector is a hollow steel tube placed within the hole drilled on CLT panels, connecting panels to the foundation by a threaded rod that goes through the panels. Apart from the improved mechanical performance, this connector is also designed for limited timber damage, and easy installation and replacement.	[71, 72]
CLT-C11	High-Force-to-Volume (HF2V) damping devices		The HF2V damping device is a substitute to the conventional tensile connections with loading resistance and energy dissipation being provided by the reversible plastic extrusion of lead. It also enables self-centring of shear walls with insignificant damage in both device and timber, and can therefore be fully reused.	[73-75]
CLT-C12	Internal-perforated-steel-plate (IPSP) connections with self-drilling dowels (SDD)		This is a modified IPSP connector that joints timber panels using SDD instead of adhesive. It can be transformed into hold-downs and panel-to-panel connectors. The reduced area of steel plate (steel bridge) is designated weak area to deform first to prevent the bending of SDD and the crushing of timber.	[76]

CLT-C13	Energy dissipators with steel buckling restrained steel braces (BRB) concept		This connector is an energy dissipater for CLT panels that has a milled portion enclosed in a grouted steel pipe that is designed to yield first in connector. An end-pinned system is included in the connector to allow rotation at the ends of the energy dissipators and reduce internal moments.	[77]
CLT-C14	Gap Reinforced Fastened Connector (GRFC)		The GRFC is a modified hold-down incorporates a gap between two steel plates that are bonded by adhesive. The gap creates space for the yielding of fasteners, thus reducing the crushing on timber during deformation. The adhesive layer creates rigid interface between fasteners, reducing the connections space requirements in EC5.	[78]
CLT-C15	Prefabricated Metal Dovetail Connector		The prefabricated metal dovetail connector consists of a mortise part and a tenon part, which is designed for screw-free onsite installation of CLT panels.	[79]
CLT-C16	LOCK Connector from Rothoblaas Ltd.		The LOCK connector system is a concealed connector for the easy and accurate joining of CLT panels to concrete foundation by sliding, which also provide convenient disassembly after the end-of-life of structures. By varying the length of connector, this system can be used on both CLT panels and beams.	[80]

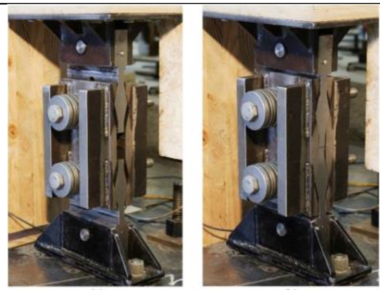
				
	CLT shear wall reinforcement systems (CLT-R)			
CLT-R1	Framing Panel Shear Walls (FPSW)		FPSW is a hybrid shear wall system formed by CLT panels, articulated hollow steel bracing and steel tendons. This system provies reduced overturning effect and improved structural performance than conventional CLT shear walls. The steel frame ensures structural integrity when the load-bearing CLT panels are damaged, thus allowing low-cost rehabilitation.	[81]
CLT-R2	Post tensioned hybrid shear wall with U-shaped flexural plates (UFPs)		This hybrid shear wall system is reinforced by prestressed tendons and energy dissipating devices (UFPs). Recentering and sufficient energy dissipation can be achieved in this system through metal yielding with litter timber damage, which allows low-cost repair by replacing the sacrificial UFPs after seismic events.	[82, 83]

Complementary to the introduction of the innovative connectors, the experimental studies carried out to prove the mechanical performance of these CLT connectors are summarised in Table 2.

