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Review of state of the art of dowel laminated timber members and densified wood materials as sustainable engineered wood products for construction and building applications

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ABSTRACT

Engineered Wood Products (EWPs) are increasingly being used as construction and building materials. However, the predominant use of petroleum-based adhesives in EWPs contributes to the release of toxic gases (e.g. Volatile Organic Compounds (VOCs) and formaldehyde) which are harmful to the environment. Also, the use of adhesives in EWPs affects their end-of-life disposal, reusability and recyclability. This paper focusses on dowel laminated timber members and densified wood materials, which are adhesive free and sustainable alternatives to commonly used EWPs (e.g. glulam and CLT). The improved mechanical properties and tight fitting due to spring-back of densified wood support their use as sustainable alternatives to hardwood fasteners to overcome their disadvantages such as loss of stiffness over time and dimensional instability. This approach would also contribute to the uptake of dowel laminated timber members and densified wood materials for more diverse and advanced structural applications and subsequently yield both environmental and economic benefits.

1. Introduction

Historically, timber has been and remains a widely used structural and environmentally friendly material (Dinwoodie, 2000; Kollmann and Côté, 1984; Bodig and Jayne, 1982). In 2016, about 122 million m^3 and 128 million m^3 of sawn wood were produced in Europe and North America, respectively (UNECE, 2017). Furthermore, wood has high specific stiffness and strength and is an economical alternative to other commonly used building materials (Da Silva and Kyriakides, 2007). However, their mechanical properties vary widely due to their natural origin. The variations are partly as a result of various growth conditions (e.g. soil type, availability of water and nutrients) and natural characteristics (e.g. presence and size of knots, the slope of grain) of a tree (Kretschmann, 2010; Porteous and Kermani, 2007) (NOTE: The words ‘wood’ and ‘timber’ are used interchangeably in this review article). As a result of some of these challenges, engineered wood products (EWPs) are increasingly being developed and optimised for structural applications leading to their significant consumption globally.

These EWPs are typically fabricated from the adhesive bonding of wood chips, flakes, veneer or sawn timber sections, and/or the mechanical fastening of timber sections to form larger sections, beams, panels or other structural elements (Woodard and Milner, 2016). The advantages of EWPs include enhanced dimensional stability, the formation of larger and more complex structural sections, reduced effect of natural defects (e.g. knots), greater durability and more homogenous mechanical properties (Ramage et al., 2017; Asif, 2009). EWPs with large

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section sizes comprising timber lamellas are also referred to as mass timber products (e.g. Cross laminated timber (CLT), glulam and dowel laminated timber) (Harte, 2017). These EWPs are used in construction and many building components (e.g. beams, columns, walls, floors, roofs), and are also viable alternatives to steel and concrete due to their technical capabilities, cost-competitiveness and environmental impact (Harte, 2017). For example, the global warming potential of the multi-storey Forté apartment building in Melbourne made from CLT panels was 22% lower than a similar building constructed with reinforced concrete (Durlinger et al., 2013).

However, there are concerns with the use of adhesives and metal fasteners which affect their sustainability, recyclability and broader environmental impact. More specifically, the predominant use of adhesives (e.g. Urea-formaldehyde (UF)) in EWPs is harmful to the environment due to the emission of toxic gases (e.g. formaldehyde and Volatile Organic Compounds (VOCs)) (Stark et al., 2010; Hemmilä et al., 2017; Adhikari and Ozarska, 2018). The inhalation of formaldehyde gas is carcinogenic, which shows the toxicity and hazardous of these adhesives (International Agency for Research on Cancer, 2004). Although cured adhesives are generally safe, formaldehyde gas is emitted from EWPs (with UF adhesives) during use, under high-temperature conditions and changes in relative humidity (Frihart and Hunt, 2010; Mantanis et al., 2018). In addition, hardeners (e.g. amine and formaldehyde) used in adhesives are irritants and skin sensitizers and therefore, constant exposure could lead to allergic reactions (Frihart and Hunt, 2010).

As a result of the points mentioned above, regulatory standards (World Health Organization, 2010; BS EN 13986, 2015; California Air Resources Board, 2009) have the incentive to limit the use of toxic adhesives in order to decrease emissions of formaldehyde and VOCs during production and in finished EWPs (Frihart and Hunt, 2010; Hill et al., 2015). The European Commission (2011) also has a specific objective of improving air quality, which can be achieved by reducing the use of harmful adhesives. Although there are ongoing developments of environmentally friendly bio-based adhesives, there are still challenges to their wider uptake due to the lower cost and better properties of synthetic petroleum-based adhesives (Hemmilä et al., 2017; Norström et al., 2015).

Therefore, this paper focusses on dowel laminated timber members and densified wood materials, which are more sustainable and adhesive free EWPs. This review of the current literature offers insights into different assembly processes (e.g. dowel welding) and the structural properties of dowel laminated timber (also referred to as “Dowellam”, “Brettstapel”, “DLT”). Although the concept of dowel laminated timber members has been around for a few decades (Henderson et al., 2012), research articles on their development and properties are limited. The review article also discusses the processing conditions and mechanical properties of densified wood alongside its moisture-dependent swelling effect. The manufacturing process typically involves the use of conditioned dowels (with moisture content of 6–8%) to fasten timber lamellas (with moisture content of 12–15%); subsequently, tight-fitting of the dowels occurs during in-service moisture equilibrium (Ramage et al., 2017; Buck et al., 2015). Also, some manufacturers compress the hardwood dowels hydraulically into holes of relatively smaller diameters to create a tight fit (Thoma, 2012). Additional benefits include the removal of toxic adhesives and metal fasteners in EWPs, and in so doing give better reusability and recyclability, availability and faster processing of softwood compared to hardwood.

2. Dowel laminated timber

This section focusses on dowel laminated timber members, which are EWPs (or mass timber products) fabricated with timber lamellas and assembled with hardwood dowels or metal fasteners (Ramage et al., 2017; Structure Craft, 2018). The modern design of this technology was developed in the 1970s and involved the use of nail fasteners (Henderson et al., 2012). However, in two decades later, metal fasteners were replaced with the use of hardwood dowels. These timber-only EWPs (fabricated without the use of metal fasteners or adhesives) are more sustainable and environmentally friendly (Chang and Nearchou, 2015; O'Loinsigh et al., 2012b). Through an EU-funded project (entitled Adhesive Free Timber Buildings (AFTB) (2016)), traditional construction techniques of dowel laminated timber was combined with advanced research on highly densified wood materials, to manufacture adhesive free EWPs. This concept takes advantage of the improved physical and mechanical properties (e.g. density, modulus of elasticity and strength) and the moisture-dependent swelling effect of highly densified wood, which can be used as alternatives to hardwood fasteners in dowel laminated timber members and connections, as shown in Fig. 1.

