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Review

Adhesive-and Metal-Free Assembly Techniques for Prefabricated Multi-Layer Engineered Wood Products: A Review on Wooden Connectors

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Abstract: Engineered wood products (EWPs) are being increasingly used as construction materials. EWPs are currently being made using synthetic adhesives or metal fasteners, which lead to poor recyclability and reusability. Therefore, this review paper focused on emerging adhesive- and metal-free assembling techniques including wood dowels, rotary-dowel welding, wooden nails, and dovetail joining as alternative ways of making prefabricated EWPs. This will contribute towards green construction and optimising the building process to minimise its negative impact on the environment and its inhabitants, while maximising the positive aspects of the finished structure. The respective advantages and shortcomings will be compared with those of equivalent EWPs. In general, the dowel-laminated timber (DLT) provides sufficient load-bearing capacity and even better ductility than EWPs of equivalent size, but its relatively low stiffness under a bending load limits its application as a structural element. Optimised manufacturing parameters such as dowel species, dowel spacing, dowel diameter, dowel insertion angle, dowel shape, etc. could be studied to improve the stiffness. The improved mechanical properties and tight fitting due to set-recovery of densified wood support its use as sustainable alternatives to hardwood dowels in DLT to overcome problems such as the loosening of connections over time and dimensional instability. The rotary welding technology could also enhance the strength and long-term performance of dowel-type joints, but its poor water resistance needs further investigation. The main obstacles to implementing DLT products in the market are missing technical information and design guidelines based on national codes.

Keywords: EWPs; wood welding; densified wood; wood modification

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1. Background

Wood is not only an ecological and environmentally friendly building material, it also exhibits a high load-carrying-strength-to-weight ratio, easy workability, good thermal insulation and good fire performance (for sufficiently massive elements), is easy to reuse and recycle, etc. As a natural material, however, wood has many inherent characteristics which impede its application in constructional situations. The anisotropic nature of wood means that its mechanical properties in the transverse direction are much poorer than those in the longitudinal direction. In addition, its properties can vary widely within the same species, and even within the same tree, due to different growth conditions and variations in characteristics such as grain angle, knot distribution, and latewood proportion. The moisture-induced dimensional changes also make it difficult for wood to meet the requirements of modern timber construction [1,2].

To overcome these problems, engineered wood products (EWPs) such as cross-laminated timber (CLT), glued-laminated timber (GLT), laminated veneer lumber (LVL), nail-laminated timber (NLT), and plywood have been developed and widely implemented. EWPs are typically manufactured by adhesively bonding together solid wood, veneer, or wood fragments such as strands, particles, and fibres, or by the mechanical joining of timber blocks to form large structural elements. Compared to simple sawn timber, EWPs enable broader applications in construction, give less variability in properties and greater dimensional stability [3]. Furthermore, the use of EWPs in prefabrication at the factory before on-site installation leads to a better quality of the final building, as well as a shorter construction time and lower construction costs [4].

Nevertheless, EWPs are predominately assembled by synthetic adhesives or metal fasteners which have been shown to be highly energy intensive in production and, therefore, to have a large environmental footprint. The energy embodied in GLT is approximately 60% greater than that of sawn timber [5]. Cadorell and Crawford [6] reviewed CLT in buildings and stated that "While CLT has clear benefits over steel and concrete in terms of minimising non-renewable material depletion, the extent of other environmental benefits is less certain." Moreover, the presence of adhesive and metal in EWPs is troublesome regarding reusability and recyclability [7]. Puettmann and co-workers [8] reported that, even though only 1.4% (mass-based) of CLT is adhesive, the cradle-to-grave environmental impact of the adhesive was typically around 31% (for global warming potential, total energy, and non-renewable fossil) and 57% of the eutrophication potential of the finished CLT. The cost to adhesively join the lamellae in the CLT is also a significant part of the total manufacturing cost, not only because of the adhesive itself, but also because maintenance of the manufacturing equipment is necessary, and because the hardening process is time-consuming unless high-cost adhesive material or machinery such as a high-frequency/microwave system is used. The presence of adhesive and metal fasteners can also induce difficulties in wood-working processes such as cutting, milling, and planing. During use, the adhesives in EWPs may also affect the environment and human health by emitting volatile organic compounds (VOCs) such as formaldehyde [1,8,9]. The emissions increase especially at high temperature and high relative humidity (RH) [10]. More importantly, the adhesives and metal fasteners are the vulnerable component of the EWPs in a fire situation as they may lead to early failure of the timber structure [11–13].

Although adhesive bonding and metal fasteners are considered to be reliable and have proven their long-term performance, there is still a need for a "greener" alternative to join the timber components in muti-layer wooden beams and panels. In recent years, several adhesive-free techniques for joining multi-layer beams and panels have emerged. These developments deserve a review of their respective advantages and shortcomings, taking into consideration their technical deficiencies, manufacturing cost, and mechanical performance.