Table 2. Comparison of the experimental results for the novel connections

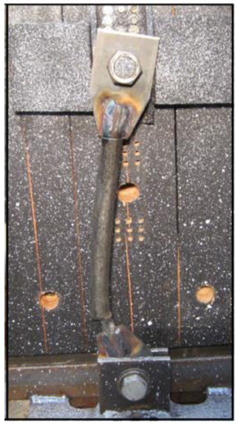
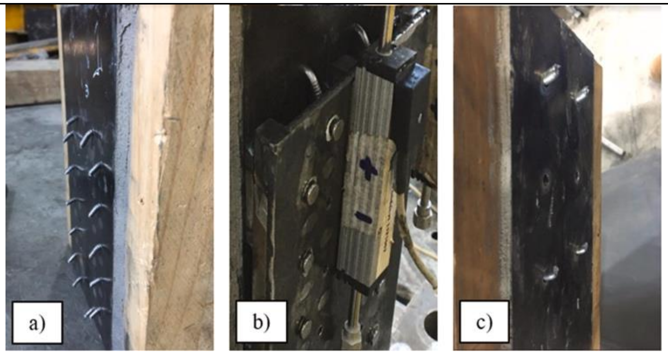
Index	Connection Type	Fasteners Type	Scale of Testing	Loading Protocol	Ductility Factor	Deformation and Failure Modes
CLT-C1	Angle bracket (Shear)	4* M16 bolts	Local/Macro	Cyclic	23.43	 • Out-of-plane buckling in the vertical web, which may cause embedment damage in timber.
	Hold-down (Tension)		Local/Macro	Cyclic	23.57	  • Out-of-plane flexural buckling under compression and extension under tension in the vertical web. • Minor steel embedment and slight plastic deformations can be observed in M16 bolts with no visible damage in timber after testing.

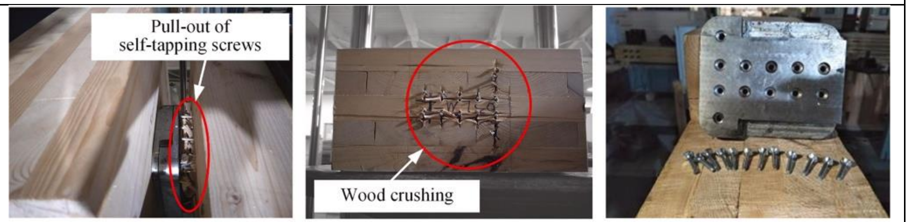
CLT-C2	Angle bracket (Shear)	6*Ø11 × 300mm Inclined screws and M12 bolts	Local/Macro	Monotonic/Cyclic	2	 • Block-tearing of the inclined metal fasteners along with the deformation at steel envelope.
	Hold-down (Tension)			Monotonic/Cyclic	6.3	 • Bending of the inclined metal fasteners along with the deformation at steel envelope.
CLT-C4	Hold-down (Tension)	4*M10/ 2*M16 bolts	Local/Macro	Cyclic	10	 • Embedment in wood and yielding in fasteners, depending on the diameters of fasteners used with the connector.

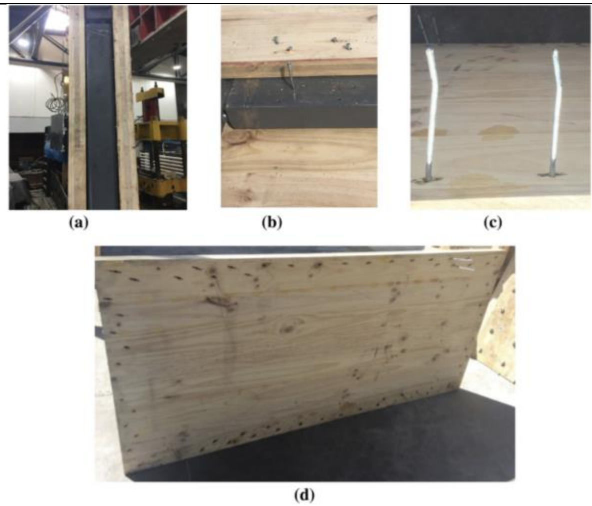
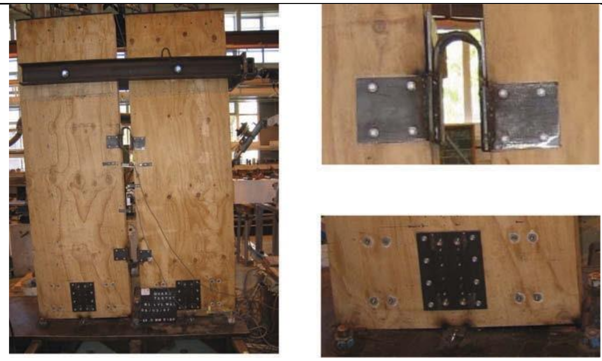
CLT-C5	Hold-down (Tension)	2*M20 bolts and 8*Ø11 × 550mm screws;	Local/Macro	Cyclic	N/A	 (a) (b) • Movement of the centre plate within the grooved outer cap plates along with the compression of the Belleville springs.
CLT-C6	Angle bracket (Shear)	8*M20 bolts	Macro	Cyclic	N/A	 • In the lateral direction, CLT-C6 has similar behaviours to conventional angle brackets. • In the vertical directions, bolts can slide within the slots along with the movement of panels.
CLT-C7	Hold-down (Tension)	27*Ø10 × 140mm screws	Local/Macro	Cyclic	N/A	 • Slipping between cap plate and brass shim • No damage to the self-tapping screws in connection was observed and no washers fell out of their slots.

