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FEASIBILITY OF CROSS-LAMINATED SECONDARY TIMBER

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ABSTRACT

The construction industry creates significant volumes of waste timber, much of which has residual quality and value that dissipates in conventional waste management. This research explored the novel concept of reusing secondary timber as feedstock for 'cross-laminated secondary timber' (CLST) through a review of the literature. If CLST can replace conventional cross-laminated timber (CLT), structural steel and reinforced concrete in some applications, this constitutes upcycling to displace materials with greater environmental impacts. The paper introduces the rationale for such an intervention and assesses its feasibility. It concludes with open research questions to advance the concept towards commercial application.

Keywords: Cross-laminated secondary timber, waste management

INTRODUCTION

The timber in existing building stocks represents a significant stockpile, with estimates in the range of 2.4-4.0 tonnes per capita (Höglmeier et al. 2013; Kleemann et al. 2017); in some countries, it is a greater quantity than the stock in forests managed for harvesting (Müller 2006). Upon building demolition, the cascading principles that contribute to a circular economy (Stahel 1982; Ellen MacArthur Foundation 2013) dictate that the resulting timber arisings should be reused (BioRegional 2006; Bergman et al. 2013; Bergman et al. 2010), with minimised processing and loss of performance, to maximise their useful lifespan (Sirkin & ten Houten 1994; Fraanje 1997) and maintain storage of sequestered carbon (Husgafvel et al. 2017). The greatest opportunities for long-term use in the built environment lie in structural applications, as structural components have the longest lifespan (Brand 1994).

Direct reuse of timber is often impractical, for reasons including the fact that buildings are rarely designed with deconstruction and reclamation in mind (Durmišević 2015; Sassi 2004). Conventional recycling therefore involves chipping timber and downcycling it into products such as particleboard and animal bedding, which achieves reliable supply and fitness for purpose, but with a considerable loss of performance and value; the recycled products are relatively short-lived and represent the final material use before incineration or disposal. Any reclaimed whole members that reach salvage yards tend towards shorter usable lengths and smaller effective sections. They may retain their mechanical characteristics (Falk et al. 2008), but are typically sold 'as seen' and without warranties, failing to provide certainty over supply and fitness for purpose, which restricts demand from mainstream construction (Rose & Stegemann 2018b).

Improving the supply of secondary structural timber to the construction industry could mitigate future supply risks, including increased competition for the use of land (Allwood et al. 2011), price rises if timber supply is curtailed while demand rises (Defra 2010), and future planning requirements, contractual obligations and regulation of whole-life greenhouse gas (GHG) emissions (BIS 2010; Giesekam et al. 2014; Steele et al. 2015; Giesekam et al. 2015; Papakosta & Sturgis 2017). However, to capitalise on residual timber properties, there is a need for new processes that upcycle secondary timber, and recertify the resulting products to meet mainstream construction industry requirements (Rose & Stegemann 2018b; Rose & Stegemann 2018a). This research proposes to exploit secondary timber as a feedstock for cross-laminated secondary timber (CLST).

REVIEW

The use of CLT has grown considerably in recent years; its advantages are well understood in academia, and it is gaining acceptance across industry (Jones et al. 2016). Production capacity is rising, with Austria and Germany reporting 20% year on year increases (Hairstans 2016) and double-digit annual growth rates expected over the next decade (Brandner et al. 2016). Replacement of primary feedstock for CLT with secondary timber holds promise: crosswise lamination of multiple lamellae minimises the detrimental influence of natural defects in individual boards of primary timber (Concu et al. 2017; Taylor 2013), and the detrimental influence of manmade defects arising from the previous use of secondary timber would similarly be minimised. Laminated timber products also provide an opportunity to control the location of higher grade timber in the engineered section to maximise structural benefit. Glulam standard BS EN 14080:2013 (BSI 2014a) already endorses production of structurally efficient sections from variable quality wood, with stiffer and stronger timber at the extremities of the section, and weaker timber at the neutral axis, the function of the latter being primarily to increase the second moment of inertia by separating the outer lamellae. Similarly, in typical current European practice based on Mechanically Jointed Beams Theory (MJBT, also known as the Gamma Method; Eurocode 5 (BSI 2014b, Christovasilis et al. 2016)), strength and stiffness calculations for CLT products largely disregard the contributions of the lamellae crosswise to the load application, e.g., horizontally-oriented lamellae in a vertical compression element (wall), or lamellae oriented orthogonally to the span in a bending element (floor) (Milner 2017).

