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A NOVEL LIMITED-DAMAGE 3D-PRINTED INTERLOCKING INTER-MODULE CONNECTION SYSTEM FOR CROSS LAMNINATED TIMBER (CLT) VOLUMETRIC STRUCTURES

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ABSTRACT: With both the sustainability of timber and efficiency of modular construction, Cross Laminated Timber (CLT) volumetric construction is considered a potential solution to the severe environmental impact of modern construction. Conventional connection systems of CLT modular structures (angle bracket, hold-down) are mainly designed for panelised and framed construction. Due to their nature, they require careful design while numerous damages have been reported not only on their steel components but also timber fibres. The UK's funded project 3DMBC (https://3dmbc.com) was established to explore new ways of connecting CLT volumetric modules, ideally being damage-free and self-locking onsite during installation, aiming to improve the efficiency, adaptability and reusability of CLT volumetric construction. Damage avoidance philosophy (controlling deformation and damage away from timber and the embedded fasteners) was a key objective in the design of a three-dimensional connector system. A novel inter-locking system was recently proposed, tested experimentally and validated via numerical analysis. The proposed connection design also showcases a new concept of module assembly in CLT volumetric construction with higher efficiency, flexibility and adaptability, meanwhile demonstrates the potential in mitigating (permanent) damage of timber, thus increase service life and enable disassembly and reuse operations. The study shows that the screw-free assembly was provided along with adequate stiffness, strength and ductility by the new connections, and no damage was observed in timber after testing, proving the feasibility of the new connection design.

KEYWORDS: CLT Volumetric Construction, Timber Panel, Interlocking Connection, Damage-controlled Connection

1 JNTRODUCTJON

Volumetric construction is a modern method of construction (MMC) that is widely applied in buildings with high repeatability such as schools, offices, residential and hotels. Forming buildings with prefabricated flat modules that contain preassembled building accessories such as cladding, internal finishes and MEP services, this construction method is highly efficient with reduced waste production, workspace requirements and reliance on on-site manual work [1-2]. Concrete and steel volumetric construction are now rapidly growing in densely populated regions due to their great efficiency, while the potential of Cross Laminated Timber (CLT) in volumetric construction is also being explored for its additional material sustainability.

In volumetric construction, the connections that joint the adjacent modules (inter-module connections) provide load transferring path and define the overall structural performance, while the installation of them is a widely acknowledged problem due to the limited space (access) between modules for installing and dismantling connections. In CLT volumetric structures, where CLT panels are used as the primary structural elements to form the enclosed flat modules, the space for inter-module connection installation can be even more limited (Figure 1). As a recently developed construction technology, specific connection products have not yet been proposed for CLT volumetric structures. Therefore, flat modules could be left disconnected in low-rise CLT volumetric buildings. Alternatively, conventional timber connections angle brackets and hold-down plates are commonly employed, while the drawbacks are evident, such as the connection accessibility requirements, intensive labour force requirement for installation, insufficient stiffness and strength as well as the unpredictable and unfavourable brittle failure modes [3-5]. To promote the development of multi-storey CLT volumetric structures, the investigations on inter-module connections are crucial.

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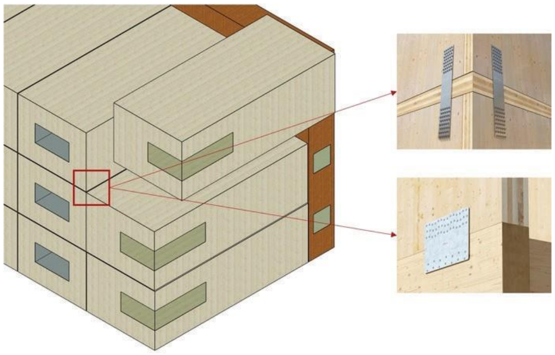

Figure 1: *Illustration of inter-module connection locations and the conventional hold-down (top) and bracket (bottom) that could be used in CLT volumetric structures*