CLT-C8	Hold-down (Tension)	8*M12 bolts and 2*M18 bolts	Local	Monotonic/Cyclic	52.2	 • Bending or fracture in the middle point of the hourglass steel plate
CLT-C9	Hold-down (Tension) & panel-to-panel connection (Shear)	Adhesive	Local/Macro	Monotonic/Cyclic	31.8	 • Deformation of steel around the holes that are covered by duct tape and not adhesively bond with timber.
CLT-C10	Hold-down (Tension)	1*Ø12.7mm threaded rod and 2* nuts rods	Local	Monotonic/Cyclic	4-8.7	 • Deformation and buckling of the steel tube.

CLT-C12	Panel-to-panel connection (Shear)	16*Ø7 × 133mm screws	Local/Macro	Monotonic/Cyclic	14.5	 • Bending or rupture at the steel bridge of the perforated steel plate.
	Hold-down (Tension)	1* M28 bolt and 16*Ø7 × 133mm screws	Local/Macro	Monotonic/Cyclic	22.1	 • Bending or rupture at the steel bridge of the perforated steel plate.

CLT-C13	Hold-down (Tension)	9* Ø6.35 × 76.2mm screws, 1* threaded rod and 1* Ø25.4mm bolt	Local	Monotonic/Cyclic	N/A	 • lateral buckling at the milled section near the shoulder, which is caused by the rotation of steel pipe during the compression of cyclic loading.
CLT-C14	Hold-down (Tension)	Adhesive and 14 *Ø3.76 × 76.2 mm nails	Local	Monotonic/Cyclic	0.44-2.55	 • Yielding of nails (b) inside the gap area and the shear-off of nails (a)&(c).

CLT-C15	Hold-down (Compression)	24*Ø5 × 100mm screws	Local	Monotonic/Cyclic	4.67	 • Pull-out of screws along with cracking in the middle layer of CLT panel.
	Angle bracket (Shear)			Monotonic/Cyclic	1.67	 (a) (b) (c) • Screw yielding (a) accompanied by wood crushing (b) and screw fracture (c).

CLT-R1	Shear wall system	$128 * \emptyset 7 \times 233$mm screws and 6*Ø38mm bolts	Local/Macro	Cyclic	4.83	 • The loss of attachment between the CLT panels and the steel frame (a) due to the pulling-out of screws (b) and embedment failure in timber (d).
CLT-R2	Shear wall system	4*Ø12.7mm tenons and self-drilling screws	Local/Macro	Cyclic	N/A	 • Bending of UFPs during shear wall rocking

Note: Detailed experimental records of CLT-C3, CLT-C11 and CLT-C16 are missing in the literature

3.3 Performance evaluation for novel CLT connectors

According to Table 1, additional two- or three-dimensional steel connectors are introduced in most of the new CLT connector designs to replace conventional steel plates. Apart from improved mechanical performance, all novel connectors have their own unique features for addressing the aforementioned limitations of conventional connectors. It is therefore difficult to directly evaluate or compare the connectors' performance when their design philosophies are somewhat, and in certain cases completely, different. In addition to the necessary structural needs, the manufacturing and constructional performance of connectors define the efficiency and the overall cost of CLT construction, and therefore should also be well considered in the design of CLT connectors to promote practical applications. Multi-attribute performance evaluation systems for steel modular connectors were previously proposed by Srisangeerthanan et al. [84] and Corfar & Tsavdaridis [85], with comprehensive considerations and explanations regarding of structural performance, manufacturability, and constructability being included. Some evaluating criteria are herein adopted and tailored based on the unique characteristics of CLT construction, to elucidate and enhance the discussions of such connections' performances.

