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Experimental assessment of a novel steel tube connector in cross-laminated timber

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ABSTRACT

This paper summarises experimental investigations conducted on a novel connector assembly consisting of hollow steel tubes placed inside cross-laminated timber panels. The criteria that drove the connector development were: (i) easy to manufacture and install; (ii) high capacity, stiffness, and ductility; and (iii) neglectable damage to the timber. A total of 24 test assemblies with varying steel tube diameters (ranging from two to four inch) were tested using quasi-static monotonic and reversed cyclic loading. The results demonstrated that – when using an appropriate connection layout – the desired ductile steel yielding failure mechanism was initiated and wood crushing of any form was avoided. The tested configurations reached load-carrying capacities up to 58 kN, exhibited high stiffness (> 15 kN/mm), and were classified as moderately to highly ductile. The research presented herein demonstrated that this novel connection assembly for cross-laminated timber panels can be utilized in seismic regions.

1. Introduction

1.1. Tall-timber structures

Structures made primarily using timber are significantly lighter than those using concrete. This lower weight advantageously leads to reduced seismic demand. While light-frame wood construction has been very successful in the North American low-rise residential market [1], the use of timber and engineered wood products (EWPs) in mid-rise and high-rise applications has been limited by restrictions such as the height limitation imposed by buildings codes [2].

The structural use of mass-timber EWPs such as cross-laminated timber (CLT), however, has gained popularity in recent years and can contribute to overcome these limitations [3]. CLT is made from several layers of boards, stacked crosswise at 90 degree angles and glued together on their wide faces [4]. With its dimensional stability, strength, and stiffness, CLT is a viable alternative to concrete in many applications, including vertical and lateral load resisting systems of large structures. The fabrication of CLT in North America is regulated by ANSI/APA PRG 320 [5]. As CLT panels behave as rigid bodies, when compared to light-frame wood shear walls, the desired ductility for seismic design must be obtained from the connections [6,7]. Canadian and US versions of CLT handbooks [8,9] contributed to the increasing popularity of CLT in the North American construction market and development and provisions for CLT were included in NDS [10] and the 2016 supplement of the Canadian Wood Engineering Design standard CSA O86 [11].

CLT has propelled wood construction to new heights all over the world; examples are the Stadthaus in London (8-storeys, 2009) and the Forté in Melbourne (10-storey, 2012). Another option for structural applications of EWPs beyond low-rise construction is the use of timber-based hybrid structural systems. Combining timber and steel, e.g. by using steel moment resisting frames with CLT infill walls [2,12–14] or the so-called FFTT system which is based on steel beams embedded in CLT panels [15,16] are two prominent examples. Amongst other findings, these studies have identified the importance of stiff but ductile connection detailing to fulfil seismic performance requirements. Combining timber and concrete enabled the construction of the 18 storey Brooks Commons building in Vancouver [17,18].

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1.2. Connection ductility

Ductility in structures ensures that failure occurs after large deformations, allows for stress redistribution and energy dissipation under seismic loading, and increases structural robustness [19]. Timber is a renewable constructing material with advantageous strength to weight ratio; however, due to its brittle failure modes in shear parallel to the grain and tension, timber structural members are not able to develop ductile failure mechanisms without careful joint detailing [19]. As a consequence, structures assembled of mass timber products (i.e. CLT) rely on the connections for ductility. CLT wall assemblies have been demonstrated to provide adequate seismic performance when ductile fasteners are used [20–22].

The desire to quantify structural ductility makes it necessary to quantify connection ductility numerically [23]. Jorissen et al. [19] compared different approaches and identified the conversion of the experimental load-displacement curve into a linear elastic-plastic curve as the key for any applicable method. To be able to compare connections and assemblies focusing on ductility versus brittle, Smith et al. [24] proposed a classification scale based on the ductility ratio D of ultimate displacement, Δ_{ult}, to yield displacement, Δ_y, as brittle ($\mu \leq 2$), low ductility ($2 \leq \mu \leq 4$), moderate ductility ($4 \leq \mu \leq 6$), and high ductility ($\mu > 6$).

Bruehl et al. [25] evaluated various connectors ranging from split rings, unreinforced dowel connectors to punched metal plate fasteners and concluded that the majority of connectors reach low to moderate ductility (according to the classification of Smith et al. [24]). One approach utilized to increase the ductility is the use of connectors which can easily deform without damaging the surrounding wood; e.g. Araki et al. [26] used steel knife plates manufactured with slotted holes to reduce the commonly observed pinching behaviour and to provide higher ductility.