BS EN 1995-1-1 (2004) provides guidance on timber connections with steel dowel fasteners. However, there is a lack of statutory structural design standard for dowel laminated timber members assembled with wooden dowels. Furthermore, there is a limited number of studies that have dealt with the development and characterisation of dowel laminated timber members. It is however expected that their mechanical properties are dependent on different factors (such as lamella/dowel species and size, dowel arrangement, loading orientation). More recently, an European technical assessment (2018) was acquired and reported for a dowel laminated timber product under the trade name of THOMA Holz 100. This product comprises timber lamellas in the longitudinal, transverse and diagonal directions fastened with beech dowels, as illustrated in Fig. 2, and are currently used as building components (e.g. walls).

Furthermore, Rombach, 2018 developed a design for dowel laminated timber panels that utilised threaded beech dowels to fasten the lamellas, as shown in Fig. 3. The development of dowel laminated timber is also on the rise in North America with notable projects, including their use in the expansion of Smithers Airport in Canada (Structure Craft, 2018). About 300 buildings with Nur Holz dowel laminated timber members have been built worldwide (Habitat Naturel, 2009; Rombach, 2018; Thoma, 2012). Specific applications of dowel laminated timber include shear walls and floor diaphragms in buildings as alternatives to traditional materials (e.g. reinforced concrete) (Rombach, 2018).

Dauksta (2014) and Henderson et al. (2012) stated that the benefits of dowel laminated timber construction include better indoor air quality (compared to the use of adhesives), on-site fabrication and lower embodied carbon. However, these claims are based on qualitative research with the need for supplementary data on the life cycle impact assessment to understand and quantify their environmental impact.

On the other hand, there are shortcomings associated with traditional dowel laminated timber constructions, which include dimensional changes of hardwood dowels due to in-service moisture and temperature variations, leading to loose and imperfect connections between the dowels and the lamellas (Henderson et al., 2012). Also, hardwood fasteners undergo stress relaxation, which causes loosening of the joint over time, necessitating regular tightening (Guan et al., 2010). In light of the foregoing comments, this makes hardwood fasteners unfavourable and uneconomical from the point of strength and stiffness of the joint and maintenance required.

2.1. Development and characterisation of dowel laminated timber beams

This section examines and reviews the manufacturing processes and properties on dowel laminated timber members. Table 1 gives the mechanical properties of some dowel laminated timber beams from literature. Plowas et al. (2015) fabricated and tested five dowel laminated timber beams which comprised UK larch lamellas and beech dowels (20 mm in diameter) spaced at 300 mm centres. A row of the beech dowels was inserted (perpendicular to the loading direction) to fasten the lamellas. Based on the test setup shown in Fig. 4, the dowels were inserted near the neutral axis, therefore, they do not contribute to the bending properties of the beam. Four-point bending tests were carried out on the beams and the average modulus of elasticity and bending

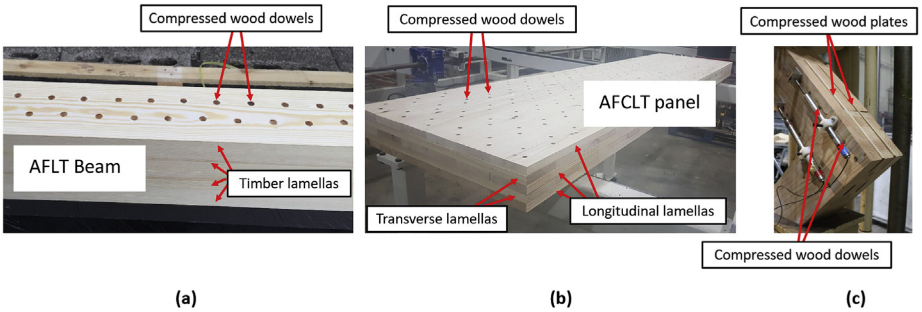

Fig. 1. Images of dowel connected structural members: (a) Adhesive free laminated timber beam (b) Adhesive free cross laminated timber panel (c) Timber-to-timber connection.

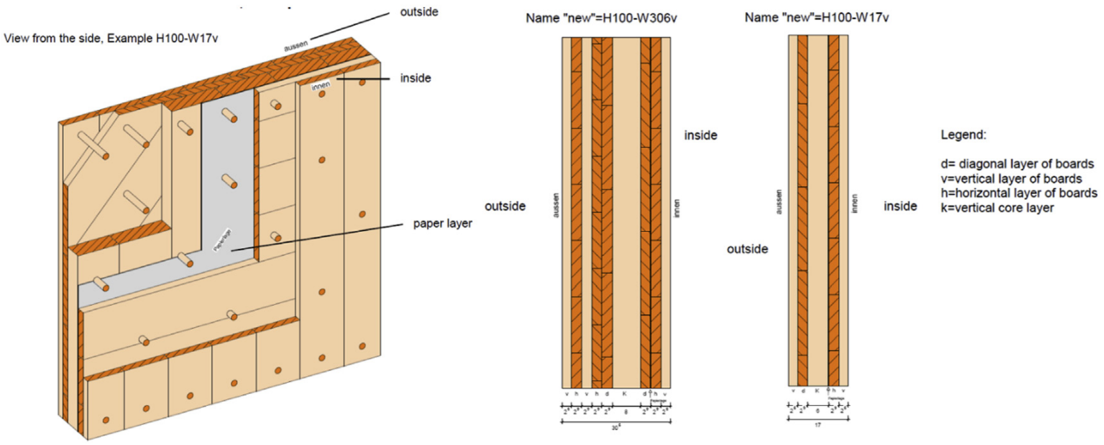

Fig. 2. Diagrams of the THOMA Holz 100 (BS EN 1995-1-1, 2004; Deutsches Institut für Bautechnik, 2018).

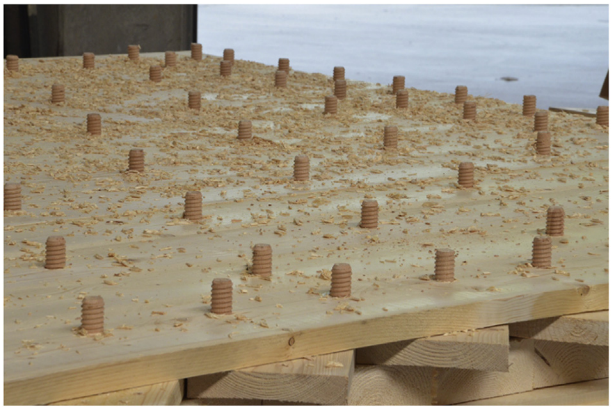

Fig. 3. Nur Holz dowel laminated timber panels (Habitat Naturel, 2009).

strength were approximately 10 GPa and 34 MPa, respectively (see Table 1). These average values reported are similar to those of standard timber sections, with the beams being failed in tension.