The objective of this review is to investigate and compare different adhesive-free and metal-free assembly techniques for joining lamellae in multi-layer load-bearing components. The focus has been on dovetail joining, rotary wood welding, wooden dowels, and wooden nails. An extensive literature review including international peer-reviewed journals and related research projects has been carried out, and we hope that the analysis and conclusions will contribute to the future development of adhesive-free joining techniques for multi-layer load-bearing components, and thereby improve the competitiveness and sustainability of large-scale wooden construction material.

2. Joining Multi-Layer Timber with Wooden Dowels

2.1. General Fundamentals of Wooden-Dowel Assembly Techniques

2.1.1. Untreated Hardwood Dowel

Wooden dowels have been used to join solid wood in the manufacture of furniture and in traditional timber framing for centuries. When steel nails were industrially made and became considerably cheaper than handmade nails, wooden dowels were replaced with steel nails. In the USA, nail-laminated-timber components have been used for over 150 years in construction, sawn-timber posts and beams being combined with nail-laminated floor panels [14]. The use of wooden dowels to assemble sawn timber into prefabricated EWPs was further developed in 1970s [15]. The end-product on the market is called dowel-laminated timber (DLT), Dowellam or Brettstapel (German). The DLT can be divided into three types depending on the lamella stack orientation and loading direction: DLT beam and panel with lamella stacking in parallel or dowel cross-laminated timber (DCLT) with lamella stacking in crosswise (Figure 1). Normally, the connection can be easily achieved by hydraulically or pneumatically hammering the dowels into pre-drilled holes with a slightly smaller diameter [16].

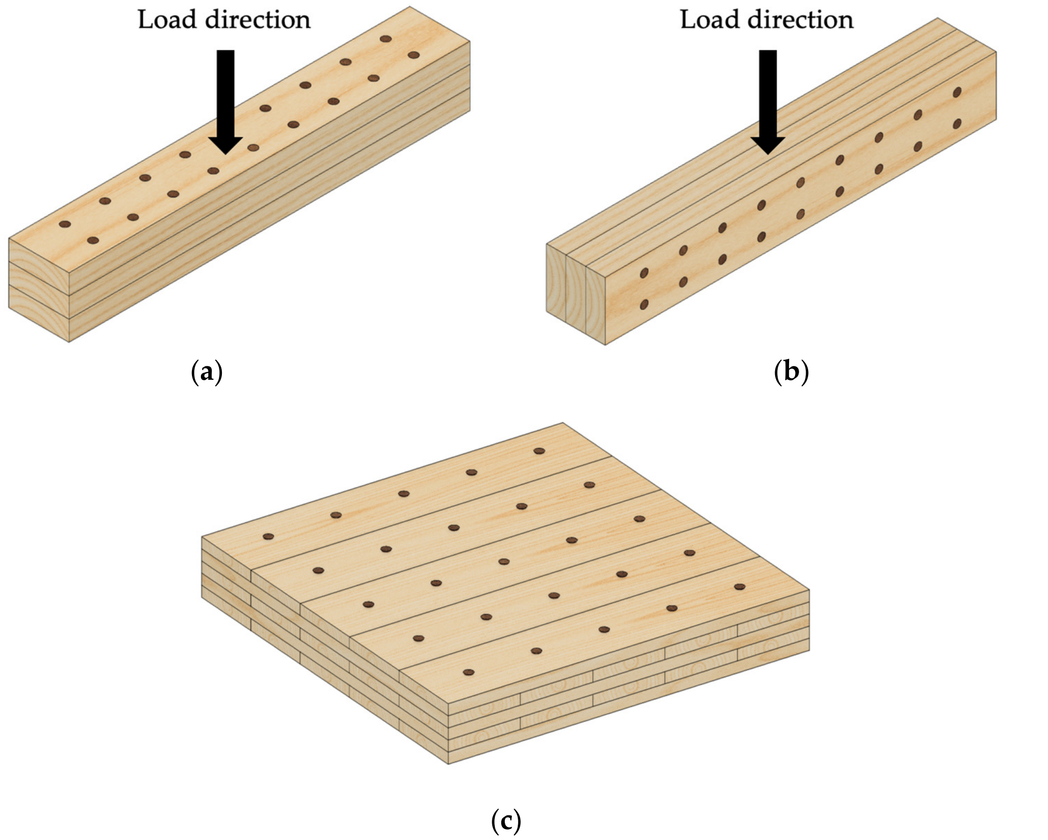


Figure 1. Multi-layered timber EWPs assembled using wooden dowels: (**a**) DLT beam (parallel lamella stack with loading direction parallel to the fiber direction of dowels), (**b**) DLT panel (parallel lamella stack with loading direction vertical to the fiber direction of dowels), and (**c**) DCLT (crossed lamella stack).