A few bespoke connections (Figure 2) have been proposed recently for bespoke CLT volumetric projects to address the connection accessibility problem. These connections employ slot (groove) and ridge (tongue) designs that have matched shape, which can fit together without additional joining operations, such as adhesive or fasteners. In this way, the needs for access to install fasteners can be eliminated, and thus achieve a more efficient assembly and accurate positioning of modules. However, such connection designs require panel modifications for connection fitting, which may cause cross-sectional loss in structural elements and limit their applicability to other CLT volumetric structures [5]. A universal connection solution was still missing for the ease of design and construction for this structural system. Therefore, a novel interlocking connection system is developed within 3DMBC group, exploring convenient onsite joining methods with enhanced structural performance.

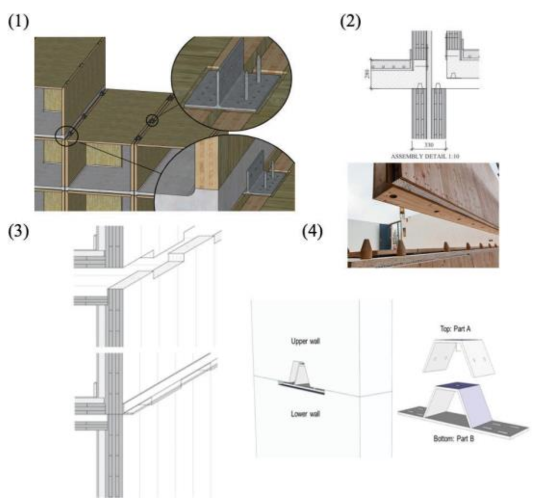

Figure 2: *Novel connection systems for specific CLT volumetric projects: (1) Jakarta Hotel [6]; (2) Heidelberg Student Accommodation [3]; (3) Moxy Modular Hotels (Marriott) [3]; (4) A novel system proposed by the University of British Columbia [7]*

2 CONNECTION DESIGN

2.1 INTERLOCKING CONNECTION SYSTEM

The proposed interlocking connection system consists of a tensile and a shear connection (Figure 3) [8]. Both are strip-like devices that formed by repetitive 3D unit elements. Both shear and tensile connections include two parts, named male connectors and female connectors, which self-lock after assembly, prohibiting module movement on their primary and secondary working directions (Figure 3).

Connection strips are fastened to CLT flat modules in the factories to achieve precise position, proper tightening, as well as improved project efficiency. Utilising this interlocking technique, modules with pre-installed connections can be accurately assembled on-site by simply sliding or stacking them (Figure 3) without additional onsite fastening. The pre-installed sliding connection units (Figure 4) also act as guiding devices to help locate the modules into the right positions and avoid potential construction errors from manual operations advancing the overall construction management tasks. Different from the conventional point-to-point connections, continuous reinforcement is formed along the edges of modules after guided assembly, which is suitable to CLT volumetric structures, where translational forces are important in structural design. The tensile connections provide vertical constraints at the edge of the structure and help resist uplifting. The shear connections provide horizontal constraints at the middle of the structure to resist lateral movement from wind and seismic load (Figure 5).

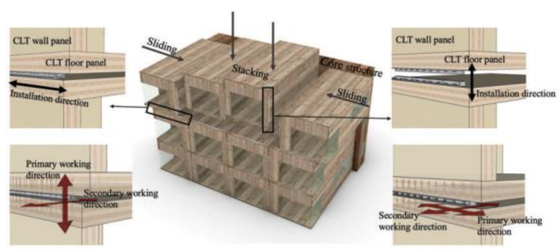

Figure 3: *Interlocking tensile (left) and shear (right) connection and CLT modules assembly (middle) with the pre-installed connections*