Belleville (2012) manufactured laminated timber beams fastened with hardwood dowels via high-speed rotational welding, as shown in Fig. 5a. The rotational welding involved the generation of friction between the dowel and lamellas through the high-speed rotation of the dowel causing an increase in temperature, thereby softening the lignin and forming a bond between the dowel and the timber lamellas (Michel Leban et al., 2005; Belleville, 2012). The dimensions of the laminated beams were 225 mm (width) x 30 mm (depth) x 300 mm (length), and the dowels were inserted perpendicular to the loading direction as shown in Fig. 5b. The 10 mm dowels were inserted into two adjacent timber lamellas (50 mm depth). The laminated beams comprised 12 timber lamellas with dimensions of 225 mm × 30 mm x 25 mm, and were fastened with 44 welded dowels.

Two different species (sugar maple (Acer saccharum) and yellow birch (Betula alleghaniensis) were used as the timber lamellas. The dowel species in the beams also corresponded to those used for the lamellas. For comparison, glued-laminated beams (polyvinyl acetate (PVAc) was the adhesive) with similar configuration and dimensions were also manufactured and tested in three-point bending. Five samples of each type of beam were tested.

Similar trends were observed for both timber species. Table 1 also gives the average bending stiffnesses, failure loads and standard deviations for the welded dowel and glued-laminated timber beams. This work could be improved by further analyses of the bending modulus and strengths (presented in N/mm^2) of the beams, which would be useful for comparison with other EWPs. Nevertheless, the results show that the initial stiffnesses and maximum loads of the glued timber beams were about three to four times greater than those of the welded dowel laminated beams. However, the dowel laminated beams showed a more ductile response than the glued-laminated beam. Belleville (2012) reported that the failure mode of the dowel laminated beams was the fracture of the dowels in tension. Also, there was visible edge separation between the timber lamellas during a humidity cycle experiment, which is a major issue to be considered in the design and use of dowel laminated timber beams and structures.

Nevertheless, Belleville (2012) stated that the wood-dowel welding process reduces the use of petrochemicals, gives better recyclability, increases productivity and lowers production costs compared to the use of adhesives in laminated timber structures. However, this statement necessitates further research to understand and quantify the economic and environmental benefits of the wood-dowel welding assembly process.

Dourado et al. (2019) manufactured and tested laminated timber beams fastened and bonded with hardwood dowels. The assembly

Table 1
Mechanical properties of dowel laminated timber beams from literature.

Reference	Lamella species	Dowel species	Beam type	Modulus of elasticity [GPa]	Bending strength [MPa]	Test Method
Plowas et al. (2015)	UK larch	Beech	Dowel laminated beam (single row)	10	34	Four-point bending
Belleville (2012)	Sugar maple	Sugar maple	Welded dowel laminated beam	**Bending stiffness [kN/mm]** 0.37 ± 0.04	**Failure load [kN]** 1.70 ± 0.14	Three-point bending
		N/A	Glued-laminated beam	1.52 ± 0.05	5.75 ± 0.76	
	Yellow birch	Yellow birch	Welded dowel laminated beam	0.34 ± 0.01	1.79 ± 0.04	
		N/A	Glued-laminated beam	0.98 ± 0.04	5.21 ± 0.52	
Dourado et al. (2019)	Maritime pine	N/A	Glued-laminated beam	3	14.9	Three-point bending
		Beech	Bonded dowel laminated beam (dowel insertion angle of 30°)	1.5	8.9	
			Bonded dowel laminated beam (dowel insertion angle of 45°)	1.6	12.1	
			Bonded dowel laminated beam (dowel insertion angle of 60°)	1.3	11.7	
			Bonded dowel laminated beam (dowel insertion angle of 90°)	1.5	9.8	
Bocquet et al. (2007)	Spruce	N/A	Nailed laminated beam (double row)	0.04	3.20	Four-point bending
		Beech	Bonded dowel laminated beam (single row)	0.06	3.21	
		Beech	Welded dowel laminated beam (single row)	0.08	3.25	
	Beech	N/A	Nailed laminated beam (double row)	0.08	7.00	
		Beech	Bonded dowel laminated beam (single row)	0.12	7.06	
		Beech	Welded dowel laminated beam (single row)	0.15	7.20	
O'Loinsigh et al. (2012a)	Irish spruce	N/A	Unfastened beam with no dowels/adhesive (i.e. stacked lamellas)	0.18	21	Four-point bending
		Beech	Dowel laminated beam (20 dowels)	0.4	22	
		Beech	Dowel laminated beam (32 dowels)	0.465	22.75	
		Beech	Dowel laminated beam (44 dowels)	0.565	24	

Fig. 4. Four-point bending test setup on a dowel laminated timber beam by Plowas et al. (2015).

technique incorporated the use of an epoxy adhesive to join the dowels to the lamellas. However, the authors stated that the volume utilised (although not quantified) was substantially smaller when compared with glued-laminated beams. The beams comprised two maritime pine lamellas and four beech dowels (15 mm in diameter), and the overall dimensions of the beams were 75 mm (width) by 40 mm (depth) by 380 mm (length). For a like-to-like comparison, glued-laminated beams with similar dimensions were tested. The study also investigated the effect of dowel insertion angles (30°, 45°, 60° and 90°), with five samples of each configuration being tested. The average bending stiffnesses and failure loads of the beams tested are given in Table 1, with all the beams being failed in tension. The results showed that the bending stiffnesses and failure loads of the bonded dowel laminated beams were ranged from 1.3 – 1.6 kN/mm and 8.9–12.1 kN. The configuration with the highest properties (i.e. bending stiffness of 1.6 kN/mm and failure load of 12.1 kN) was the beam with dowels inserted at a 45-degree angle. Nevertheless, these aforementioned properties were 53% (bending stiffness) and 81% (failure load) of a similar glued-laminated beam. The study also showed that the dowel insertion angle did not have a substantial influence on the bending stiffness (Dourado et al., 2019).

Bocquet et al. (2007) fabricated laminated timber beams via high-speed rotational welding of beech dowels, which was a similar procedure to that of Belleville (2012). However, Bocquet et al. (2007) inserted the dowels at an angle of 30° with respect to the longitudinal face of the lamellas, which was intended for enhancing structural properties. The beams were 2 m long, with 56 beech dowels (10 mm in diameter) being used to fasten two lamellas. Fig. 6a shows the schematic diagram of the single-row welded dowel laminated timber beam, with the central 300 mm region of the beam left without dowels. Further work was carried out in this study (Bocquet et al., 2007), by fabricating and testing double-row nailed laminated beams, as shown in Fig. 6b, and single-row bonded dowel laminated beams (Fig. 6a, which were compared with the welded dowel laminated beams. The laminated beams fastened with bonded wooden dowels also had the dowels inserted at a 30-degree angle for comparison. In addition, two different species (spruce and beech) were used as the lamellas for comparison.

