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Citation: Li, Z. & Tsavdaridis, K. D. (2023). Design for Seismic Resilient Cross Laminated Timber (CLT) Structures: A Review of Research, Novel Connections, Challenges and Opportunities. *Buildings*, 13(2), 505. doi: 10.3390/buildings13020505

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1 **Design for Seismic Resilient Cross Laminated Timber (CLT) Structures: A** 2 **Review of Research, Novel Connections, Challenges and Opportunities**

3 Zhengyao Li¹ and Konstantinos Daniel Tsavdaridis²

4 School of Civil Engineering, Faculty of Engineering and Physical Sciences, University of
5 Leeds, Woodhouse Lane, LS2 9JT, Leeds, UK

6 Department of Engineering, School of Science & Technology, City, University of London,
7 Northampton Square, EC1V 0HB, London, UK

8 9 **Abstract**

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

31 32 **1 Introduction**

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



(a)



(b)

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

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

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

69

70 2 CLT Shear Wall System and Conventional Connections

71 2.1 CLT shear wall system

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



(a)



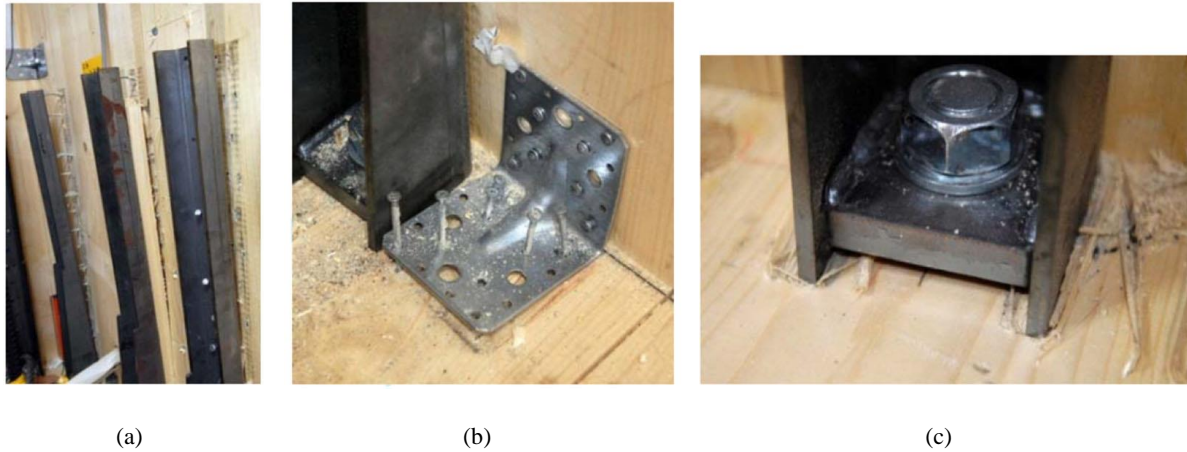
(b)

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

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

87 When the CLT buildings being tested statically in the lateral directions, damages can also be
88 observed in the CLT panels (Figure 4) at the later loading stage under large displacements,
89 including the embedment of wall panels due to the panel rocking and cracking in the corner of
90 the large openings of door and windows due to the in-plane panel deformation [19-21]. It can
91 therefore be concluded that, the potential deformation modes of CLT buildings can be: the in-
92 plane deformation (shear, bending, axial) in the wall panels, the rigid rotation of wall panels,

93 and the deformation in wall-to-wall and wall-to-foundation connections [22]. In common
94 practice, yielding of metal fasteners in the wall-to-floor connections is considered as a
95 favourable ductile failure mode in CLT buildings, as it provides better ductility and has lower
96 risks of sudden strength loss, while it also damages the CLT elements.



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



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

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

112 Consequently, both dynamic [16, 18, 26] and static [19-23, 25, 27] tests on CLT panelised
113 systems indicated that structures made of CLT panels generally demonstrated high strength