In general, wooden dowels have two main functions:

(1) They prevent the joined lamellae from sliding apart when a force acts parallel to the grain of the dowel. To achieve a tight dowel–lamella connection, the dowels are conditioned to a low moisture content (MC), typically 6%–8%, and inserted into pre-drilled holes in lamellae with a higher MC, typically 12%–15% [15]. Additional water can also be added when the dowel is inserted. Hardwood dowels are usually used because of their high swelling coefficient and greater strength [17]. As Figure 2 shows, when the dowel re-conditions to meet the RH in the ambient air, the dowel swells and exerts a force (N_{swell}) on the surrounding wood, and this creates a frictional resistance force (F_{mob}) along the dowel–lamella interface when the dowel is subject to a pull-out force (P) [18].

(2) When the connection is subjected to a tensile or compressive force and/or by a bending moment, the load is transferred through the dowel to the neighbouring lamella via a combination of flexure and shear in the dowel itself and its embedment in the timber.

Wood is a viscoelastic material and its deformation under load is time dependent. Strength loss, stress relaxation, and creep deformation are related to the viscoelasticity of a material, and, in the case of a wooden-dowel joint, they could lead to a loosened connection. When the ambient RH varies, the viscoelastic behaviour becomes more evident due to a phenomenon called mechano-sorption. Sydor and co-workers [19] studied how the diameter of holes drilled in softwood changes due to changes in RH in the ambient air, and they showed that swelling of the wood material reduced the hole diameter and that shrinkage increased the diameter. The diameter of a wooden dowel changes in the opposite way, i.e., the dowel diameter decreases with decreasing ambient humidity at the same time as the hole gets larger, and this reduces the performance of the connection. The use of densified wood as a "swelling" dowel in friction-locked joints has been suggested as a way to overcome this long-term performance problem [15,20].The "swelling" is then an effect of the so-called set-recovery deformation that occurs in unmodified densified wood. The greater "swelling" of densified wood compared to that of un-densified wood could also allow the use of dowels with a dowel diameter less than the pre-drilled hole diameter, thereby facilitating the insertion of the dowel, especially in robotic fabrication [21–23].

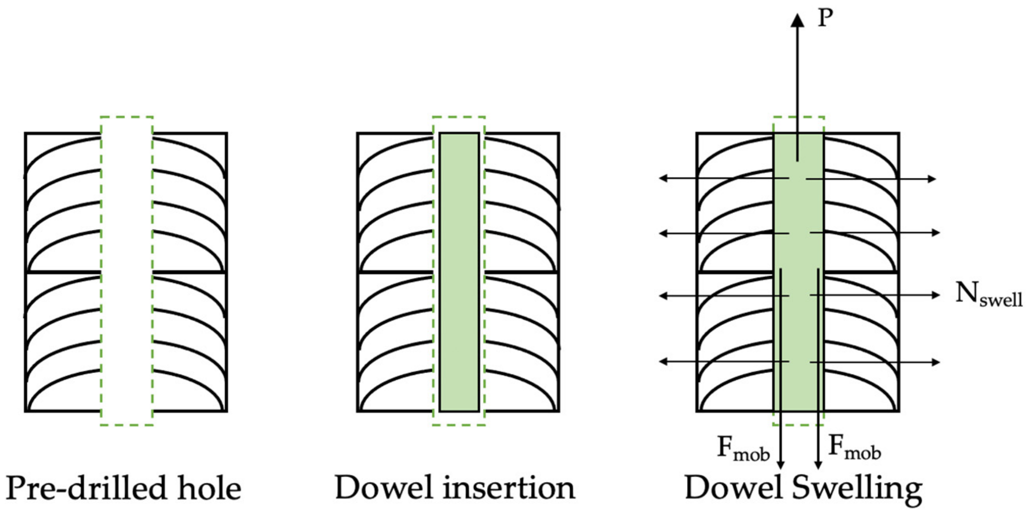


Figure 2. The friction-induced locking effect of a swelling wooden dowel joining two lamellae. Redraw from [18].

2.1.2. Thermo-Hydro-Mechanical (THM) Densified Wooden Dowel

THM densification involves heating the wood above its glass-transition temperature, moisture, and a compression force in the transverse direction to make the cells collapse without fracturing the cell walls, leading to a reduction in the lumen volume and an increase in cell density. Since it is well known that there is a strong relationship between wood density and its mechanical properties, THM densification is used to improve the performance primarily of low-density timber species to make them more attractive for use in load-bearing timber construction [24,25]. During THM densification, the lignin becomes plastic and allows the material to deform without fracture. The semicrystalline cellulose is elastically deformed, and elastic strain energy is then stored in the semicrystalline microfibrils. The densification deformation is temporarily fixed through two phenomena: (1) the transfer of lignin from a rubbery to a glassy state when the wood is cooled under load to below its glass-transition temperature, and (2) the formation of hydrogen bonds between cellulose and hemicelluloses during drying. When the densified wood is again exposed to moisture (and heat), the lignin is softened and the hydrogen bonds between cellulose and hemicelluloses re-open. As a result, the densified wood cells tend to recover their original shape and the improvement in properties resulting from the densification is lost—a phenomenon known as set-recovery [26,27]. Set-recovery is the moisture-induced release of residual compression stresses in the wood and is the main hinderance to the industrial application of THM densified wood. There are four basic ways to reduce or even eliminate the set-recovery: (1) by making the cell wall hydrophobic to prevent the wood from being re-softened by the absorption of moisture, (2) by creating covalent crosslinks between the wood constituents during densification, e.g., through chemical modification, (3) by releasing the stress stored inside the microfibrils, or (4) by mechanically fixing the densified wood in the directions in which the wood can recover (i.e., in the densification direction) [28,29]. For example, steaming wood after densification (post-steaming) is widely used to prevent the densified wood from recovering its original shape due to stress relaxation through the degradation of hygroscopic hemicelluloses or the breaking of crosslinks between adjacent cellulose molecules [27,30–32]. Other ways to reduce the set-recovery are to impregnate the wood before densification with a low molecular-weight resin that acts as a plasticiser and after curing, locks the wood in its densified shape [33–35]; by modification with an ionic liquid [36], or by mechanical locking by gluing a multi-layer EWP [37].