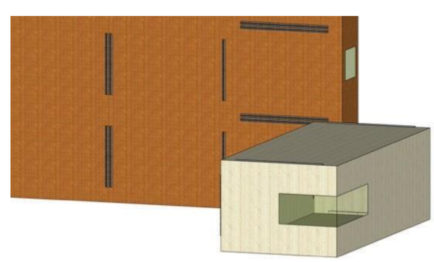

Figure 4: *The preinstalled connections that are used as guiding system to assist modules installation*

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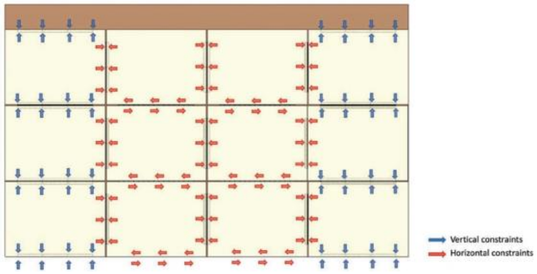

Figure 5: Continuous reinforcement along CLT modules edges provided by assembled connections [8J

2.2 CAPACITY DESIGN AND DAMAGE AVOIDANCE PffILOSOPffY

Beyond the advanced installing method, this connection system is also designed with the damage avoidance philosophy to limit the permanent damage in timber that is observed when using the conventional timber connections, hence enable reuse. In timber connection design, fastener deformation is treated as the primary source of ductility, and overstrength method (eq.1) is commonly applied to strengthen the brittle elements and ensure the activation of fastener deformation before the brittle failures happen in timber and metal plates (Figure 6), which is known as "strong plate-weak fastener" behaviour [ ].

$$y_{Rd} R_{d,ductile} \text{ '5 } R_{d,brittle} \quad (1)$$

The application of this method can, however, be problematic due to the inherent defects of timber as natural material, the unclear understanding of the interaction between timber and deformed fasteners, and the insufficient accuracy of currently available analytical models [5]. As the overstrength factor (y_{Rd}) is calculated by multiplying y_m (partial factor of material properties), y_{an} (ratio of estimated value to analytical value of the target strength) and y_{sc} (scattering of the target strength), the above reasons can lead to unrealistic values of these factors, and then lead to inappropriate overstrength factor, especially when specific overstrength factors are not provided for timber structures in EC8 [10][11]. Such overstrength factor may lead to undesirable failure modes, for example timber splitting and metal plate fracture [12][13]. In addition, the deformed fasteners can crush the timber and create permanent cavities around timber fibres, which lead to degraded stiffness and strength [ ], reducing structure's capacity in energy dissipation during seismic events as well as develop large residual displacements that reduce the structure's resistance to aftershocks [14-16]. Consequently, relying on fastener deformation for ductility is not ideal as it imposes difficulties to the design prediction and repair of timber connections (for reuse), and ultimately reduces seismic resistance.

Interlocking connection design benefits from utilising the metal connectors which are treated as the ductile elements (Figure 6). Shifting the ductility source from the timber-fastener interaction to the metal connector deformation (not the screws) can make connection properties dependent on the stable metal material properties, instead of the timber grain orientations and conditions, reducing the risk of brittle failures and providing controlled and easily predicted connection performance.

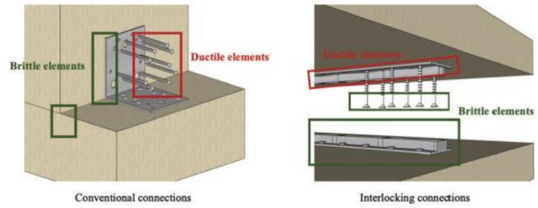

Figure 6: Capacity design of conventional plate connections (left) and novel interlocking connections with damage avoidance philosophy (right)

2.3 ADAPTABLE CLT VOLUMETRIC BUILDINGS

In addition, the special functionalities of this proposed connection system, such as the interlocking and damage avoidance effect, can be used for adaptable structures that possess the ability to address changes during construction and meet different functionality requirements during service life, such as partial disposal, change of use, re-usability and extension of buildings, for coping with future building obsolescence and redundancy [17]. The adaptability of such structures is attributed to the design of connections. The below criteria are recognised as crucial factors for developing adaptable connections [17][18]:

Demountability: Adaptable connections should be demountable to comply with the potential modifications in building design, and allow for easy dismantlement without demolition and damage of the structural members at the end-of-service life. The undamaged structural components or even the entire flat modules can be directly reused or recycle at their highest extent, improving the resources scarcity and environmental degradation brought by the building-related activities.