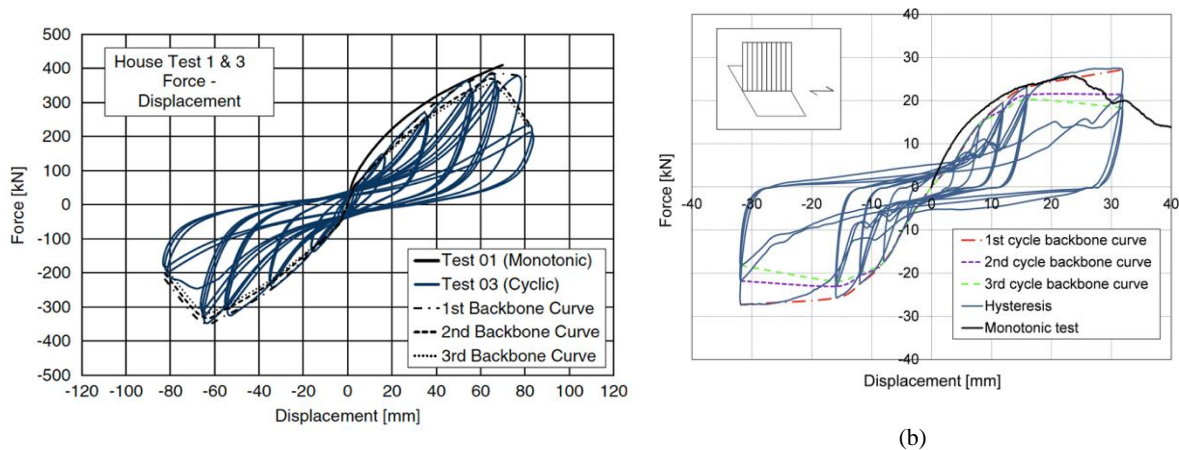
114 and stiffness with most of the deformation and energy dissipation being developed by the steel
115 connections and the friction between timber panels, proving the feasibility of low-rise CLT
116 construction in earthquake-prone regions. The governing role of steel connections in defining
117 the overall structural performance necessitates the development of high-performing
118 connections for reducing high accelerations of CLT buildings, providing better ductility and
119 enabling rocking and recentering behaviours in the shear wall systems [16].

120 2.2 Conventional CLT connections

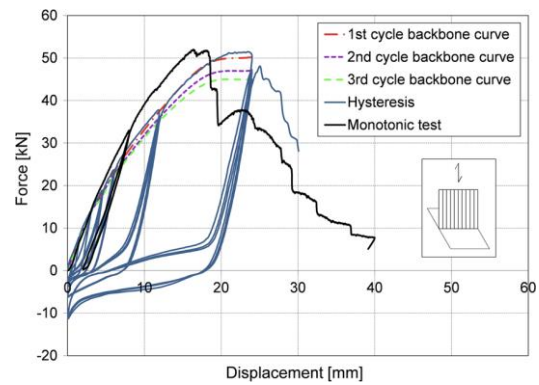
121 In CLT buildings, two kinds of connections are commonly used: splice or nailed and screwed
122 connections in wall-to-wall and floor-to-floor connections [28], and metal plate connectors
123 (hold-downs and angle brackets) with dowel type fasteners in wall-to-floor and wall-to-
124 foundation connections [29]. As prescribed in EC8, the structural elements (timber) in timber
125 buildings should remain elastically, while the dissipative zones should be located in the
126 connections for resisting seismic actions. Therefore, the wall-to-floor and the wall-to-
127 foundation connections are normally designed as energy dissipating devices in CLT structures,
128 while the wall-to-wall and floor-to-floor connections are designed as non-ductile and should
129 be overstrengthened. The metal plate connectors used in CLT structures are then the primary
130 source of ductility and mechanical performance that govern the delivery of secured structures
131 [30].

132 2.2.1 Experimental studies

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



(b)



(a)

(c)

146
147

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]

148 In addition to timber damage, both angle brackets and hold-downs are characterised by high
 149 stiffness but insufficient ductility [24, 34], belonging to L-low ductility class ($2 < \mu < 4$) or M-
 150 medium ductility class ($4 < \mu < 6$) as prescribed in EC8 [35] in their primary directions. As
 151 dissipative timber connections are required to achieve ductility class M-medium or H-high
 152 ($6 < \mu$), increasing the number of connectors and using small-diameter fasteners are the
 153 recommended methods of designing ductile timber structures with conventional connections
 154 [35, 36]. The large amount of connectors and fasteners can lead to time-consuming on-site
 155 fastening work with hard-to-verify assembly quality [37], and also limit the potential of fully
 156 reusing timber components, as the removal of nails and screws can be labour-intensive and
 157 further damage the structural material [38]. Also, small-diameter fasteners can introduce high
 158 stress in timber and pinch through the fibres before the capacity of timber is fully developed,
 159 causing brittle failure with sudden reduction in connection strength and large residual
 160 displacement even after the removal of the external loading.