Table 1 also gives the bending stiffnesses and failure loads of the beams manufactured and tested by Bocquet et al. (2007). Overall, the stiffnesses and failure loads of the laminated beams with beech lamellas were greater than those with spruce lamellas. For the beams with spruce lamellas, the study showed that the welded dowel laminated beam had a bending stiffness being twice that of steel nailed laminated beam and about 33% greater than that of a laminated beam connected via bonded wooden dowels. Furthermore, the failure loads of the nailed laminated beam, beams with bonded dowels and welded dowels were 3.20, 3.21 and 3.25 kN, respectively, which reflect no significant difference.

A similar trend can be seen in the beams with beech lamellas (see Table 1). The welded dowel laminated beam had the highest bending stiffness and the nailed laminated beam had the lowest. Also, there were no substantial differences in the failure loads between the three beams with beech lamellas. These results also show that the species and mechanical properties of the lamellas have a significant effect on the failure loads of the beams. The relatively higher stiffnesses of the bonded dowel

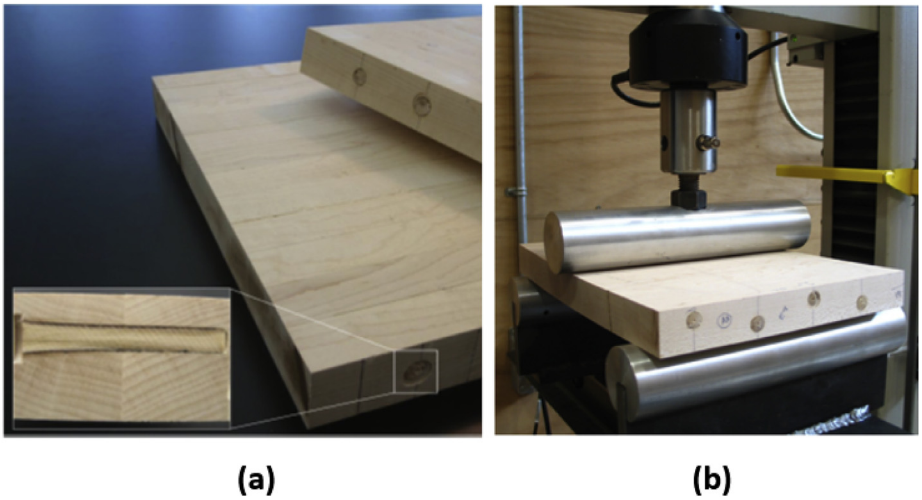

Fig. 5. (a) Image showing hardwood dowels connecting timber lamellas via high-speed rotational welding and (b) Three-point bending test setup on the dowel laminated timber beam by Belleville (2012).

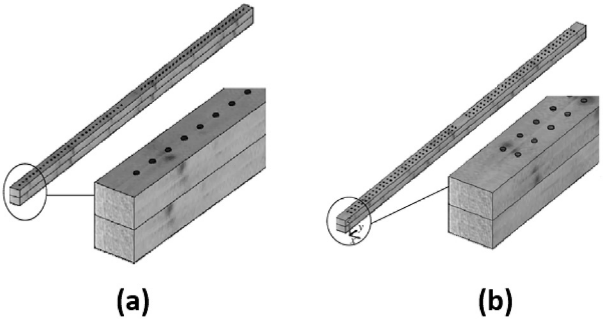

Fig. 6. Schematic diagrams of laminated timber beam manufactured by Bocquet et al. (2007): (a) Single-row welded with dowels and (b) Double-row nailed.

and welded dowel laminated beams compared to the nailed laminated beam may also be attributed to the dowel insertion angle of 30°.

O'Loinsigh et al. (2012a) manufactured and tested laminated timber beams that were also assembled via rotational welding of beech dowels. The beams comprised Irish spruce lamellas and a single row of dowels. The dowels were inserted at a 60-degree angle (with respect to the longitudinal axis of the beam), as shown in Fig. 7. The dimensions of the beam were 140 mm (width) by 152 mm (depth) by 2200 mm (length), and the dowels were 10 mm in diameter. The study entailed four-point bending tests on beams with 20, 32 and 44 dowels, which were compared with an unfastened beam with no dowels/adhesive (i.e. stacked lamellas). One limitation of this work was that although one of the objectives for the paper (O'Loinsigh et al., 2012a) was to demonstrate the fabrication of laminated timber beams without adhesives, experimental work was not carried out to compare the results with those of a similar glued-laminated timber beam. An additional observation was the presence of gaps between the lamellas (see Fig. 7), which was also shown in the dowel laminated timber beam developed by Bocquet et al. (2007).

The initial stiffness and ultimate loads of these beams are given in Table 1. The beam with 44 dowels resulted in a higher initial stiffness of 0.565 kN/mm, which is 41% greater than the beam with 20 dowels. As expected, all the dowel connected beams had initial stiffnesses which were at least two times greater than the unfastened beam. The study also investigated the stiffness of a laminated beam with 56 dowels, which gave a similar stiffness to the beam with 44 dowels. The authors (O'Loinsigh et al., 2012a) thereby concluded that the stiffness increased with an increasing number of dowels, however, beyond 44 dowels (i.e. less than ~50 mm dowel spacing), there was no substantial improvement in the stiffness of the beam.

On the other hand, although the beam with 44 dowels resulted in the greatest ultimate load, this was only 14% larger than that of the unfastened beam (see Table 1). Therefore, the dowels had a more significant influence on the initial stiffness of the beam than on the ultimate load. The paper (O'Loinsigh et al., 2012a) also reported that there was no dowel failure in the bending tests on the beams, with the failure mode being a tension failure occurring at the bottom lamella where knots were located. The insignificant influence of the type/number of the dowels on the ultimate failure loads was also shown in the work carried out by Bocquet et al. (2007) (see Table 1).

O'Loinsigh et al. (2012b) carried out further research and parametric studies using FE modelling to supplement their prior experimental work (2012a). Although the load versus deflection responses of the beams (with different parameter changes) were shown, the values of the initial stiffnesses and failure loads were not reported for a quantifiable comparison. Nonetheless, the paper (O'Loinsigh et al., 2012b) stated that the FE study showed that independently increasing the mechanical properties of the dowels, lamella (or layer) at the top and bottom of the laminated beam, number of dowels and the thickness of the lamella at the centre of the beam (close to the neutral plane) led to increases in the initial stiffness of the laminated beam.

Fig. 7. Dowel laminated timber beam fabricated by O'Loinsigh et al. (2012a).