3.3.1 Structural performance

From the structural performance perspective, panelised structures like CLT shear wall systems require connectors to have adequate shear and tension capacity. While all new connectors can achieve adequate resistance in their primary working direction, some connectors (CLT-C4-8, 11, 13, 16) are designed to work in only one direction and their capacities in the secondary direction are limited. This may help establish a clearer relationship between the connection properties and the shear wall performance with no coupling behaviours between shear and tension, while limited capacity and undesirable failure modes in the secondary working direction may lead to unexpected failure (for example, buckling failure observed in Table 2. CLT-C13 under compression) without achieving full capacity. Therefore, having adequate capacity in both working directions would be desirable, and the strength in the secondary working direction can be treated as additional reinforcement to structures.

Contrary to the "strong plate-weak fasteners" concept for conventional connections, most of the newly proposed connectors (CLT-C1, 4-14) achieve strong fasteners-weak metal connector behaviours along with the much-improved ductility (Class H) (Table 2), which is achieved by adopting big-diameter fasteners for higher yielding strength in timber-fastener connection than that in metal connectors. In this way, the source of inelastic deformation switches from the yielding of fasteners and the crushing of timber as in conventional connections, to the more ductile bending (CLT-C1, 8-10 and 12) or sliding (CLT-C4-7) of the steel connectors (Table 2). Owning to the well-standardised homogeneous properties of steel material, the controlled deformation of metal elements can provide improved ductility and predictable mechanical performance, meanwhile eliminate the impact from the inherent defects in the connected timber elements. The reduced deformation in fasteners can also help eliminate damage in timber and avoid brittle failure in structural elements. The common application of the so-called 'damage avoidance philosophy' in the novel connector design reflects the widely recognised concerns toward timber damage with regards to conventional connections.

Also, the better ductility in those connectors (Table 2. CLT-C4-8, 10, 11and 13) designed as the alternatives to conventional hold-downs connections can promote rocking behaviour for improved energy dissipation in CLT shear wall systems, which also satisfies the increasing demands in uplift resistance and energy dissipation of large timber construction. To further enhance the performance of recentering during the rocking of panels, some new connectors (CLT-C4, 5, 7, 11) adopt special elements such as springs and reversible plastic extrusion to achieve higher stiffness in unloading process with much plumper hysteresis curve.