161 2.2.2 Analytical models and design rules

162 As a new structural material, specific design code or guidance for CLT have not yet developed
 163 [39]. The general rules for timber buildings in EC5 and EC8 or information in relevant literature
 164 are applied when designing CLT structures, though they are not fully applicable. Previous
 165 comparative studies between analytical and experiment results [24, 34, 36] indicated the
 166 conservative approach for strength prediction (lower than 80% of the tested results) and the
 167 significant stiffness overestimation (up to 9 times higher) of the existing analytical models of
 168 timber connections [24, 40].

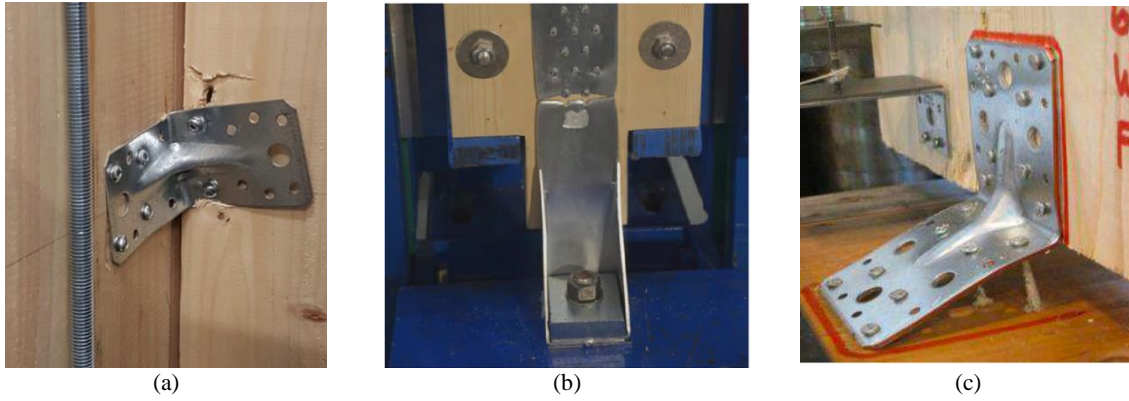
169 The prediction errors can be attributed to several factors of timber connections. The bearing
 170 capacity of conventional timber connections is defined by the combinations of the embedment
 171 strength, the sensitivity to splitting, the connection configurations as well as the variation of
 172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

179 To ensure the full activation of all ductile elements and avoid plasticisation in non-ductile zones
180 [43], as required in EC8 [35], the overstrength method that developed by Jorissen and
181 Fragiaco (Eq.1) [13] is widely used on both building and connection levels in timber
182 structure design. This can also lead to errors in the analytical predictions. At building level, all
183 timber elements and connections in non-dissipative zones (e.g., wall-to-wall and floor-to-floor
184 connections) are strengthened to avoid plasticisation. At connection level, timber elements are
185 strengthened to ensure the development of cyclic yielding in fasteners [44]. In this method, the
186 introduction of the overstrength factor γ_{Rd} in the design strength of brittle elements ($R_{d,brittle}$)
187 is for eliminating the impacts of all possible factors that may lead to unexpected stronger
188 capacity in ductile elements ($R_{d,ductile}$).

$$189 \quad \gamma_{Rd} R_{d,ductile} \leq R_{d,brittle} \quad (1)$$

190 However, the embedment strength calculated with Johansen's theory in EC5 [45] can be
191 significantly inaccurate due to the greater scattering of timber material properties than the steel
192 material [46], and specific overstrength factors for different connections are not yet in standards
193 [39]. The estimated overstrength factor could therefore be insufficient and limit the attainment
194 of the overstrength effect. Thus, in addition to the overstrength method, common strategies in
195 EC5 of avoiding brittle failure in timber connection are introducing prescriptive safeguards in
196 connection configuration design, such as minimum spacings, minimum number, slenderness
197 ratios and edge distances of fasteners, and the effective number of fasteners [36]. However, the
198 conventional steel connectors may experience brittle failure even with these safeguarding
199 factors being properly applied, as recorded in an experimental study [47].