Standardisation: Adaptable connections should be standardised, hence allow for general application without modifications required, facilitating design simplifications.

Size, shape and position tolerance: Adaptable connections should be project-independent products that can fit with structural elements (here CLT panels and volumetrics) with varied dimensions at different positions within the structure. This refers to the connections that need no modification requirements for the fitting of connections.

Individual removability: The structural elements with adaptable connections should be removable without interfering with other elements, in response to external factors.

Direct usability: Adaptable connections should be operational immediately after installation without further modifications, such as fixing, adjusting and controlling to speed up the construction process, eliminate the onsite manual work and ensure safety.

Based on the above criteria, the proposed connections are highly adaptable, as they are demountable, standardised, flexible and can provide immediate reinforcement after self-locking.

3 NUMERICAL AND EXPERIMENTAL ANALYSIS

3.1 EXPERIMENT PREPARATION

To evaluate the realistic performance of the proposed connection design, monotonic and cyclic push-out and pull-out tests were performed on the connection specimens, using loading protocol as prescribed in EN12512 [19]. The unit elements of each connection were tested; first screwed to 5-ply GL24h CLT panels and then assembled together without any fastener (Figure 7). Six LBS7100 and four HBSP12120 from Rothoblaas were used in each of the tensile and shear unit connectors to achieve higher timber-fasteners connection capacity than the estimated interlocking connector capacity, ensuring the successful attainment of damage avoidance effect.

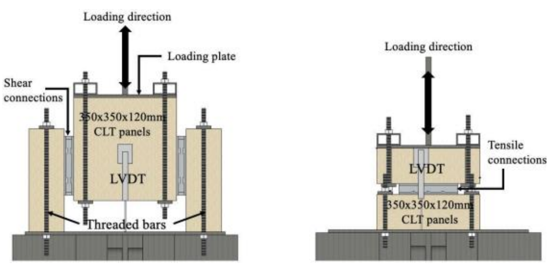

Figure 7: *Experimental set-ups of the push-out (left) and pull-out test (right) on shear and tensile connectors*

Due to the complex geometric design (cantilevering and curvy features) of interlocking connectors and the limited number of specimens needed for testing, 3D printing was used as the manufacturing method to produce the testing specimens using SS420/BR (Figure 8), considering its manufacruting freedom without requesting moulding [20]. All specimens were printed with satisfying accuracy, and both male and female connectors fitted well with 1mm printing tolerance. To determine the actual properties of connection material to be used in the numerical validation, coupons tests were conducted on the specimens from the undeformed female connectors, which confirmed the modulus of elasticity E=130GPa, yield strength a_y =304MPa, ultimate strength a_u=638MPa and ultimate strain of E_u=5.9 % of the 3D printed steel.

Figure 8: *3D printed specimens of shear (top) and tensile (bottom) connection units*

3.2 EXPERIMENTAL RESULTS

As demonstrated in Figures 5 and 6, the deformation of both connections was localised on part of the connections (the male connectors). After removing the screws, only slight wearing can be observed around the screw holes on the connector plates without visual deformation in the screws and timber, indicating the successful attainment of damage avoidance effect on the structural material.

The primary deformation mode in the shear connection was buckling of the middle of steel plate on both sides. Also, slight close-up at the end suckens can be observed (Figure 9). The primary deformation mode in the tensile connection was bending of the L-shaped elements in the male connector (Figure 10). The female connectors and screws of both connections remained mostly undeformed; only very slight open-up in the bearing walls and slight bending in the bottom plate in the tensile female connector were recorded at the end of testing. Thus, it can be concluded that the deformation of the interlocking connections was well controlled within both male connectors.