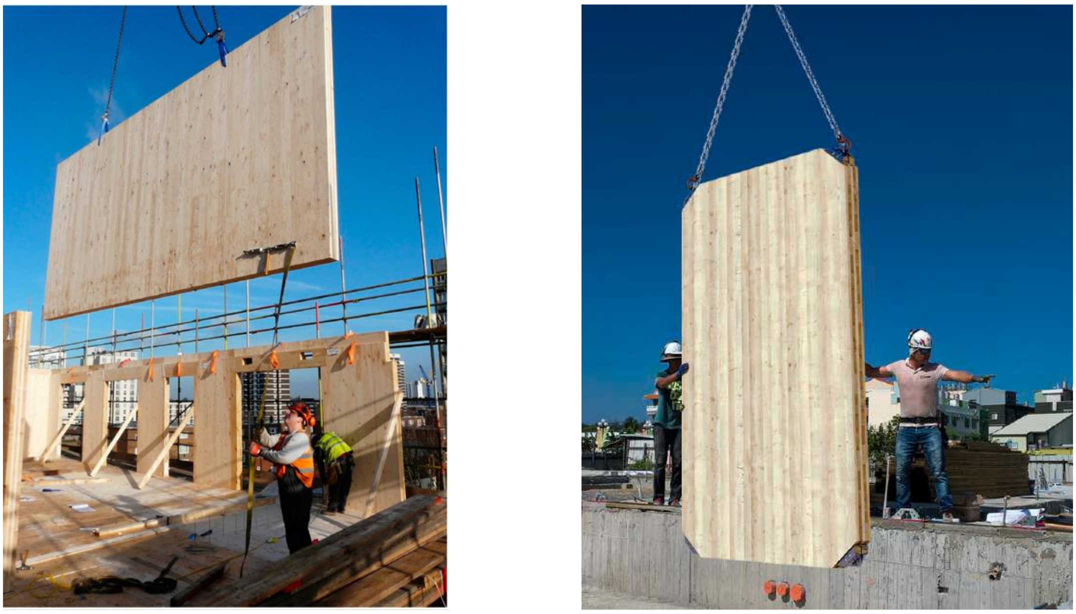
3.3.2 Constructability

In additional to the mechanical performance, construction requirements should also be carefully considered in the connector design stage, as they determine the ease, speed and quality of CLT construction. The ideal CLT connections for efficient construction should be compact, easy to install with reduced manual efforts, able to address tolerance requirements, and be demountable to enable disassembly and reuse in the future.

When designing connectors for constructional performance, some specific factors should be considered. Firstly, connectors should provide easy onsite assembly methods of structural elements for increased construction efficiency and lower construction costs, under the context of rapidly increasing labour cost. Most of the new connections are still using onsite screws fastening that similar to conventional steel plate connectors. CLT-C15 and 16, on the other hand, employ interlocking technique that requires no fastners onsite, which is a connecting method used in ancient timber strucutres and is readopted in modern connection design to promote more efficient assembly in construction.

Secondly, the fasteners that joint the connectors and structural elements should be carefully chosen, as the fastening of screws in conventional connectors takes up most of the workload. Different from the small-diameter fasteners used in conventional plate connections that are labour-intensive to install, big-diameter screws or bolts are adopted more frequently in novel connectors (CLT-C1, 4-7 and 13). The adoption of bigger fasteners can increase the capacity of timber-to-fastener connection with reduced fastener number, for the improved construction efficiency as well as the realisation of the “strong fasteners-weak metal connector” and ‘damage avoidance’ philosophy. Connectors designed with these philosophy, expercially those use big-diameter bolts and dowels (CLT-C1, 4, 5, 7-11 and 13) can be repaired or replaced with introducing less damage in timber, which are ideal for facilitating structure maintenance, strucutral matrial recycle or reuse, especially for those located at the exterior surface of CLT panels and require no panel modification for the fitting of connectors (CLT-C1, 4, 8 and 13). Some connectors (CLT-C2, 5, 7, 9, 10 and 12) require profiling (cutting, drilling) on timber for connector placement, which can cause cross-sectional loss of the structural elements and thus increased workload and cost. In addition to the conventional fixing method of mechanical fasteners, chemical adhesive can be found in some new connectors (CLT-C9 and 14). Though very high stiffness can be achieved in these connectors, the adhesive formation process could be problematic for onsite installation, as it may be affected by numerous factors such as weather and site conditions. Thirdly, connectors should be able to accommodate considerable levels of construction tolerances for unexpected onsite adjustments. Connectors (CLT-C2, 10 and 15-16) that have complex profile and require accurate onsite operation may be difficult to assemble onsite when unexpected construction errors happen, while those (CLT-C1, 4, 6, 8, 13 and 14) attached at the exterior surface of CLT panels can be easily adaptable to project and construction changes.

For further achieving better installation quality and efficiency with reduced onsite workload, connectors CLT-C2, 15 and 16 are designed as prefabricated connectors. These connectors can be accurately pre-assembled and installed onto the timber in controlled environment, which is especially beneficial for those that require special tooling. For prefabricated connectors, it is crucial to have suitable design for transport vehicles and be able to use as temporary support system during panel lifting, such as the X-RAD connector (CLT-C2) (Figure 7(b)). It can be treated as an additional constructional benefit, as traditional panel lifting involves hole drilling and filling on panels for placing lift devices (Figure 7(a)). For CLT-C15 and 16 that adopting interlocking technique, structural elements can be self-locked onsite with less effort, and can be disambled without the need of demolition, which means that the strucutres are adaptable to potential environmental or functional changes.