200 Furthermore, the capacity of brittle elements (timber) and ductile elements (fasteners) are
201 considered independently in the overstrength method, which however is unrealistic, because of
202 the simultaneous deformation in timber, steel plate and fasteners in conventional plate
203 connections. Desirable fasteners yielding (ductile behaviour) normally appears along with
204 other failure modes such as timber crushing or splitting (brittle behaviour), steel plate fracture
205 (brittle behaviour) or bending (ductile behaviour), as well as nail breakage and pulling-out
206 (brittle behaviour) [29, 48-51] (Figure 6). The primary failure modes varied according to
207 different connection factors, such as fastener types, arrangements and geometry, timber
208 properties, loading directions, connection locations, as well as connector configurations. The
209 interaction between these factors is still unknown, making it difficult to predict the primary
210 failure mode of connections using existing analytical models, in which only timber crushing
211 and fastener yielding are considered along with the assumption of rigid steel plates. The
212 ignorance of the composite effect and the rigid plate assumption taken in current analytical
213 models could lead to significant estimation errors, especially for connections with small steel
214 plate thicknesses, as they overlook the deformation contribution of steel elements [24, 34]. For
215 example, it is suggested in EC5 that, the stiffness calculated for steel-to-timber connections
216 should be doubled up to account for the strengthening of steel plate, which was proved to lead
217 to greatly higher connections stiffness [40, 52]. The inaccurate representation of connection
218 stiffness, which is especially crucial to the global stiffness of CLT shear wall system as
219 discussed above, can lead to significant errors in the estimation of the principal elastic vibration
220 period in seismic design, as proved in a numerical parametric study [53]. When having all
221 brittle failure modes considered, some newly proposed analytical models [54-56] showed better
222 agreement with the test results and provided clearer identifications of the related failure modes
223 [36, 57], indicating the need of further improving the design guideline of the conventional
224 metal plate connections.



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

227 **2.3 Overview conclusion**

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


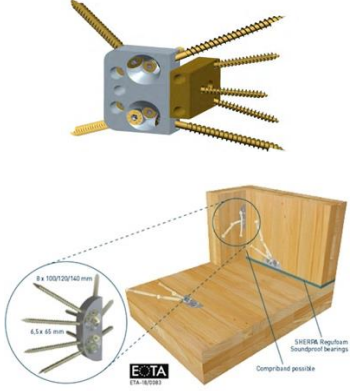
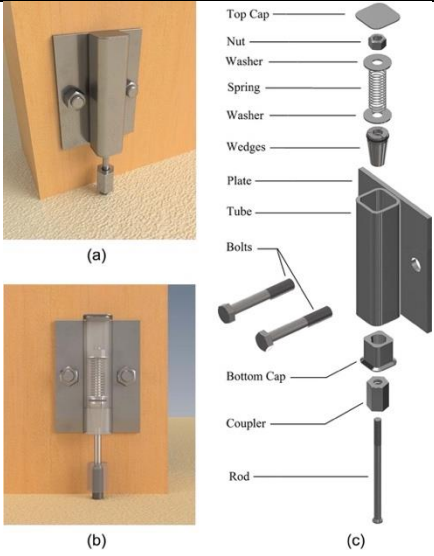
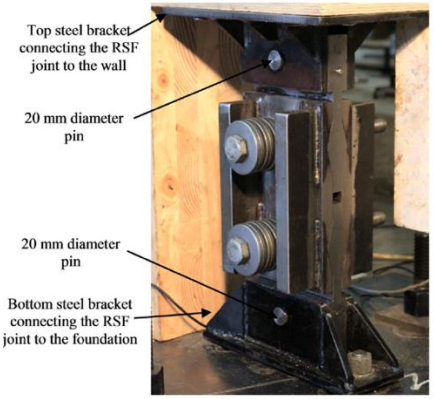
239 **3 Innovative Connections for CLT Shear Walls**


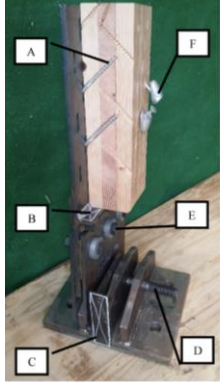

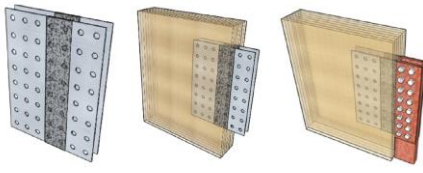
240 **3.1 Innovative connections for CLT shear wall systems**

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


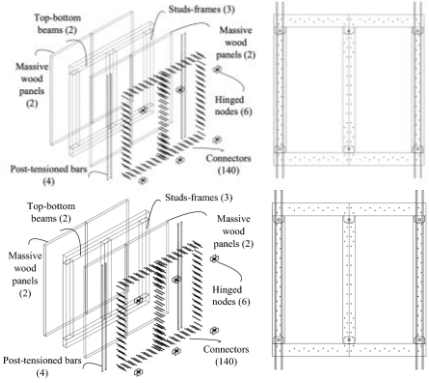
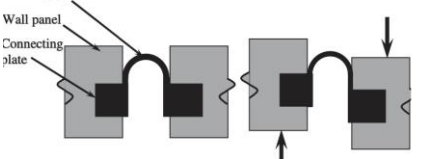
244 Table 1. Innovative connectors for CLT shear wall system