Set-recovery can however be beneficial for the long-term performance of multi-layered solid-wood EWPs joined by densified wooden dowels, since it can contribute to a tighter joining between the densified wooden dowel and the surrounding wood. The set-recovery is highly dependent on the densification parameters and climate conditions (RH and temperature) to which the densified wood is exposed. Anshari and co-workers [38] investigated the set-recovery in the radial direction of densified Japanese cedar, manufactured with different compression ratios (CR = 33%, 50%, 67%, and 70%) and at different RH levels (35%, 40%, 85%). They showed that the set-recovery in the radial direction of all types of densified wood was considerably higher than the swelling of un-densified wood in the same direction. When the densified wood was remoistened, the dimensional expansion, i.e., the combined swelling and set-recovery, in the radial direction increased sharply in the first few days, followed by only a small increase thereafter. The general set-recovery behaviour is that most of the compression deformation is totally recovered as soon as the densified wood material absorbs moisture, and this means that the time to effectuate set-recovery depends on the species, on the size of the densified wood, and on the treatments etc [39]. The set-recovery is mostly several magnitudes greater than the swelling of the wood material, but the value is highly dependent on the compression ratio.

Li et al. [40] found that densified wood exerted a swelling pressure 5 times higher than un-densified wood when soaked in water at a temperature of 60 °C. Whereas the swelling pressure of un-densified wood results only from the swelling of the cell wall, extra stress is released from densified wood both by swelling of the bulked cell wall and by cell-shape recovery. Their study confirmed that the swelling pressure of densified wood increased with increasing CR [41]. Since this set-recovery deformation of a densified wooden dowel is almost irreversible under climate change, densified wood dowels can provide a consisting swelling pressure, which prevents significant contact-stress relaxation over multiple MC changes (Figure 3) [21].

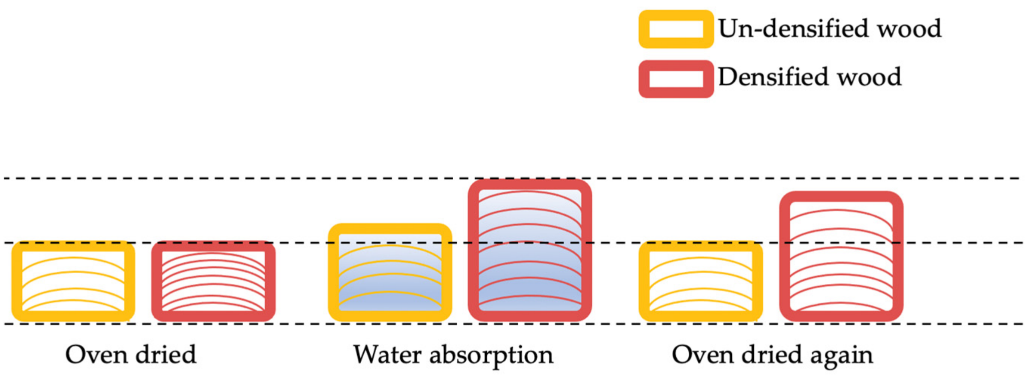


Figure 3. Schematic representation (cross-section views) of the swelling and set-recovery of un-densified and densified wood under a moistening–drying cycle.

2.1.3. Rotary Welding of Wooden Dowels

The frictional-welding technique is widely used in metal and plastic joining and for some decades it has been studied for the joining of wooden parts. The technique is tribologically driven since the connection is achieved by the relative movement of two pieces of material under pressure. The friction generates heat at the contact interfaces, and this leads to melting of the material in the contact region and the formation of a bond-line or a weld after solidification of the melted material.

For wood, these techniques involve four different oscillatory movements: linear, orbital, circular, and rotary movements [42]. Figure 4 shows rotary welding of a cylindrical wooden dowel forced into a pre-drilled hole through two pieces of timber with simultaneous rotation. When the rotation stops, the lignin softened by the generated heat will solidify to bond the dowel and the pieces of timber together [43–45]. Joining by rotary welding yields a bond-line strength comparable to that of a conventional wood adhesive within several seconds, whereas it may take hours for a synthetic wood adhesive to cure [42].