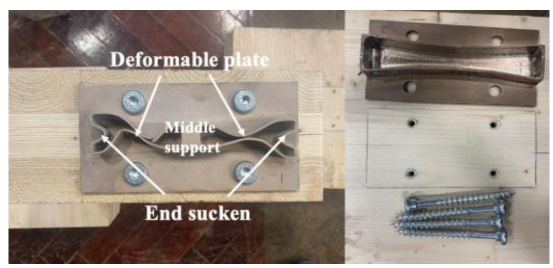

Figure 9: *The tested shear connection specimens and screw removal*

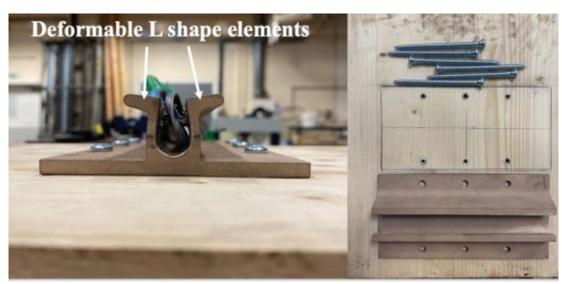

Figure JO: *The tested tensile connection specimens and screw removal*

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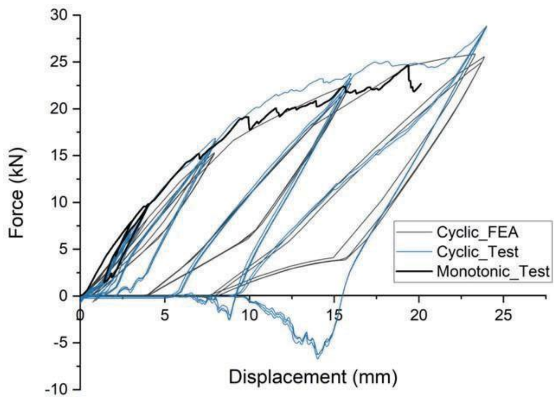


Figure 11: *Force-displacement curve of the tensile connections [8}*

Figure 11 demonstrates the cyclic performance of the tensile connections, and shows adequate strength, stiffness and ductility. The stiffness and maximum strength in the first cycle of each loading step during the cyclic test were well consistent with the monotonic tests, indicating that the plastic deformation in the steel male connector does not affect the maximum capacity in the subsequent loading. On the contrary, conventional timber connections normally demonstrate reduced maximum capacity in cyclic test in comparison to the monotonic test due to the damage of timber in the vicinity of deformed fasteners. However, the plastic deformation causing a gap between the male and female connectors, consequently sliding of the male connector with no reaction force can be identified at the initial phase of each loading cycle.

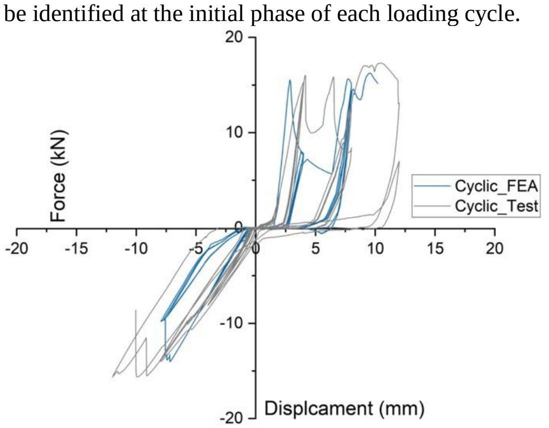


Figure 12: *Force-displacement curve of the shear connection [8}*

As depicted in Figure 12, the shear connections demonstrated higher stiffness but reduced ductility than the tensile connections in the cyclic testing. Three sudden resistance reductions can be identified at the displacement of 4mm, 6.5mm and -8mm, respectively, corresponding to the three buckling points observed in the failed shear specimens. After the buckling, the connection strength continued to develop in the deformed steel band and the end sunken in the male connector, leading to the plump hysteresis loop at large displacement until the breakage happened at the buckling point (Figure 9). Therefore, buckling at the middle of the deformable plate and bending at the sunken design at the end of the steel band are the two major deformation modes identified in the shear connections, and the buckling locations were relatively consistent among all the specimens.