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 degradation and pinching effect.	[46, 50, 58]

CLT-C2	The X-RAD from Rothblaas Ltd.		<p>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.</p>	[37, 59, 60]
CLT-C3	SHERPA-CLT-connector		<p>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.</p>	[61, 62]
CLT-C4	Pinch-free Connector (PFC)		<p>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.</p>	[32]
CLT-C5	Slip-friction connector (Tectonus)		<p>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].</p>	[63-66]

CLT-C6	Shear key with slots		<p>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.</p>	[63-66]
CLT-C7	Slip-friction connector (Slotted-bolted connection)	 <p> A: Inclined self-tapping screws (STS) B: Corner bearing ledge with hatched surface C: Lateral bearing cog with hatched bearing surface D: Reaction bolt E: SFC clamping bolts with Belleville washers F: 45-degree washer </p>	<p>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.</p>	[67, 68]
CLT-C8	XL-stubs		<p>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 achieving improved energy dissipation capacity.</p>	[31, 69]
CLT-C9	Holz-Stahl-Komposit (HSK) System		<p>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.</p>	[12, 70]

<p>CLT-C10</p>	<p>Novel connector tube</p>		<p>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.</p>	<p>[71, 72]</p>
<p>CLT-C11</p>	<p>High-Force-to-Volume (HF2V) damping devices</p>		<p>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.</p>	<p>[73-75]</p>
<p>CLT-C12</p>	<p>Internal-perforated-steel-plate (IPSP) connections with self-drilling dowels (SDD)</p>		<p>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.</p>	<p>[76]</p>



				
CLT shear wall reinforcement systems (CLT-R)				
CLT-R1	Framing Panel Shear Walls (FPSW)		<p>FPSW is a hybrid shear wall system formed by CLT panels, articulated hollow steel bracing and steel tendons. This system provides 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.</p>	[81]
CLT-R2	Post tensioned hybrid shear wall with U-shaped flexural plates (UFPs)		<p>This hybrid shear wall system is reinforced by prestressed tendons and energy dissipating devices (UFPs). Recentring and sufficient energy dissipation can be achieved in this system through metal yielding with little timber damage, which allows low-cost repair by replacing the sacrificial UFPs after seismic events.</p>	[82, 83]




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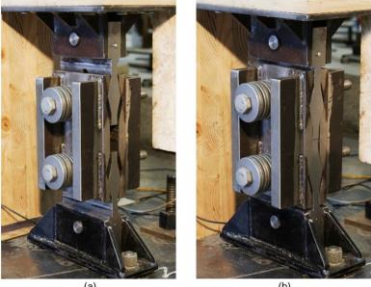


246 Complementary to the introduction of the innovative connectors, the experimental studies
 247 carried out to prove the mechanical performance of these CLT connectors are summarised in
 248 Table 2.




249



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


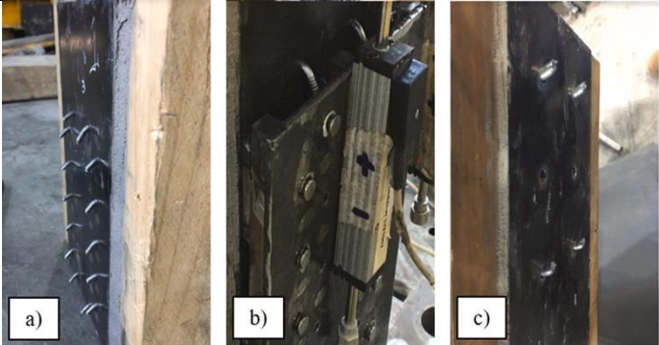
Index	Connection Type	Fasteners Type	Scale of Testing	Loading Protocol	Ductility Factor	Deformation and Failure Modes
CLT-C1	Angle bracket (Shear)	4* M16 bolts	Local/Macro	Cyclic	23.43	 <ul style="list-style-type: none"> Out-of-plane buckling in the vertical web, which may cause embedment damage in timber.
	Hold-down (Tension)		Local/Macro	Cyclic	23.57	 <ul style="list-style-type: none"> 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.