Mining the existing timber stocks in cities could enable their greater self-sufficiency in managing their construction and demolition waste (e.g., GLA 2017) and help to localise CLT supply chains (Brunner 2011). For example, in the UK, which has little forest cover (12% of total land area, compared to 47% in Austria; FAO 2011), CLT is imported from Austria and other parts of Europe. On the other hand, the timber fraction of UK construction and demolition waste is estimated at 0.9-5.0 Mtpa, of which something in the region of 55-75% is solid wood, and a growing proportion of this waste is exported for energy generation in Europe (Pöyry 2009; Tolvik 2011; WRAP 2011; Defra 2012; Defra 2016). Using secondary timber stocks would contribute to policy goals: fostering a more circular economy with new employment in manufacturing (Gavron et al. 2017) and reindustrialisation of the European (and British) economy (European Commission 2012; European Commission 2014; European Commission 2015), and production of net negative- or low-carbon building components. The lifespan at high value of timber in a circular economy could be further extended by designing the CLST panels for deconstruction and reuse (Campbell 2018). If CLST can replace conventional CLT, structural steel and reinforced concrete in some applications, this is enhancement of the performance of waste: upcycling into a new closed loop.

Timber for different structural uses is graded based on its tree species, origin, strength reducing characteristics and geometrical characteristics (BSI 2016a; BSI 2016b; BSI 2017; BSI 2013). CLT is typically made from Norway spruce and common strength classes are C24, C18 and C16 (Brandner 2013). There is growing interest in use of locally abundant, under-utilised timber resources for which there are no established structural properties as CLT feedstock (Espinoza & Buehlmann 2018). Examples include the use of Sitka spruce (Crawford et al. 2014; Crawford et al. 2015; Sikora et al. 2016), Italian marine pine (Fragiacomo et al. 2015; Concu et al. 2017), European beech (Franke 2016; Aicher, Christian, et al. 2016; Aicher, Hirsch, et al. 2016), large-leaf beech (Essoua Essoua & Blanchet 2017), Southern pine (Hindman & Bouldin 2015; Sharifnia & Hindman 2017), hybrid poplar (Kramer et al. 2014), tulipwood (Mohamadzadeh & Hindman 2015; Thomas & Buehlmann 2017), poplar (Wang et al. 2014), eucalyptus (Liao et al. 2017) and Japanese cedar (Okabe et al. 2014). Investment in a new CLT and glulam plant in Alabama that exploits local Southern pine (Vloysky 2017) suggests that alternative feedstocks to those used in typical European CLT production can become economically viable if abundant local materials are used.

Although European Standard BS EN 16351:2015 (BSI 2015) does not allow used wood in CLT as a precaution, it has previously been suggested that secondary timber could be used to produce engineered wood products (Geldermans 2009; Sakaguchi 2014; Bergsagel 2016; Kremer & Symmons 2015). Researchers at the University of Utah with industry partners investigated the manufacture of interlocking ‘ICLT’ without adhesives or fasteners (Smith 2011). Their work considered sourcing the timber from existing buildings, but they chose instead to explore pilot manufacture and mechanical testing of ICLT using standing trees that have been affected by pine bark beetle (Wilson 2012). The present authors conducted preliminary research to explore the technical feasibility of using secondary timber to produce CLST (Rose et al. 2018).

For certifiable mass production of CLT, consistency of supply of raw materials and raw material quality is crucial. However, as a natural material, the properties of primary timber are variable: the extent of variability can be greater between two members sawn from the same tree than from two different species (Ridley-Ellis et al. 2016). Strength classes are based on characteristic properties and individual members may well fall short of the characteristic values; BS EN 16351:2015 (BSI 2015) makes allowance for this by permitting deviation of up to 35% from the declared strength parallel to the grain in 10% of boards in any given lamella. Despite this acceptance of uncertainty, achieving equivalent levels of confidence in secondary timber requires an understanding of how ageing and use affect both its characteristics and the variability of these characteristics.

Natural ageing results from biological, chemical, mechanical, thermal, water and other weathering effects (Nilsson & Rowell 2012). When ‘stored’ in use in a building’s structure, timber is typically protected from weathering, and moisture content should be below 20%, such that it is largely protected from biological degradation. Softwoods, which make up the majority of secondary timber, may benefit from increasing cellulose crystallisation for the first few hundred years of life (Kohara & Okamoto 1955; Nakao et al. 1989), leading to increases in density, hardness, dimensional stability, tensile strength, and Young’s modulus (the ratio of elastic stress and corresponding strain, also known as the Modulus of Elasticity, MOE) (Lionetto et al. 2012). However, two recent review papers (Cavalli et al. 2016; Kránitz et al. 2016) found that there has been no overall consensus on the effect of natural ageing on strength, stiffness and other physical properties of various species of timber. Ageing during use inside a building, e.g., through fluctuations in temperature, humidity or the effects of ultraviolet radiation, may affect timber’s mechanical properties, but findings are often ambiguous, and could result from other factors (Froidevaux & Navi 2013; Sonderegger et al. 2015; Kránitz et al. 2016; Holzer et al. 1989; Attar-Hassan 1976). Surface characteristics of timber change with time (Kránitz et al. 2016) and, for use in CLST, the faces of secondary boards would need to be planed to provide good surfaces for durable bonding, as well as to produce consistent board thicknesses.