(a) (b)

Figure 7.Panel lifting with (a) conventional method [86] and (b) novel connectors (CLT-C2) [60]

3.3.3 Manufacturability

The manufacturability of connectors governs the speed and quality of mass production; that can be considered from the connector complexity (geometry, component number, material, processing procedures). Connection parts that can be easily fabricated using conventional manufacturing methods can contribute to much faster commercialisation and significantly lower construction costs. For those have being more geometrically complex, special manufacturing methods such as 3D printing, is required, which can significantly increase the manufacturing cost – on a positive note, the supply chain issue can be solved, especially when quick replacement is required after the damage of a connection component. All novel connections listed in Table 1 can be fabricated using conventional manufacturing methods. The planar connectors such as CLT-C1, 8, 9, 12 and 14 are the most mass-producible, they can be simply cut from steel sheets. For those 3D connectors, multi-process manufacturing may be required with significantly higher cost. For example, the cap and centre plates of CLT-C5 can be sawn from merchant flat bar and then milled to achieve the toothing shape on surface. Alternatively, they can be produced from a custom rolled special section in 6m lengths, and then be sawn, drilled and slotted, which however would require minimum ordering of 100 tonnes, according to UK steel manufacturer SC4. For CLT-C13, different components require different manufacturing methods. The wall support of it can be produced from either a stock PFC or a press braked channel, while the foundation support should be produced from either a tee section or fabricated from profiled/drilled plate. The steel sleeve in the middle also requires separate manufacturing from a profiled and formed plate before being integrated with other components.

As some of the new connectors have more than 2 components (CLT-C4, 5, 7, 10, 11 and 13), careful assembly (installation) processes in factories or onsite will be required, which also governs the cost and efficiency of production. Moreover, in some cases, special operations are required during the assembly process (e.g., welding in CLT-C10 and 13) which can further reduce the production efficiency and increase cost. In addition, tolerances in the assembly processes should also be carefully considered during the connection design phase. Considering the accuracy of conventional manufacturing methods, 1-2mm tolerance between components should be achievable to avoid fitting difficulties caused by dimensional errors.