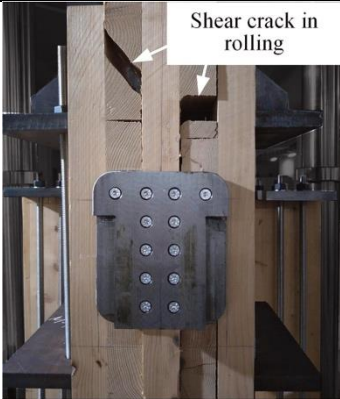
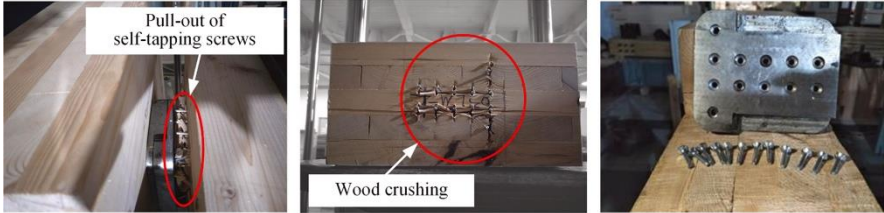
CLT-C2	Angle bracket (Shear)	6* \varnothing 11 × 300mm Inclined screws and M12 bolts	Local/Macro	Monotonic/Cyclic	2	 <ul style="list-style-type: none"> Block-tearing of the inclined metal fasteners along with the deformation at steel envelope.
	Hold-down (Tension)			Monotonic/Cyclic	6.3	 <ul style="list-style-type: none"> 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	 <ul style="list-style-type: none"> Embedment in wood and yielding in fasteners, depending on the diameters of fasteners used with the connector.

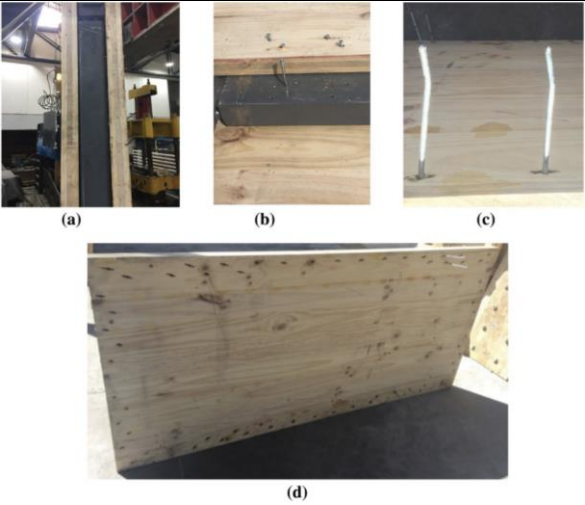

CLT-C5	Hold-down (Tension)	2*M20 bolts and 8*Ø11 × 550mm screws;	Local/Macro	Cyclic	N/A	 <ul style="list-style-type: none"> • Movement of the centre plate within the grooved outer cap plates along with the compression of the Belleville springs.
CLT-C6	Angle bracket (Shear)	8*M20 bolts	Macro	Cyclic	N/A	 <ul style="list-style-type: none"> • 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	 <ul style="list-style-type: none"> • 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	 <ul style="list-style-type: none"> 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	 <ul style="list-style-type: none"> 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	 <ul style="list-style-type: none"> Deformation and buckling of the steel tube.

CLT-C12	Panel-to-panel connection (Shear)	16*Ø7 × 133mm screws	Local/Macro	Monotonic/Cyclic	14.5	 <ul style="list-style-type: none"> 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	 <ul style="list-style-type: none"> Bending or rupture at the steel bridge of the perforated steel plate.

CLT-C13	Hold-down (Tension)	9* $\text{Ø}6.35 \times 76.2\text{mm}$ screws, 1* threaded rod and 1* $\text{Ø}25.4\text{mm}$ bolt	Local	Monotonic/Cyclic	N/A	 <ul style="list-style-type: none"> 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 * $\text{Ø}3.76 \times 76.2$ mm nails	Local	Monotonic/Cyclic	0.44-2.55	 <ul style="list-style-type: none"> 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	 <p>Shear crack in rolling</p> <ul style="list-style-type: none"> • Pull-out of screws along with cracking in the middle layer of CLT panel.
	Angle bracket (Shear)			Monotonic/Cyclic	1.67	 <p>Pull-out of self-tapping screws</p> <p>Wood crushing</p> <p>(a) (b) (c)</p> <ul style="list-style-type: none"> • Screw yielding (a) accompanied by wood crushing (b) and screw fracture (c).