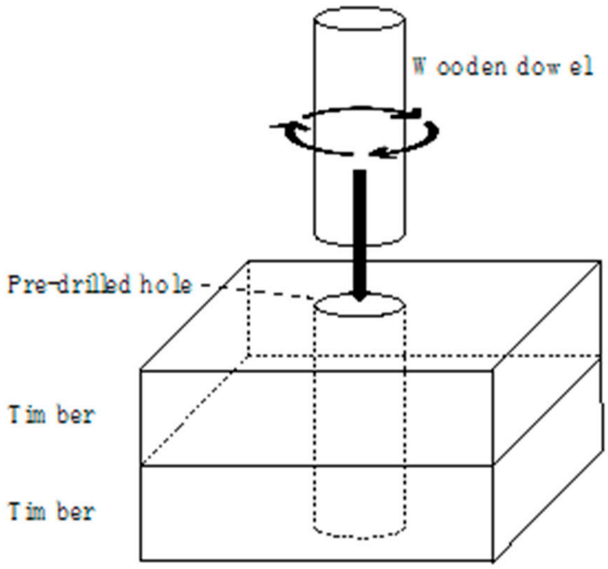


Figure 4. Schematic representation of wooden dowel rotary welding.

Figure 5 shows a circular-welded bond-line between two pieces of Norway spruce. The bond-line consists of two distinct regions: (1) a central region of "melted wood" with a completely destroyed cell structure where the lumen of the cells has collapsed due to densification and severe degradation of the cell-wall material has occurred. (2) Adjacent area where cells have collapsed, but the thermal degradation was not as severe, resulting in a more wood-like densified cell structure. The compression ratio of these two regions gradually decreases with increasing distance from the central bond-line until unaffected wood cells are reached.

The performance of the welded bond-line is strongly dependent on the applied process parameters, the assembled wood species, and its properties. On the one hand, the rotary-welding process parameters, such as rotation speed, time, dowel length, and diameter directly affect the tribological properties of the interface of the welded surfaces. On the other hand, the chemical composition, anatomy, and MC of the welded wood affect the heat generated and change the microstructure and chemical composition, and thereby indirectly affect the tribological properties of the welded surface interface and in the end, the welded bond-line strength [46].

Rotary welding with wooden dowels has been successfully introduced for both softwoods (fir, pine, spruce) and hardwoods (beech, birch, fir, larch, maple, oak), and also for bamboo [47–54]. Due to differences in the anatomical structures and chemical compositions of the main wood components (particularly hemicelluloses and lignin), the welding performances of different species are highly variable [48]. Belleville and co-workers [55] reported that wood species containing more condensed chemical components could form stronger welded bond-lines. Beech wood is the most studied species and has been found to be very suitable for the rotary welding of dowels [51]. In general, the strength of a welded bond-line increases with increasing wood density [47,49]. Wood-based panels such as medium-density fibre board (MDF), particleboard, plywood, and oriented strand board (OSB) can also be welded with dowels in the same way as solid wood [56].

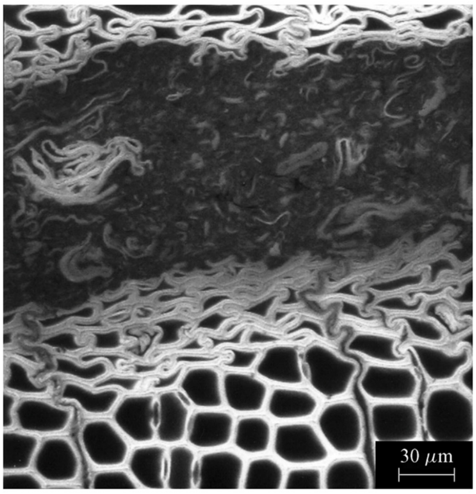


Figure 5. Micrograph of a bond-line between two pieces of Norway spruce joined by circular friction welding [24].

During rotary welding, the rotation speed needs to reach 1200–1600 rpm to generate enough heat to achieve a melted interface. If the rotation speed is above 2500 rpm, the interface temperature will exceed 300 °C and severe degradation of all the main wood constituents will occur, resulting in a weaker welded bond-line [57,58]. To keep the welding time short in rotational welding, it is needed to optimise the dowel insertion rate and dowel rotation speed to achieve a proper bond-line performance [59]. The critical parameter to obtain a high welded bond-line strength is the difference in diameter between the dowel and pre-drilled hole. The dowel diameter is always larger than the hole diameter, and the greater the difference in diameter, the greater is the lateral pressure between the wood dowel and the boundary surfaces of the hole. Consequently, the frictional force increases, and more heat is generated, but the densification of the welded bond-line material also increases. Several studies have confirmed that the optimal ratio of dowel-to-hole diameter is 1.25 [48,60,61].