Several of the existing studies are limited by the lack of information on the moduli of elasticity and bending strengths, which are typically the mechanical properties used in design and structural analysis. Belleville (2012), Dourado et al. (2019), Bocquet et al. (2007) and O'Loinsigh et al. (2012a) presented only the bending stiffness (kN/mm) and failure loads (kN) of the beams, and did not report the moduli of elasticity and bending strengths. The provision of these mechanical properties would have been useful for investigating the effects of the different assembly techniques (e.g. dowel insertion angle, dowel species and dowel arrangement) on the structural behaviour as well as a quantifiable comparison with other EWPs.

3. Densified wood materials

This section focuses on densified wood (also referred to as compressed wood in the literature) materials, which is considered as a type of EWP and belongs to the category of hydro-thermo-mechanical modifications of wood (Riggio et al., 2016) (NOTE: The words “densified” and “compressed” are used interchangeably in this review article). A primary aim for densification is to increase the mechanical properties of low-density wood by reducing the pores and voids (called lumen) between the cell walls, as shown in Fig. 8 and Fig. 9, thus increasing the density and other mechanical properties (e.g. strength, Young's modulus and hardness). Asako et al. (2002) also stated that the effective thermal conductivities in the tangential and fibre directions of wood increased proportionally due to the densification process.

Following densification, low-density timber species can be used as an alternative to hardwood species (Kutnar and Šernek, 2007). The higher mechanical properties of densified wood products allow their use in diverse and advanced applications (such as jigs and tooling in the construction, aerospace and automotive industry) (Permali Deho, 2010). For example, Anshari et al. (2012) utilised the moisture-dependent swelling and improved mechanical properties of densified wood as a reinforcement material in glulam beams. The authors reported a bending stiffness increase of up to 46% compared to that of unreinforced glulam. FE modelling was also used to supplement the study by investigating the influence of geometry and arrangement of the densified wood on the pre-camber, bending stiffness and maximum load of the reinforced glulam beams (Anshari et al., 2017). Glass and Zelinka (2010) used densified wood plates and dowels to replace steel plates and dowels in a timber beam-column connection. These connections utilised the moisture-dependent swelling effect of densified wood materials to create a tight fit in the connections. Additional benefits of densified wood include recyclability, reusability and relatively lower density when compared with steel (Riggio et al., 2016).

Wood densification can be classified into two categories, which are bulk densification and surface densification (Sandberg et al., 2017). Bulk densification refers to the compression of wood cells through the total volume of the timber section, whereas surface densification involves the partial compression of the wood cells close to the surface of the timber section (Sandberg et al., 2017; Kutnar et al., 2015; Rautkari et al., 2008). The research on densified wood products goes back to the 1930s (Kollmann, 1936; Kollmann et al., 1975). Additionally, timber can be densified by impregnating the voids between the cell walls with different materials such as molten metals/sulphur and polymers (Kollmann et al., 1975).

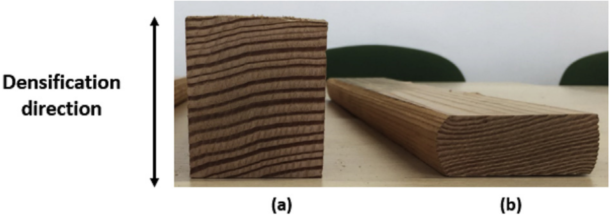

Fig. 9. Image of: (a) Undensified and (b) Densified Douglas Fir.

Densification of wood is typically carried out in the radial direction, which involves flattening the wood cells without fracture (Kutnar et al., 2015). It is essential to densify wood in the radial direction (rather than tangential direction) to avoid damage caused by the buckling of the latewood annual rings or the formation of a zigzag pattern on the cross-section faces on the densified wood (Sandberg et al., 2013; Kutnar et al., 2015). At low moisture contents and low temperatures, wood exhibits a glass behaviour (stiff and brittle). On the other hand, at high moisture contents and high temperatures, it has rubbery behaviour (Kutnar and Šernek, 2007; Salmén, 1990). Hence, the temperature at which transition occurs from glassy to rubbery behaviour is known as the glass transition temperature. Fig. 10 shows the glass transition temperature of wood polymers as a function of their moisture content (Salmén, 1990). The figure shows that the glass transition temperature of wood is affected by the moisture content. When wood is above the glass transition temperature, densification can occur without damaging wood cells. The temperature required for the densification of wood typically ranges between 120 – 160 °C (Kutnar et al., 2015). The quality and mechanical properties of densified wood are also dependent on different factors such as species, pre/post-treatment conditions, pressing time, pressing

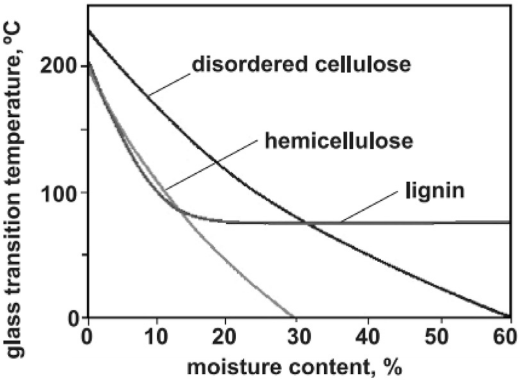

Fig. 10. The glass transition temperature of wood polymers as a function of the moisture content (Salmén, 1990).

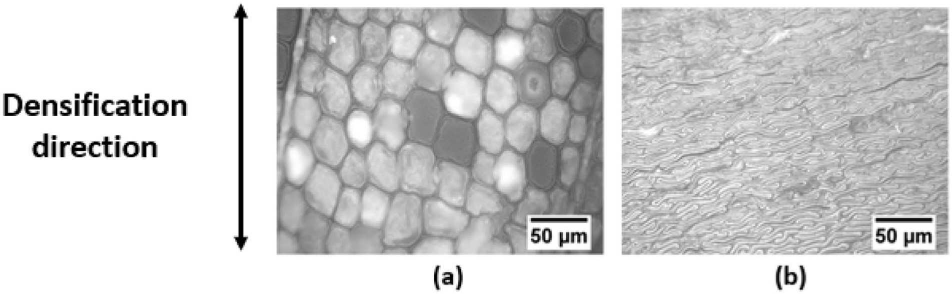

Fig. 8. Optical microscopy images of: (a) Undensified and (b) Densfied Douglas Fir (Pseudotsuga menziesii), using a Nikon Epiphot TME inverted microscope.

temperature, pressure applied, pressing speed and compression ratio (Santos et al., 2012; Islam et al., 2014).