CLT-R1	Shear wall system	128 * \varnothing 7 × 233mm screws and 6* \varnothing 38mm bolts	Local/Macro	Cyclic	4.83	 <ul style="list-style-type: none"> 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* \varnothing 12.7mm tenons and self-drilling screws	Local/Macro	Cyclic	N/A	 <ul style="list-style-type: none"> Bending of UFPs during shear wall rocking

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

252 3.3 Performance evaluation for novel CLT connectors

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

267 3.3.1 Structural performance

268 From the structural performance perspective, panelised structures like CLT shear wall systems
269 require connectors to have adequate shear and tension capacity. While all new connectors can
270 achieve adequate resistance in their primary working direction, some connectors (CLT-C4-8,
271 11, 13, 16) are designed to work in only one direction and their capacities in the secondary
272 direction are limited. This may help establish a clearer relationship between the connection
273 properties and the shear wall performance with no coupling behaviours between shear and
274 tension, while limited capacity and undesirable failure modes in the secondary working
275 direction may lead to unexpected failure (for example, buckling failure observed in Table 2.
276 CLT-C13 under compression) without achieving full capacity. Therefore, having adequate
277 capacity in both working directions would be desirable, and the strength in the secondary
278 working direction can be treated as additional reinforcement to structures.

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

293 Also, the better ductility in those connectors (Table 2. CLT-C4-8, 10, 11 and 13) designed as
294 the alternatives to conventional hold-downs connections can promote rocking behaviour for
295 improved energy dissipation in CLT shear wall systems, which also satisfies the increasing
296 demands in uplift resistance and energy dissipation of large timber construction. To further

297 enhance the performance of recentering during the rocking of panels, some new connectors
298 (CLT-C4, 5, 7, 11) adopt special elements such as springs and reversible plastic extrusion to
299 achieve higher stiffness in unloading process with much plumper hysteresis curve.

300 3.3.2 Constructability

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

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

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

338 For further achieving better installation quality and efficiency with reduced onsite workload,
339 connectors CLT-C2, 15 and 16 are designed as prefabricated connectors. These connectors can
340 be accurately pre-assembled and installed onto the timber in controlled environment, which is
341 especially beneficial for those that require special tooling. For prefabricated connectors, it is

342 crucial to have suitable design for transport vehicles and be able to use as temporary support
343 system during panel lifting, such as the X-RAD connector (CLT-C2) (Figure 7(b)). It can be
344 treated as an additional constructional benefit, as traditional panel lifting involves hole drilling
345 and filling on panels for placing lift devices (Figure 7(a)). For CLT-C15 and 16 that adopting
346 interlocking technique, structural elements can be self-locked onsite with less effort, and can
347 be disassembled without the need of demolition, which means that the structures are adaptable to
348 potential environmental or functional changes.