Figure 6 shows how the dowel and the hole change from being a cylinder to a truncated cone during rotary welding, caused by the enforced insertion of the dowel into the pre-drilled hole with a smaller diameter. There is a risk that the progressive reduction in diameter of the dowel reduces the welding quality in the deeper welding area. It has been reported that the lowest welding temperature along the pre-drilled hole was detected at the bottom of the hole due to the wear of the tip of the dowel [49,60,62].This problem can be remedied by making the hole with two different diameters at different depths [49,52,60,63]. In Figure 6, it can be seen that a mix of fused intercellular material and some detached wood fibres has seeped into the gap between the two wooden blocks. By applying pressure, the seepage of the molten material can be avoided, and a stronger weld can be achieved. Figure 6 also shows that the welded bond-line is tight only in a part of the interface. There are two reasons behind this uneven welding: (1) The alignment of the pre-drilled hole is seldom perfect, especially when a hand-held drill is used, and this means that the pressure and friction force are higher on one side of the dowel, and that the welding is better on one side [64]; (2) The contraction on cooling of dowel and pre-drilled hole differ. Nonetheless, the pull-out resistance of an uneven bond-line is comparable with that of a bond-line of polyvinyl acetate (PVA) adhesive. If a perfectly welded bond-line can be achieved, the performance of the welded joint can be further improved [49].

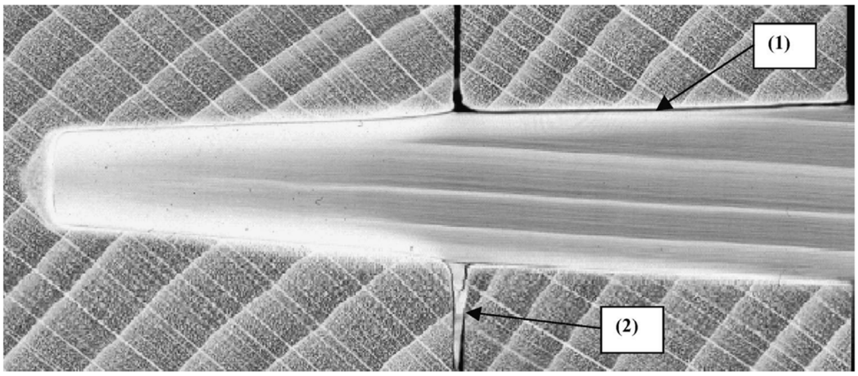


Figure 6. X-ray micrograph of a rotary-welded dowel of beech inserted in beech blocks. The white regions around the dowel correspond to high degree of densification of the welded bond-line; (1) welding has not occurred, or the bond-line has been damaged during the welding; (2) Molten intercellular material which has seeped into the fissure between the two blocks [24,49].

The welded depth, and consequently the welded area, is a factor determining the pull-out strength of the welded dowel. The greater this area, the higher the strength, irrespective of the conditions used. Over a certain welded area, the dowel breaks in tension during the pull-out tests and this means that the welded bond-line is stronger than the dowel itself [50,65]. When the welded depth exceeds 200 mm, there is splintering at the base of the dowel due to the high force required to achieve deeper insertion [66] (Figure 7). Pre-lubricating the dowel surface with sunflower oil before welding has been shown to reduce the friction in the pre-drilled hole and reduce the splintering of the dowel [67]. Xu et al. [68] explored the use of THM-densified dowels in rotary welding, and the effect of welding parameters (dowel-to-hole diameter ratio, the depth of the predrilled hole, the insertion direction relative to the lamella, and type of dowel material) on the pull-out resistance was analysed. The results showed that with an increase in dowel length, the pull-out resistance was higher and that the use of a densified wooden dowel reduced the risk of dowel fracture.

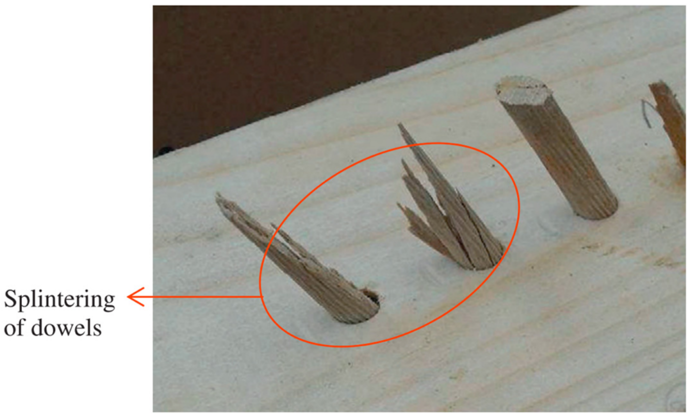


Figure 7. Splintering of beech dowels (Φ = 10 mm, length = 200 mm) in rotary welding of a 152 mm thick beam of spruce [66].