It is well established that timber can carry substantially greater loads over a short period of time than for long durations of loading; Fridley et al. (1995) present a history of research investigating this ‘duration of load’ (DOL) effect going back to the eighteenth century. Much of the research into creep-rupture, the failure mode attributed to the DOL effect, uses results of impact testing and short- and long-term loading to estimate expected times until failure for loading at a given stress ratio (i.e., a proportion of assumed short-term strength; Hoffmeyer 2003). Higher moisture content is known to produce a shorter time to failure, while cyclical changes in moisture content further accelerate creep and reduce time to creep-failure

(Hoffmeyer & Sørensen 2007). Since at least the nineteenth century, it has been understood that timber structures intended for long life should be designed with a safety factor such that only one-half to two-thirds of the material's short-term strength is relied upon (Fridley et al. 1995). The effects of DOL and moisture content have long been incorporated into design standards for timber building structures; e.g., Eurocode 5 (BSI 2014b) sets out strength modification factors ranging from 0.50 for ‘permanent’ loading (>10 years) in climatic conditions that may lead to moisture content >20%; 0.60 for permanent loading where moisture content is <20%; to 1.10 for instantaneous loading for moisture content <20%.

It is important to note that DOL effects are particularly significant in the short- and medium-terms. In the long-term, a difference of double or triple the anticipated load duration affects the load capacity by only a few percentage points (Hoffmeyer 2003). The major reduction in load capacity predicted by DOL modelling occurs over the first few years – and certainly within a period of time in the order of a normal building lifespan of, say, 50 years – with further degradation beyond that time found to be minimal in most DOL research (Wood 1960; Dinwoodie 1975; Hoffmeyer 2003). This seems to bear out the observation that many very old timber structures remain standing. Arguably, therefore, secondary use of timber simply extends its anticipated load duration and could be expected to produce only minor reduction in load capacity, compared to the strength modification factors taken into account in its first use.

Nevertheless, uncertainties remain. Timber that has been exposed to high and especially to fluctuating moisture content, for instance through external use, is likely to have experienced significant strength loss and is unlikely to be suitable for reuse in a structural application. Evidence suggests that large solid timber members used internally do not undergo large moisture fluctuations (Holzer et al. 1989), but this may not always hold true. Repeated loading may have caused fatigue damage to have accumulated in secondary timber that cannot be perceived (Hoffmeyer 2003). The stress ratio at which loss of strength becomes permanent appears to vary widely depending on timber species and testing conditions, with an average perhaps in the region of 0.40 (Dinwoodie 1975). On the other hand, different conclusions arise from the extensive work by the USDA Forest Products Laboratory on the structural properties and grading of North American secondary timber (Falk et al. 2008; Falk et al. 1990; Falk et al. 2012; Falk et al. 2000; Falk 2002; Falk, Green, et al. 1999; Falk et al. 2003; Falk & Green 1999; Janowiak et al. 2014; Falk, DeVisser, et al. 1999; Falk 1999; Williams et al. 2000; Fridley et al. 1996). They acknowledge that ‘overloading’ can degrade timber, but their testing indicates that MOE and bending strength appear to be unaffected by ageing and previous load history (Falk et al. 2008), and that reductions in strength arise from observable macro-level defects, such as nail holes, rather than from the molecular structure of aged timber. They therefore recommend regrading before reuse but conclude that wholesale visual downgrading is currently too conservative. The group consider some reuse options for different species of reclaimed timber (Janowiak et al. 2007; Janowiak et al. 2005), including nail-laminated posts (Janowiak et al. 2014). They were able to conclude that the tested material has potential for reuse in this structural application, but have not extended their investigation into CLT.

The fabrication process and mechanical properties of CLST were tested by the present authors (Rose et al. 2018) in small-scale laboratory experiments. These showed no significant difference between the compression stiffness and strength of CLST and a control. Finite element modelling suggested that typical minor defects in secondary timber have only a small effect on CLST panel stiffness in compression and bending. Mechanically Jointed Beams Theory calculations to examine the potential impacts of secondary timber ageing on CLST panels found that this has little effect on compression stiffness if only the crosswise lamellae are replaced.

FURTHER RESEARCH

As a pilot research project, the findings from Rose et al. (2018) stimulate further research questions to advance the concept of CLST towards commercial application through additional laboratory- and pilot-scale experiments and modelling:

- What are the properties and variability of secondary timber feedstock? How can these best be characterised for commercial-scale quality control?
- How does variability in the properties of secondary timber affect the variability of CLST stiffness and strength properties?
- Does physical testing bear out modelled findings on the effectiveness of various CLST formats?
- Is there any difference in the bond strength, dimensional stability, rolling shear behaviour and fire behaviour of CLST and conventional CLT?
- What quantities of secondary timber are available and useable in CLST, and at what cost relative to conventional CLT?
- What scale of operation is needed to be commercially viable?
- Can conventional PUR and melamine-urea-formaldehyde adhesives be replaced with a non-toxic biodegradable alternative, or other joining technique (e.g., Brettstapel, friction-welding of wood: Stamm et al. 2005; Hahn et al. 2014; Buck et al. 2015; Wójcik & Strumiłło 2014; Ramage et al. 2017), for a product that is consistent with biological metabolism in a circular economy (Campbell 2018; McDonough & Braungart 2002)?

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