4 Novel Proposed Demountable Connection System for Multi-storey CLT Buildings with Damage Avoidance Capacity

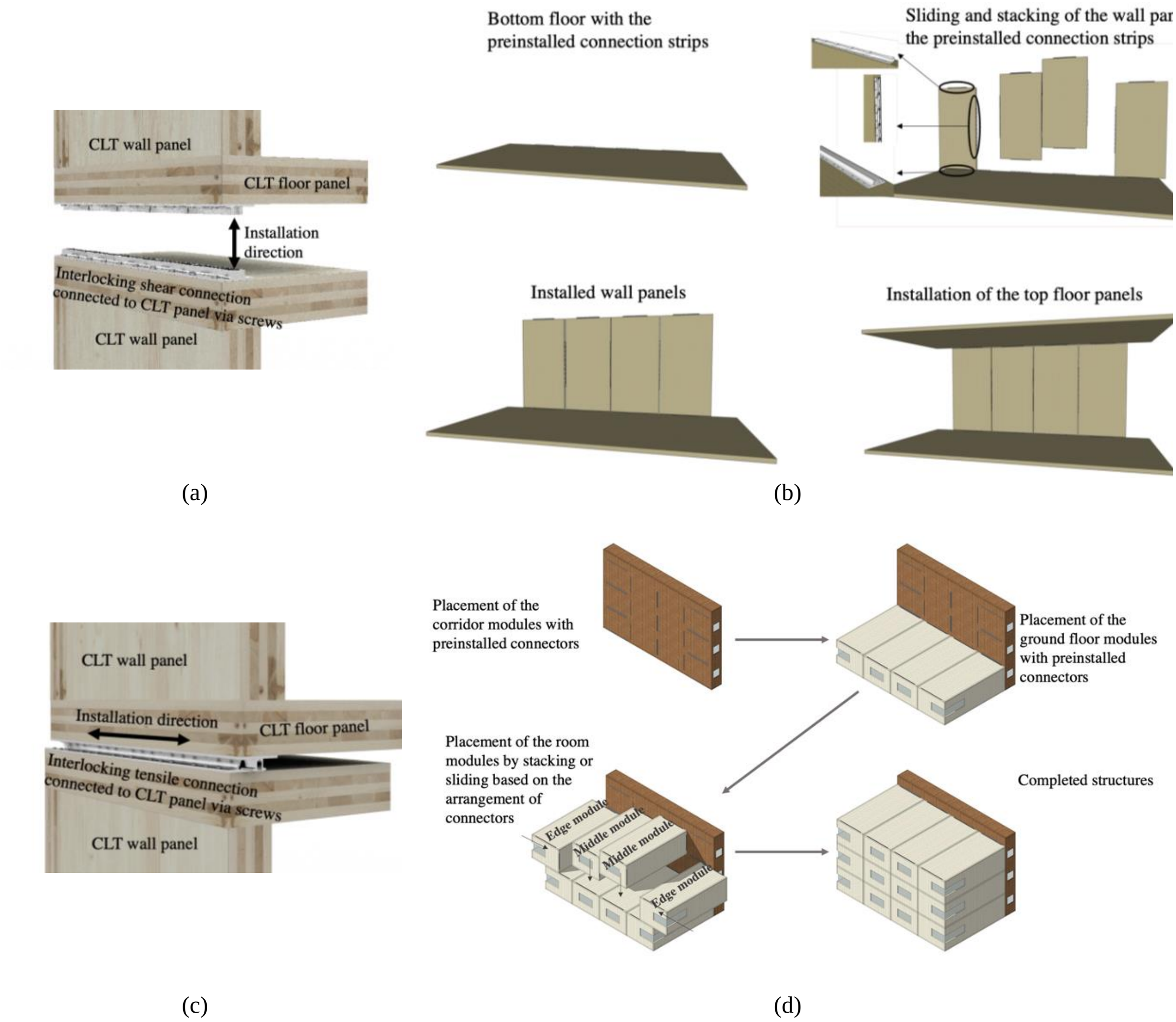


Figure 8. Novel interlocking connectors for CLT modular construction: (a) shear stacking connector and (c) tensile sliding connector, and their application in (b) CLT panelised structures and (d) CLT volumetric structures

Based on the connector performance discussions, a novel prefabricated connection system that provides new connecting solutions for CLT modular (panelised & volumetric) construction by interlocking was proposed [87] (Figure 8), aiming to achieve high-quality of CLT construction with reduced time, labour and waste. With the interlocking techniques employed in this connection system, structural elements can be easily and accurately assembled onsite by stacking (Figure 8(a)) or sliding (Figure 8(c)) without the need of onsite screw fastening. The sliding connector in the system can also act as a guiding device during assembly process, contributing to accurate alignment of the structural elements.

In addition to the advanced connecting method, this connection system also offers damage avoidance effect with the specially-designed 3D metal connectors. In both tensile and shear connectors, complex geometries are applied on the metal components to achieve lower resistance than the yielding capacity of the surrounding fasteners, making them the weakest elements in the connection system and always fail first (strong fasteners-weak metal connector philosophy), when all other components remain intact (act elastically). In this way, chunky fasteners are used to reinforce the connection between timber and fasteners and avoid plasticisation, which reduces the reliance on small-diameter metal fasteners as in conventional connectors. Being designed as a continuous strip connector, the proposed system can provide continuous support along the edge of structural elements, instead of the conventional discrete point-to-point connecting methods.

Considering the higher dimensional accuracy for connector fitting and the high-cost of moulding conventional manufacturing methods, the prototypes of this new connection were 3D printed integrally with 1mm tolerance for the fitting of connectors. The mass production of this kind of complex 3D connector is potentially achievable with the conventional method but a more complex process. For the male connector in shear connection, the cantilevering curving element and the central support should be produced separately from 3D formed strips, and then weld to the drilled base plate. For the tensile connectors that have continuous section along the length, production could be easier from a special hot rolled section, and then sawn to length.