The compression ratio (or densification ratio) refers to the difference between the initial and final thickness of the wood as a percentage of the initial thickness. Equation (1) gives the formula for the compression ratio (CR), where t_0 and t_1 are the thicknesses (in the compression direction) before and after compression, respectively.

$$CR = \frac{t_0 - t_1}{t_0} \times 100\% \tag{1}$$

Different studies have been undertaken to investigate the effect of compression ratios on the mechanical properties of densified wood. The type and species of wood can limit the compression ratios, as the degree of densification is dependent on anatomical features and initial density of the wood. For example, Riggio et al. (2016) compressed black locust (Robinia pseudoacacia L.) with an initial density of 750–900 kg/m^3 to a maximum compression ratio of 50%; exceeding such compression ratio would lead to damage of the cells. Therefore, wood with relatively higher densities (commonly hardwood species) would need to be compressed less, to avoid macroscopic damage. The same study also showed that 60% radially compressed beech reached the highest density values in the range of 1103–1246 kg/m^3 and compressing it further would have fractured the cells (Riggio et al., 2016). Thus, there are compression limits for different wood species to avoid damage.

Several studies have reported on different densification processes of wood. However, this review article focusses on some of the processing conditions and mechanical properties of 'bulk' densified wood without a second phase addition of resin and other chemical products. Some of the fundamental mechanical properties of densified wood are reviewed and compared, with the effect of compression ratios on the mechanical properties highlighted.

3.1. *Processing conditions and mechanical properties of densified wood*

Anshari et al. (2011) carried out compressive and shear tests on uncompressed and compressed Japanese cedar and evaluated their mechanical properties at different compression ratios (33, 50, 67 and 70%). A maximum compression ratio of 70% was set to avoid cell damage. The manufacturing conditions included pre-heating the timber samples for 1 h at 130 °C, before pressing for 30 min, and cooled for about 1.5 h. These properties were analysed, compared with those of uncompressed Japanese cedar and are reproduced in Table 2 (NOTE: Materials with a CR of 0% refers to uncompressed wood). Table 2 also shows that an increase in the compression ratio typically led to an increase in the density and longitudinal Young's modulus. The samples with a 70% compression ratio showed the highest mechanical properties, for example, there was over a 300% increase in the longitudinal modulus compared to that of the uncompressed wood. This research investigated the elastic properties of compressed wood but did not report their strengths. Further study on the strengths of compressed wood is therefore important, as they are an essential set of properties used in the design of load-bearing structures.

Jung et al. (2008) fabricated 70% compressed Japanese cedar (Cryptomeria japonica D Don.). Processing conditions included pressing at 130 °C for 30 min. They carried out flexural tests on the timber samples and also reported their strength properties. From the data given in Table 2, there were significant increases in the density, flexural modulus and flexural strength. The longitudinal flexural modulus increased from 11 GPa to 30 GPa. This value is slightly smaller than that of the 70% compressed Japanese cedar (~33 GPa) by Anshari et al. (2011). Furthermore, there was an increase in the bending strength from 86 MPa to 245 MPa (185% increase).

Jung et al. (2008) used 70% compressed Japanese cedar dowels (square and circular) as an alternative to maple hardwood dowels, with the flexural modulus and strength of the maple dowels being 16 GPa and 152 MPa, respectively (see Table 2). Double-shear tests showed that the ductility of compressed wood dowels was greater than that of maple dowels and reasonably close to that of a steel pin, which indicate the prospect of utilising compressed wood dowels in connections. The study also highlighted that the insertion of the compressed wood dowels with the annual ring of the dowel perpendicular to the loading direction

Table 2
Mechanical properties of uncompressed and compressed wood from literature.

Reference	Species	CR [%]	Density [kg/m^3]	Young's modulus			Shear modulus		
				E_L [MPa]	E_R [MPa]	E_T [MPa]	G_{LR} [MPa]	G_{LT} [MPa]	G_{RT} [MPa]
Anshari et al. (2011)	Japanese cedar (Cryptomeria japonica D. Don)	0	322	8017	753	275	972	784	31
		33	403	19864	338	1592	300	669	122
		50	564	27028	354	2267	178	787	170
		67	886	28415	523	2347	208	1208	256
		70	1162	32858	3111	5061	1590	5717	878
Jung et al. (2008)	Japanese cedar (Cryptomeria japonica D. Don)	**CR [%]**	**Density [kg/m^3]**	**Flexural modulus [GPa]**	**Flexural strength [MPa]**				
		0	330	11	86				
		70	1000	30	245				
Li et al. (2013)	Balsam fir (Abies balsamea (L.) Mill.)	**CR [%]**	**Young's modulus E_R [MPa]**	**E_T [MPa]**	**Shear modulus G_{RT} [MPa]**				
		0	830	234	38				
		60	284	2551	21				
Yoshihara and Tsunematsu (2007)	Sitka spruce (Picea sitchensis Carr.)	**CR [%]**	**Density [kg/m^3]**	**Flexural modulus [GPa]**	**Flexural strength [MPa]**	**Shear modulus G_{LT} [GPa]**	**G_{LR} [GPa]**	**Shear strength S_{LT} [MPa]**	**S_{LR} [MPa]**
		0	458	14	90	1	1.1	23	18
		33	606	25	120	1.7	0.7	23	16
		50	700	26	108	2.6	0.4	15	16
		60	817	30	96	1.2	0.6	25	18
		67	800	31	115	1.4	0.6	24	17
Song et al. (2018)	N/A	**CR [%]**	**Density [kg/m^3]**	**Compressive strength σ_L [MPa]**	**σ_R [MPa]**	**σ_T [MPa]**			
		0	460	29.6	3.9	2.6			
		80	1300	163.6	203.8	87.6			

(during a push-out double shear test) led to a greater ductile response compared to insertion parallel to the loading direction.

As a result of their improved mechanical properties, compressed wood dowels and plates were utilised as fasteners in column-sill and column-beam joints (Jung et al., 2009, 2010a,b). The authors also stated that satisfactory pull-out and moment-rotation properties were obtained, thereby demonstrating the potential of compressed wood in connections. In a separate study on glued-in-rod joints by Jung et al. (2010a,b), 67% compressed Japanese cedar dowels had a pull-out strength of up to 1.6 times greater than maple hardwood dowels.

Li et al. (2013) densified balsam fir (Abies balsamea) at a temperature of 230 °C for 20 min and was cooled until the temperature was below 60 °C. The processing temperature of 230 °C is higher than those reported in the literature and risk wood damage (Navi and Heger, 2004). The compression ratio was 60%, with Table 2 giving the mechanical properties of uncompressed and compressed balsam fir. The Young's modulus of the compressed wood in the radial direction, E_R, was 284 MPa, which was 66% lower than that of uncompressed balsam fir (830 MPa). However, Young's modulus (E_T) of the compressed balsam fir was 2551 MPa compared to the uncompressed wood of 234 MPa. The reduction of the E_R of compressed wood was attributed to minor fractures of the cell walls during densification. However, Li et al. (2013) did not report Young's modulus and the strength properties in the longitudinal direction of the 60% compressed balsam fir.