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

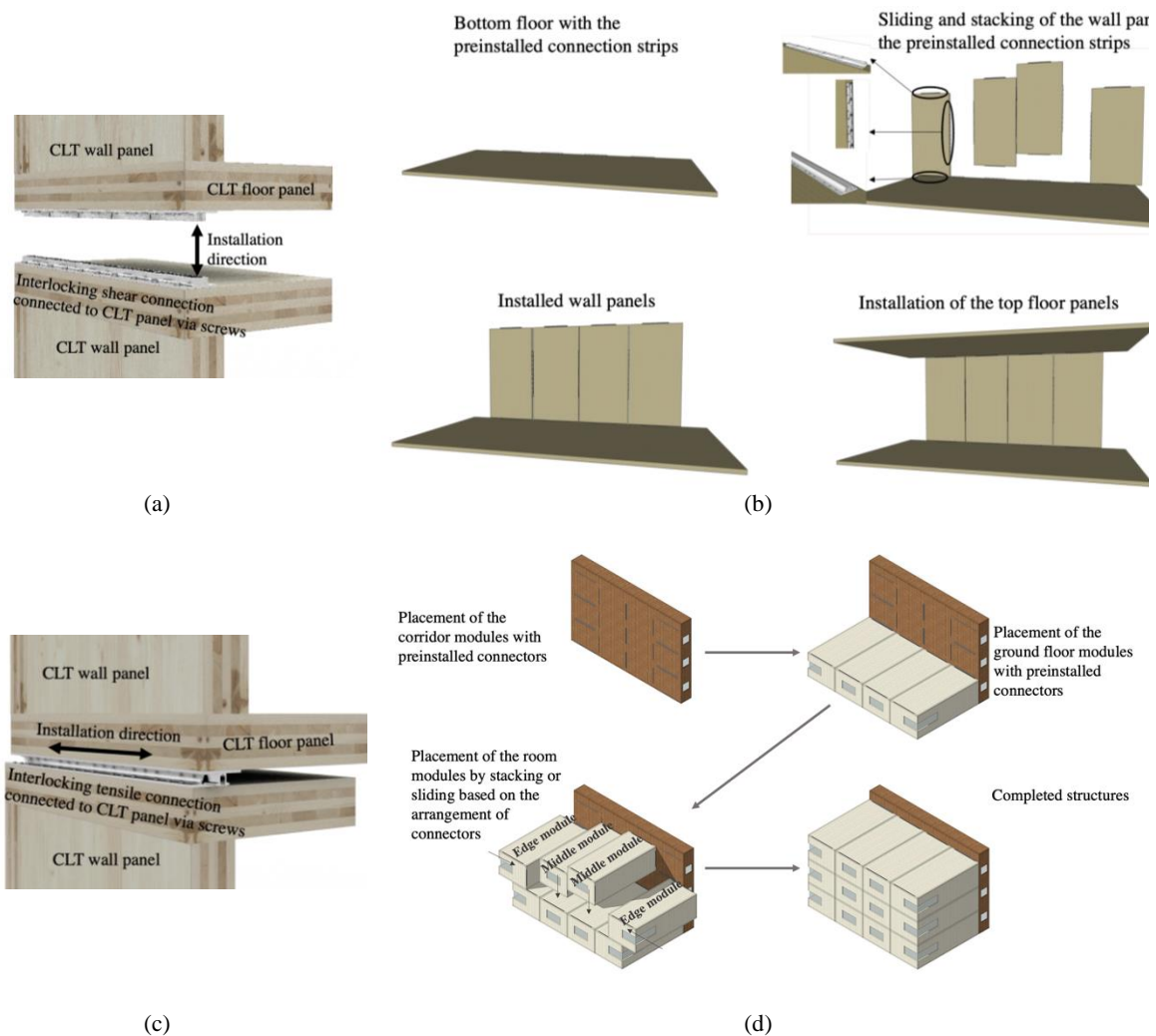
350 3.3.3 Manufacturability

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

370 separate manufacturing from a profiled and formed plate before being integrated with other
371 components.

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

380 4 Novel Proposed Demountable Connection System for Multi-storey CLT 381 Buildings with Damage Avoidance Capacity



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

384 Based on the connector performance discussions, a novel prefabricated connection system that
385 provides new connecting solutions for CLT modular (panelised & volumetric) construction by
386 interlocking was proposed [87] (Figure 8), aiming to achieve high-quality of CLT construction

387 with reduced time, labour and waste. With the interlocking techniques employed in this
388 connection system, structural elements can be easily and accurately assembled onsite by
389 stacking (Figure 8(a)) or sliding (Figure 8(c)) without the need of onsite screw fastening. The
390 sliding connector in the system can also act as a guiding device during assembly process,
391 contributing to accurate alignment of the structural elements.

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

403 Considering the higher dimensional accuracy for connector fitting and the high-cost of
404 moulding conventional manufacturing methods, the prototypes of this new connection were
405 3D printed integrally with 1mm tolerance for the fitting of connectors. The mass production of
406 this kind of complex 3D connector is potentially achievable with the conventional method but
407 a more complex process. For the male connector in shear connection, the cantilevering curving
408 element and the central support should be produced separately from 3D formed strips, and then
409 weld to the drilled base plate. For the tensile connectors that have continuous section along the
410 length, production could be easier from a special hot rolled section, and then sawn to length.

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

418 **5 Conclusions**

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

433 interest in high-rise CLT structures and the increasing concerns for their seismic performance,
434 construction efficiency and reusability.

435 **6 Future Perspectives**

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

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

463 The new generation of Eurocode 8—timber part— will introduce an updated list of timber-
464 based structural systems with clear definitions of dissipative and non-dissipative zones in
465 structures, which are needed for the newly-introduced capacity design rules and overstrength
466 factors for each type of structural system. CLT shear wall systems that are not present in the
467 current version, will be included as an independent timber structural system in the Standards
468 [44]. Further, a new procedure for application of non-linear static (pushover) analysis will be
469 provided [11]. In this context, rapid development of CLT panelised construction is foreseeable
470 in the near future, necessitating the proposal of connectors that can help achieve rapidly
471 deployable and reusable structures with adequate structural performance. Therefore, all three
472 aspects (structure, construction and manufacture) should be considered comprehensively in the
473 design of future CLT connectors, for achieving not only better efficiency and lower cost in
474 CLT construction, but also easier standardisation and commercialisation.

475 **Aknowledgements**

476 The authors would like to thank Mr Marco Pagliarin, Design Manager of Hybrid Structures
477 (William Hare), for his very valuable and continuous technical support. His experience and

478 expertise was instrumental to complete this review work. The authors would also like to thank
479 Mr Shay Eddy, Commercial and Technical Director of SC4, for his technical support with
480 regards to the fabrication of certain complex connection systems.

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