3.3 NUMERICAL ANALYSIS

The numerical models of all experimental models were developed for validation (Figure 13). CLT panels were modelled with an orthotropic elastoplastic material; the properties are summarised in Table 1.

Table 1: *Material properties adopted for CLT panel model (spruce) [21}*

Elastic modulus (MPa)					
11		*22*		*33*	
11000		3 0		3 0	
Poisson's ratio					
v_{12}		v_{13}		v_{23}	
0.48		0.48		0.22	
Shear modulus (MPa)					
G_{12}		G_{13}		G_{23}	
690		690		50	
Parallel-to-grain (MPa)		Perpendicular-to-grain (MPa)		Shear strength (MPa)	
f_{e11}	f_{t11}	f_{e22}	f_{t22}	f_v	$f_{v,roll}$
36	24	4.3	0.	6.9	0.5

Grade-300PLUS steel (a_y = 320MPa and a_u =440MPa) and Grade 10.9 carbon steel ($a_y = a_u$ =940.3MPa) [22] were used for steel fixture devices and screws, respectively, and the material properties of SS420/BR that determined from coupon test were used for the connectors. Different published modelling methods were employed to simulate the screw-timber interactions of screw working in different directions. To model the pull-out behaviours of LBS 100 of the interlocking tensile connectors that rely heavily on the threaded part of screws, an efficient approach presented in the literature was adopted [23] [24]. This method introduces a fictitious layer of 'soft material' that wraps the shank of screws as the simplified threaded part (Figure 13). The 'soft material' is assumed to be perfectly elastic with the same capacity as CLT (Table 1) except for the radial modules (E_{33}). A reduced value of 50MPa was used instead to simulate the weakened compressive capacity of timber around the threads. To model the bending capacity of HBSP12120, only the screws shank was modelled (Figure 13) [25], as it is the primary part that defines the bending behaviours of screws. For all other interfaces, the surface-to-surface discretisation method was adopted with the "Hard Contact" option in the normal direction, and the "penalty friction formulation" option in the tangential direction. The good agreement between the experimental results and numerical output in terms of the maximum strength, initial and reduced stiffness of each loading cycle, as well as the deformation modes, proves the feasibility of the adopted modelling methods for both interlocking connections (Figure 11&12).

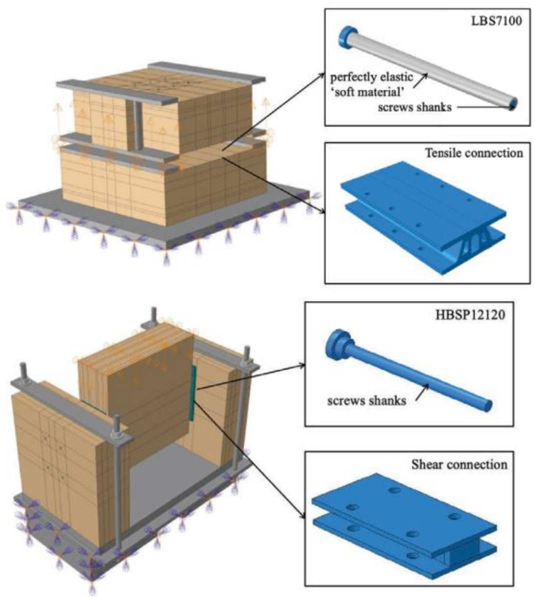
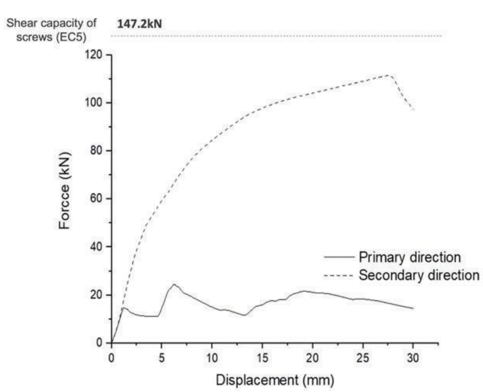