Yoshihara and Tsunematsu (2007) determined the flexural and shear properties of uncompressed and compressed Sitka spruce (Picea sitchensis), which are given in Table 2. The processing conditions included pre-soaking the wood in water (20 °C) for two days, before compressing at a temperature of 180 °C for 10 min. Further processing involved the addition of steam at a temperature of 180 °C for about 1 h before cooling to limit the moisture-dependent swelling of the compressed wood. When the wood was compressed by 67%, the density increased from 458 kg/m^3 to about 800 kg/m^3, reflecting a 75% increase. The flexural moduli were 14 GPa and 31 GPa for the uncompressed and 67% compressed wood, respectively. On the other hand, an increase in the compression ratio did not correlate with the flexural strengths, with the maximum flexural strength (120 MPa) being the samples with a 33% CR. Similarly, there was no direct correlation of the compression ratio to the shear properties, as shown in Table 2. The soaking and steam treatments may have caused the lower shear properties of the compressed wood. Also, a study by Navi and Heger (2004) showed that processing timber at a temperature of 180 °C or higher could lead to macroscopic cracks and a reduction in mechanical properties. Furthermore, although post-treatment of wood with steam reduces the moisture-dependent swelling, Inoue et al. (1993a) showed that it also led to a reduction in the mechanical properties of compressed wood.

More recently, Song et al. (2018) carried out a processing method, which combined high-temperature compression and chemical treatment to fabricate compressed wood. The chemical treatment involved the use and mixture of sodium hydroxide and sodium sulphite, to partially remove lignin and hemicellulose, before being compressed at a temperature of 100 °C. Table 2 gives the average mechanical properties. The density of the 80% compressed wood was 1300 kg/m^3 (an increase from 430 kg/m^3), reflecting an approximate 200% increase. Furthermore, the compression strengths showed gains of about 450%, 5100% and 3300% in the longitudinal, radial and tangential directions, respectively. The relatively greater compression ratio (i.e. 80%) and lower processing temperature (i.e. 100 °C) compared to those commonly used in the literature (120–160 °C) (Kutnar et al., 2015), were perhaps attributed to the partial removal of lignin.

The authors (Song et al., 2018) also reported the ultimate longitudinal tensile strengths for different species (oak, poplar, cedar, pine and basswood), which are reproduced in Table 3. These results show that the processing conditions utilised by Song et al. (2018) increased the ultimate tensile strengths for both softwood and hardwood species from 47 – 115 MPa to 432–587 MPa. These notably improved mechanical properties are greater than other studies reported in the literature and are attributed to the chemical treatment of the wood. It is, however, unclear if the chemical processing stages are costly or energy-intensive. Therefore, further research on the sustainability of the processing conditions could be carried out. The addition of chemical solutions might also decrease the environmental benefits of densified wood.

Table 3
Longitudinal tensile strengths of uncompressed and compressed wood species by Song et al. (2018).

Species	Longitudinal tensile strength [MPa]	
	Uncompressed	Compressed
Oak (Quercus)	115.3	584.3
Poplar (Populus)	55.6	431.5
Western red cedar (Thuja plicata)	46.5	550.1
Eastern white pine (Pinus strobus)	70.2	536.9
Basswood (Tilia)	52.0	587.0

3.2. Moisture-dependent swelling of densified wood

Though densification of wood has improved mechanical properties, a drawback for some applications is the irreversible swelling characteristic and dimensional instability due to moisture changes or high relative humidity conditions. When subjected to these conditions, the internal stresses introduced to the wood during densification are released. Furthermore, in the literature (Navi and Heger, 2004; Rautkari et al., 2010; Rautkari et al., 2011; Morsing, 1998; Laine et al., 2013; Pelit et al., 2014; Skyba et al., 2009; Peyer et al., 2007; Anshari et al., 2011; Islam et al., 2014; Welzbacher et al., 2007), this phenomenon is commonly used interchangeably with other words (such as moisture-dependent swelling, spring-back, shape-memory, set recovery, irreversible swelling) and is significantly accelerated when densified wood is put in water. It is also worth clarifying that when densified wood is exposed to moisture, both reversible and irreversible swelling occur. Reversible swelling is due to the natural hygroscopicity of wood (moisture absorption makes wood swell, whereas, wood shrinks as it loses moisture or when dried) but irreversible swelling (which is the focus of this section) of densified wood causes a partial or full return to its original dimensions (Laine et al., 2013; Glass and Zelinka, 2010; Thelandersson and Larsen, 2003).

Anshari et al. (2011) evaluated the moisture-dependent swelling of compressed Japanese cedar (Cryptomeria japonica D. Don). The radially compressed wood with dimensions of the 67% were 20 mm (radial) x 20 mm (tangential) x 60 mm (longitudinal) were placed in ambient environmental conditions to attain a moisture content of approximately 12%. The results showed maximum moisture-dependent swelling strain values of 12, 1.4 and 0.1% in the radial, tangential and longitudinal directions, respectively, over a 15-day period. As expected, due to compression occurring in the radial direction, maximum swelling occurred in the radial direction compared to the tangential direction. Also, a miniscule 0.1% swelling occurred in the longitudinal direction. The authors (Anshari et al., 2011) carried out further study on 70% compressed wood with dimensions of 15 mm (radial) x 30 mm (tangential) and 65 mm (longitudinal). The maximum moisture-dependent swelling strains recorded in the radial and tangential directions were 17% and 1.5% respectively, over 60 days. The study also showed that an increase in the compression ratio of the densified wood led to a rise in the moisture-dependent swelling strain in the radial direction.

To reduce and/or eliminate moisture-dependent swelling of densified wood, studies have shown that additional treatments such as heat/steam/chemical treatments can be used to alleviate this phenomenon (Islam et al., 2014; Hsu et al., 1988; Peyer et al., 2007; Cloutier et al., 2008; Ispas, 2013; Stamm and Seborg, 1941). More specifically, thermo-hygro-mechanical treatments of wood, which typically involves high-temperature densification combined with stream treatments (with post-treatment temperatures in the range of 140–180 °C) have been used to limit the moisture-dependent swelling and enhance dimensional stability (Skyba et al., 2009). Furthermore, Welzbacher et al. (2007) combined oil-heat treatment (OHT) with thermo-mechanical densification to improve the dimensional stability of densified spruce.