1.3. Connections for CLT panels

Since CLT panels are commonly assumed to act as rigid bodies when loaded in shear in-plane in lateral load resisting systems, the required ductility needs to be provided by the connections [27,28]. Much research has focused on the connections between individual panels e.g. [6,7,22,29,30]. but also the connections from panel to floors and foundations have to be considered [31]. Dowel-type fasteners, e.g. nails, bolts, drift pins, wood screws and Rivets made of steel with a solid cross-section are commonly used connectors for timber structures [8,9]. A number of studies investigated CLT connections and CLT assemblies under cyclic load and confirmed that the connectors are the critical element defining capacity and ductility [22,27,32–34].

Recent research to expand the knowledge towards effective lateral system in CLT focused on developing analytical models to estimate the resistance of multi-panel CLT shear walls [35], displacement-based approximations of connections' behaviour to beyond the peak load [36], hysteretic models to capture the performance of panel joints [37,38], non-linear procedures for the seismic design of CLT systems [39], analytical models to determine the elastic stiffness and strength of multi-panel CLT shearwalls [40] and numerical models to represent the connections' hysteresis behaviour under cyclic loading [41]. As a consequence of this research 'and the increasing interest in CLT construction has resulted in multiple countries adopting provisions for CLT into their engineering design standards' and 'designing and building CLT structures, also in earthquake-prone regions is no longer a domain for early adopters, but is becoming a part of regular timber engineering practice' [42].

Steel brackets attached with dowel-type fasteners are the most common method to create a connection between walls and floors in CLT structures. Steel bracket attached with dowel-type fasteners were originally used for post and beam structures, mainly wood to wood connections. With the development of CLT, these steel bracket connection were adapted into mass timber structures to secure and fasten solid shear walls to the CLT floors but also to the foundation [8]. Brackets applied to prevent uplift of the ends of a wall are called hold-downs. Commercially available traditional bracket hold-downs can provide the required strength (around 52 kN) for low-rise wood buildings but are usually not suited for tall mass-timber structures, where lateral loads are significantly larger. Schneider et al. [12] showed that bracket connections provide little stiffness and low ductility (usually less than 5 kN/mm and ductility values μ less than 3.8) under reversed cyclic loading, tend to buckle and can cause significant damage to CLT panels, which would hamper post-earthquake restoration. Since the hold-down performance, and as a consequence the structural performance, depends on the failure mechanisms, there is a need for hold-downs that provide ductility and stiffness, avoid damage to the wooden members in addition to meeting the strength target.

Latour et al. [28] proposed a symmetrical bracket design with stubs welded to steel L-shape brackets and achieved a significant improvement in energy dissipation. This set-up is not suitable for exterior walls as the second bracket cannot be installed. Another potential solution is to use glued-in perforated steel plates known under the tradename HSK™ system [43–45]. The adhesive bond provides strength and stiffness and the perforations introduced in the steel plates allow for the formation of a ductile steel failure. Amongst the drawbacks of that system are the high requirements on workmanship and that it is not easily possible to replace damaged parts.

1.4. Existing steel tube connectors

One approach to increase ductility and energy dissipation in laterally loaded joints is to replace solid dowel-type fasteners with steel tubes [46]. The tube is longer than the total thickness of the assembly and fit into oversized holes. To achieve a tight fit, the ends of the tube are expanded over washers attached on the outside. To prevent splitting when the tube diameter is increased, densified veneer plywood is glued on the timber members as reinforcement. The ductility in tube fastener connections is controlled by the ratio of wall thickness to tube diameter (cross-section buckling) and the ratio of fastener length to diameter (fastener slenderness).

The connection was tested in tension, four-point bending, and in a set-up as knee joint and exhibited high strength, stiffness and ductility under reversed cyclic loading [47]. Unprecedented energy dissipation capabilities were recorded with equivalent viscous damping ratios up to 0.35 [48]. By applying tubes instead of pins in a portal frame, the number of fasteners was reduced from sixteen 16 mm dowels to four 35 mm tubes while increasing the capacity three-fold. The large plastic range after yielding provided ductility ratios larger than 8, placing the connection in the range of high ductility. Several structures were built with one of these alternative joints [49]. More recent research on the DVW tube joint focused on its application in moment transferring connection [50,51]. The rotational stiffness and possible failure modes were analyzed using experimental and numerical approaches.

Guan and Rodd [52] also used a steel tube combined with the concept of densified veneer reinforcement, but they used resin injection to fill up the voids between the oversized hole and the steel tube which was not expanded in diameter. However, the quality control during production appeared to be a drawback of this method. Another tube-type connector was developed and investigated by Murty et al. [53,54] who used three sizes of small diameter steel tube fasteners (6.4 mm, 9.5 mm and 12.7 mm). The tubes were inserted in tight-fitting holes in conjunction with slotted-in steel plates to create tension connections. The tubes are driven perpendicular to the axes of wood members and pass through both those members and steel link elements. Tests were conducted under quasi-static loads with multiple-fastener arrangements obeying spacing rules of bolted connections in sawn softwood lumber. The response was ductile with failure occurring mainly in the fasteners and the Johansen yield model (EYM) provided good strength

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