This connection system employed different advanced technologies in timber connection design, such as fastener-free assembly and damage avoidance philosophy and it requires no profiling on timber panels for the connector placement, it is therefore easily adjustable for different projects by simply varying the length of connection strips. With automotive lifting system and improved manufacturing methods, this connection system can be a promising solution for CLT modular construction with effort-less, more accurate onsite assembly, reduced construction waste production and fully reusability in both structural elements and connectors.

5 Conclusions

This paper summarises the design features of 18 recently developed novel steel connections newly proposed reinforcing methods for CLT shear wall system. The structural, constructional and manufactural performance of these connections were discussed to determine their viability of addressing the identified disadvantages of achieving rapidly deployable and reusable CLT modular construction. A series of common strategies for achieving more stable performance, improved ductility and reduced installation effort in connectors can be identified from the summarised connector designs. In terms of structural performance, much improved ductility can be observed in the new connectors with damage avoidance philosophy. Some of them can help achieve better dynamic performance in structures by promoting rocking and re-centering of panels. The common adoption of large diameter dowel type fasteners is expected to further improve CLT construction efficiency and new ways of joining structural elements, such as interlocking and chemical adhensive, are explored in connectors. In addition to the structural and constructional performance, the potential of mass production should also be well considered in the design of new connectors. All these design tendencies reveal the growing interest in high-rise CLT structures and the increasing concerns for their seismic performance, construction efficiency and reusability.

6 Future Persepctives

Design of future CLT connectors requires comprehensive considerations on the structural, constructional and manufactural aspects. The connection design that with simple but efficient geometries and can be easily fixed to modular elements, are urgently needed in current CLT modular construction, ensuring the fast realisation and commercialisation of the connections concepts for practical applications. For future large CLT buildings with more complex structures and increased functional requirements, 3D connectors with multiple functionalities, such as damage free effects, optimised energy dissipation, re-entering capacity, interlocking and demountability, are believed to be the more promising solutions and the adoption of which is now a growing trending in steel modular construction. These functionalities contribute to not only better strucutral performance, but also improve efficiency and adaptability in construction. Considering the great modifiability of timber, adaptable connection design can promote the re-arrangment, recycle and reuse of material during or after the service life of buildings, extending the life cycle of material and further improving the sustainability of timber construction. Advanced manufacturing techniques such as 3D printing can be used to produce such complex connector components or even to provide customised solutions for specific projects or structural requirements [88]. The incorporation of such innovative functionalities and manufacturing techniques can also foster the achievement of high-performing CLT connectors as well as automative CLT construction.

Despite the improved mechanical behaviours of the innovative CLT connectors observed in experimental and numerical studies at micro- and meso-scale level, testing of these connectors in full-scale CLT buildings has not yet performed. Full-scale global tests are necessary to access the effectiveness of these solutions in improving structural performance and overall stability under complex loading conditions such as wind, earthquake and blast loads, as well as validating accurate and reliable numerical local and global models. Further experimental investigations are therefore necessary for the development of detailed guidance on numerical analysis for assessing CLT building performance, which can promote the use of new connector products in CLT construction.

The new generation of Eurocode 8—timber part— will introduce an updated list of timber-based structural systems with clear definitions of dissipative and non-dissipative zones in structures, which are needed for the newly-introduced capacity design rules and overstrength factors for each type of structural system. CLT shear wall systems that are not present in the current version, will be included as an independent timber structural system in the Standards [44]. Further, a new procedure for application of non-linear static (pushover) analysis will be provided [11]. In this context, rapid development of CLT panelised construction is foreseeable in the near future, necessitating the proposal of connectors that can help achieve rapidly deployable and reusable structures with adequate structural performance. Therefore, all three aspects (structure, construction and manufacture) should be considered comprehensively in the design of future CLT connectors, for achieving not only better efficiency and lower cost in CLT construction, but also easier standardisation and commercialisation.

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