Figure 13: *FE models for tensile connection (top) and shear connection (bottom) validation*

After the validation, complimentary FE analyses were performed to further investigate the performance of the connectors with more common grade of steel S235 (E=21OGPa, a_y =235MPa and a_u =36OMPa) and better understand the deformation progression in the connectors, which are not visual during the testing due to the enclosed connection design.

Both connection models were tested numerically under primary and secondary directions (Figure 3), confirming the adequate stiffness and ductility in both translational directions. In the primary working direction, the damage avoidance effect was attained in both connections with most deformation being localised in male connectors. Negligible strain can be observed in the fasteners and timber. In the secondary working direction, both connections behaved more like conventional connections and all elements deformed including male connectors, female connectors and screws (Figure 14&15).



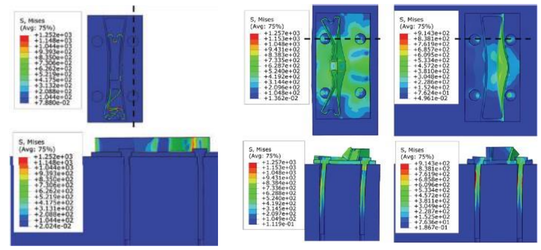


Figure 14: *Force and displacement curve of shear connection with S235 and connection deformation on primary (bottom left) and secondary directions (bottom right) under 15mm displacement [8J*

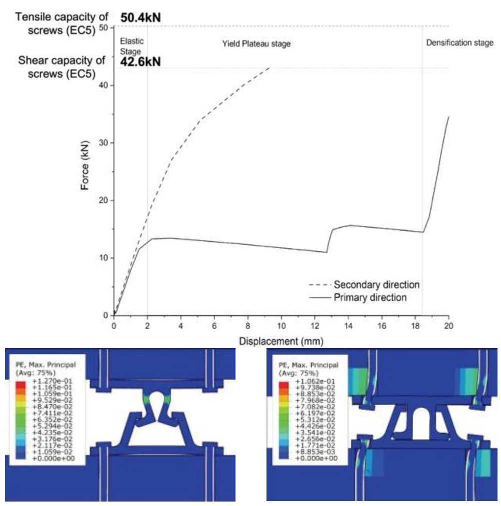


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Figure 15: *Force and displacement curve of tensile connection with S235 and connection deformation on primary (bottom left) and secondary directions (bottom right) under 15mm displacement [8J*

4 CONCLUSIONS

This research proposed a novel connection system for CLT volumetric construction, as part of the modern methods of construction (MMC), to enable safe and efficient assembly as well as fast erection and dismantling. Without the need of panel modifications, the interlocking connectors can be easily applied to different projects with varied mechanical performance requirements and modules' specifications by simply adjusting the connector strip length. The adoption of unit element design also allows for easy standardisation, as the connections can be directly applied in construction without changes in geometries. Therefore, the proposed connection system can improve the constructability, adaptability and reusability of CLT volumetric structures. The conducted experimental and numerical analyses proved that the proposed connections have adequate translational strength, stiffness and ductility in both primary and secondary directions. The application of plug-and-play connections can enable automation/robotic construction methodologies with accuracy and speed,

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resulting to less resources consumption and waste production, thus reduced environmental impact and destruction to the surrounding area. Though construction operations need to be somewhat altered for the sliding operations, this interlocking connection system can be a promising solution to efficient and adaptable multi-storey CLT volumetric construction.

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