The fibre orientation has a considerable influence on the friction coefficient during welding and on the type of fibre entanglement which develops during the welding process. The friction coefficient is higher when the fibre direction of the dowel is perpendicular to the blocks to be joined, than if the orientation is parallel [69]. This influences the strength of the welded bond-line. The pull-out resistance of the welding dowel inserted perpendicularly to the substrate grain is greater than when the dowel is inserted along its longitudinal direction [49,60] (Figure 8). The dowel welding in the radial direction of a block showed a higher strength than welding in the tangential direction [47,60], although contradictory results have also been reported [51].

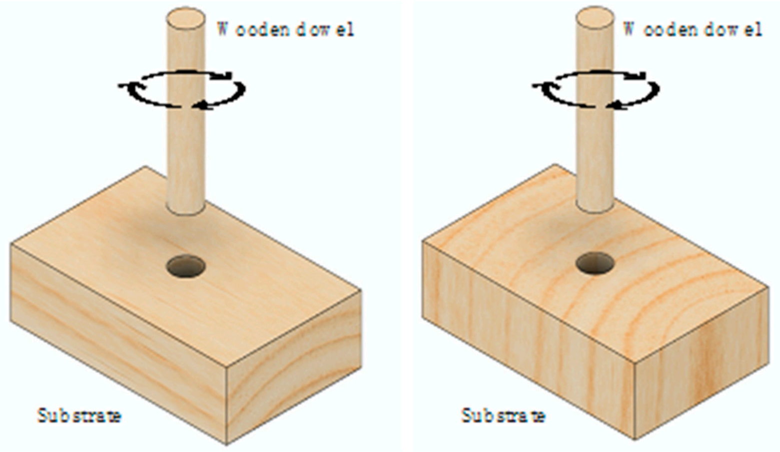


Figure 8. A dowel inserted into a wooden block in rotary welding: (**a**) perpendicular to, and (**b**) parallel with the fibre orientation of the block.

Preheating and drying of the dowels at 100 °C before rotary welding gives a bond-line with a better mechanical performance in three ways: (1) the preheating helps the temperature to reach the "melting" state, (2) the elimination of moisture in the wood leads to increased friction and increases the generated heat [70], and (3) the dry dowels absorb moisture from the surrounding and swell, increasing the pull-out resistance [47,60,71].

The addition of rosin, a non-toxic, water-repellent derived from wood substance, to the wood surfaces before rotational welding increases the water resistance of the welded bond-line [72,73], and low molecular weight acetylated lignin derived from wheat straw or from depolymerised wood lignin has been shown to improve both the strength and the water resistance of rotary-welded dowel joints. Although the improvement in water resistance is not as good as that achieved by adding rosin, the welded dowel joints with added acetylated lignin exhibit a considerable ductile behaviour of the welded bond-line in pull-out resistance tests of the joint after the maximum force is achieved. It is suggested that this ductile behaviour is an effect of the thermoplastic behaviour of the acetylated lignin which is intermeshed with the interphase in the bond-line [74]. Immersion in a copper (II) chloride ($CuCl_2$) solution can be used to pre-treat wood dowels before rotary welding. Due to its slightly acidic nature, $CuCl_2$ can promote hydrolysis of cellulose and hemicelluloses by reducing the hydrolysis temperature and providing more molten materials for welding and the pull-out resistance of the dowel is then increased [75–77]. Additives such as ethylene glycol, a chemical known to lower the glass-transition temperature of lignin may also increase the bond-line strength [49,60]. Yin et al. [73] studied the influence of various additives, including rosin, guaiac resin, glucose, tung oil, nitrogen oxides, and nano-crystalline cellulose materials on the tribological and mechanical properties of wood-dowel rotary-welding joints and showed that the strength of the welded bond-line increased when glucose and rosin were added but that nitrogen protection during welding had no effect on the strength. Tung oil, cellulose, and guaiac resin lowered the bond-line strength.

2.2. *Dowel-Laminated-Timber (DLT)*

The mechanical behaviour of wooden dowel-type connections under load is affected by physical and geometric factors, including but not limited to the species of the lamellae and dowels, the number and thickness of the lamellae, the direction of load, the MC of lamellae and dowels, the dowel diameter and its mechanical properties, the spacing of dowels, the tolerance of the fabrication, embedding strength and embedding modulus of lamellae. The results of various property tests on DLT members based on different manufacturing processes are presented in Tables 1 and 2. Most of the research on DLT has focused on bending and shear tests on materials made up of Norway spruce and Scots pine lamellae, and European beech dowels, and on DCLT also European oak lamellae combined with Norway spruce dowels.

Table 1. Summary literature data on dowel laminated timber (DLT) panels and beams.