Polycarboxylic acid (PCA) resin was used to minimise the moisture-dependent swelling of densified wood (Peyer et al., 2007). Inoue et al. (1993b) used melamine-formaldehyde resin to significantly reduce the moisture-dependent swelling (<2%) in densified wood, and the study also stated that the addition of 25 wt. % of the resin resulted in a 54% increase in the hardness of the compressed wood. Inoue et al. (1993a) post-treated compressed wood with steam (under pressure) at 180 °C (for 8 min) and 200 °C (for 1 min), which eliminated the moisture-dependent swelling. The aforementioned conditions, however, led to 3.3% and 8.6% reductions in the modulus of elasticity of the compressed wood, respectively. 50% radially compressed sugi wood (Cryptomeria japonica D. Don) was heat-treated (160–200 °C) to eliminate the moisture-dependent swelling. However, the post-treatment conditions led to reductions of 11% and 19% in the modulus of elasticity and modulus of rupture, respectively (Dwsanto et al., 1998).

In line with the preceding statement, Navi and Heger (2004) found that processing wood at a temperature greater than 180 °C led to a reduction in mechanical properties, which could be referred to as the maximum temperature for processing timber. Heat treatment also helps improve the dimensional stability of wood but takes a long time (e.g. 20 h) and reduces its mechanical properties due to thermal degradation (Morsing, 1998; Ispas, 2013; Pelit et al., 2014). This is because lignin (a major component of timber) cracks when subjected to a temperature exceeding 180 °C (Navi and Heger, 2004). Inoue et al. (1993a) also highlighted that in order to reduce or eliminate the moisture-dependent swelling in compressed wood, steam post-treatment (under pressure) was more effective than steam pre-treatment. Furthermore, steam post-treatment time decreases exponentially with increasing steam temperature (Navi and Heger, 2004). However, an increase in the steam temperature used for the post-treatment of densified wood also leads to a reduction in mechanical properties (Morsing, 1998).

4. Concluding remarks

As a result of environmental concerns, there is a growing interest in the use of timber and the development of timber-based structural members. This has led to a wide range of EWPs used in innovative ways, to replace traditional construction materials, such as steel and concrete. The development and characterisation of innovative EWPs provide new possibilities for the efficient use of wood. Although EWPs have relatively low embodied energies and embodied carbon, a major drawback is the inclusion of adhesives during their manufacture and service life. The key issues with these adhesives (e.g. UF adhesive) are the health and environmental concerns associated with the release of toxic gases (e.g. formaldehyde and VOCs) as well as recyclability and reusability. As such, one of the objectives of the EU-funded AFTB project is to develop novel and adhesive free EWPs by using densified wood materials as fasteners in dowel laminated timber members and connections.

Therefore, this review article has focussed on dowel laminated timber members and densified wood materials. Design guidelines for the aforementioned EWPs are not available in current European standards. Nevertheless, several studies have demonstrated the feasibility of dowel laminated timber members and have provided insight into their structural properties. The fabrication processes mainly involve high-speed rotational dowel wood-welding or the use of hardwood dowels (conditioned to a lower moisture content) as fasteners for assembling timber lamellas. Some of the studies has highlighted that an increase in the number of dowels leads to an increase in the initial stiffness of the dowel laminated timber members, whereas the number of dowels has a negligible effect on the maximum failure loads. Collectively, the studies show that the initial stiffnesses and maximum loads (in bending) of similar glued timber beams are about three to four times greater than those of welded dowel laminated beams. It should be highlighted that there are some drawbacks with the use of hardwood dowels (such as loss of stiffness over time, dimensional instability, maintenance requirements) as fasteners in traditional dowel laminated timber constructions.

In addition, some of the studies reviewed did not report the moduli of elasticity and bending strengths of the dowel laminated timber members, which would have been useful for assessing and comparing the effect of the different assembly processes on their mechanical properties. Therefore, further studies could assess and quantify the effect of dowel species, dowel insertion angle and dowel pattern on the mechanical properties of dowel laminated timber members. FE modelling and analysis could also supplement experimental work. An additional limitation with some of the reviewed articles is the low number of test samples, which limits the conclusions that could be drawn from the research work. Furthermore, although the bending tests give insights into the structural properties of the dowel laminated timber members, experimental tests under various loading conditions (e.g. shear, axial), vibration and impact tests are important which should form part of any future research. These further work, covering the different practical scenarios for these members, will enhance the understanding of their structural properties, and possibly lead to useful structural design guidance.

Although dowel laminated EWPs are fabricated without the use of toxic adhesives, their environmental impact assessments have not been reported in the literature. The embodied energy for different manufacturing processes (e.g. high-speed rotational welding) for dowel laminated timber, as well as those for densified wood (which include high-temperature mechanical compression), are unknown. As sustainability remains a major objective of the current EU environmental agenda to attain a low-carbon economy, it is vital to carry out an environmental impact assessment for novel EWPs so that each phase of their life cycle (such as production, in-service use, operational lifetime, maintenance requirements and end-of-life options) is included for the useful comparison with other EWPs and structural materials.

This review article also shows that densifying different species of wood leads to substantial increases in their key physical and mechanical properties (density, hardness, modulus of elasticity and strength). This highlights the potential of using low-density wood in more advanced and diverse structural applications. Furthermore, the effects of the processing parameters (such as compression ratio, temperature, pressure and time) for different densified wood on their mechanical properties have been reported. The processing conditions mainly include pre-heating, mechanical compression, cooling and possible post-treatment options (e.g. steaming) to limit the moisture-dependent swelling. While the concept of wood densification is not new, its uptake is limited partly due to the moisture-dependent swelling effect and is therefore not typically used for structural applications at the moment. Although research has shown that the moisture-dependent swelling can be minimised, it can, however, be time-consuming and requires high-temperature processing conditions, which may lead to a reduction in their mechanical properties. Furthermore, the treatment of wood with chemicals may be costly and reduce the environmental advantages of densified wood on account of embedded potentially harmful chemical resins.

Currently, the uptake of dowel laminated timber and densified wood for commercial and structural applications is minimal. In line with the current aim of the AFTB project, by utilising the moisture-dependent swelling effect and improved mechanical properties of highly densified wood, there is a great potential in using these materials as alternatives to hardwood fasteners in dowel laminated timber constructions. What has long been recognised as a disadvantage of densified wood for some specific applications will be used as an advantage for structural joints and connections. Once embedded, densified wood dowels and plates are exposed to moisture, therefore the moisture-dependent swelling effect can provide a permanent tight fit regardless of in-service moisture changes. This approach incorporates traditional techniques and advanced research, eliminates the use of toxic adhesives and metal fasteners, and leads to better reusability and recyclability, availability and faster processing of softwood compared with hardwood for large scale production. In summary, to contribute to green construction and low embodied energy and carbon buildings, further research is needed to develop novel and sustainable EWPs that are non-toxic, cheap, reusable, recyclable with well characterised mechanical properties and documented life cycle assessment.

Declarations of competing interest

The authors declare that they have no conflict of interest.

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