Lamellae Species	Dowel Species	Dowel Type	Test	Comparison with Equivalent GLT	Reference
Larch	Beech	Untreated	Four-point bending test	Yes	Plowas et al. [17]
Spruce	Beech	Untreated	Monotonic and cyclic tests	Yes	Sandhaas and Schädle [78]
Fir, pine, spruce	Hickory	Untreated	Pull-out resistance and four-point bending tests	Yes	Ogunrinde [79]
Pine	Beech	Untreated	Three-point bending	Yes	Dourado et al. [80]
Spruce	Oak, salvaged plywood or LVL	Untreated	Push-out shear and four-point bending tests	No	Derikvand et al. [81]
Pine	Pine	Densified	Four-point bending test	Yes	Sotayo et al. [82]
Pine	Pine	Densified	Push-out shear and four-point bending tests	Yes	Bouhala et al. [83]
Pine	Pine	Densified	Long-term pull-out resistance test	No	Mehra et al. [84]
Spruce	Spruce	Densified	Four-point bending test	Yes	O'Ceallaigh et al. [85]
Pine	Beech, pine, spruce	Densified	Four-point bending test	Yes	Sotayo et al. [86]
Spruce	Spruce	Densified	Bending creep test	Yes	Bouhala et al. [87]
Beech, spruce	Beech	Rotary welding	Push-out shear and four-point bending tests	No	Bocquet et al. [88]
Spruce	Beech	Rotary welding	Four-point bending test	No	O'Loinsigh et al. [66,89]
Maple	Maple	Rotary welding	Three-point bending	Yes	Belleville et al. [90]
Fir, spruce	Beech	Rotary welding	Push-out shear and three-point bending tests	No	Girardon et al. [91]

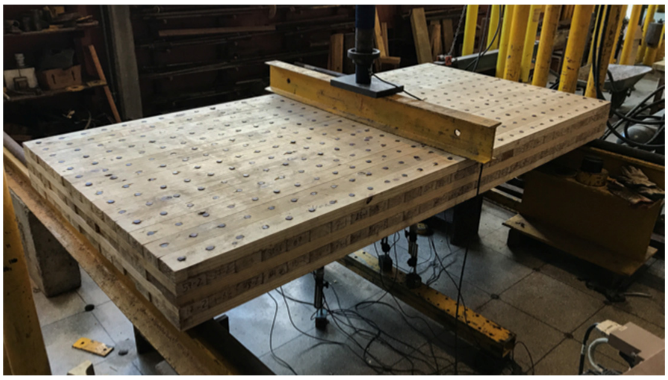
Table 2. Summary of data on dowelled cross-laminated timber (DCLT).

Lamella Species	Dowel Species	Dowel Type	Test	Comparison with Equivalent CLT	Reference
Pine	Pau-roxo	Untreated	Push-out shear and three-point bending test	Yes	Pereira et al. [92]
Fir, pine, spruce	Poplar	Densified	Push-out shear and four-point bending tests	Yes	Xu et al. [93]
Oak	Spruce	Densified	Push-out shear and four-point bending tests	Yes	El-Houjeyri et al. [94]
Oak	Spruce	Densified	Vibrational serviceability test	No	Bai et al. [95]
Oak	Spruce	Densified	Fire resistance test	Yes	Tran et al. [96,97]
Pine	Beech, pine,	Densified	Four-point bending test	Yes	Sotayo et al. [86]

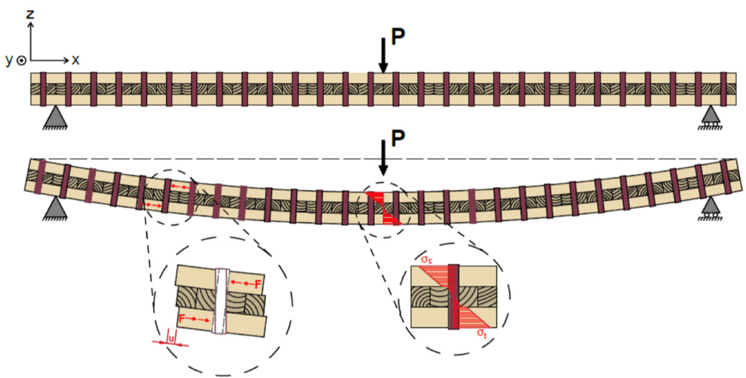
2.2.1. DLTs Assembled with Untreated Wooden Dowel

Plowas et al. [17] assembled dowel-laminated timber panels based on larch lamellae with beech dowels, the lamellae being oriented parallel to each other. Four-point-bending tests were carried out to determine the mechanical properties. The average modulus of elasticity (MOE) and modulus of rupture (MOR) of beams were about 10 GPa and 34 MPa, respectively. The panels broke mostly due to tension failure in the bottom edge of the beam where noticeable macro-defects such as knots were located. Sandhaas and Schädle [78] studied the behaviour during an earthquake of shear walls made from Norway spruce DLT and compared them with shear walls made from adhesively bonded CLT. The DLT shear walls were assembled with beech dowels with a spacing of 300 mm. Monotonic and quasi-static reversed cyclic tests on the walls proved that the DLT walls had a stiffness, load-carrying capacity, and energy-dissipation properties similar to those of the CLT walls.

Pereira et al. [92] compared wooden dowels with adhesive in CLT. Two analytical design methods (Mechanically Jointed Beams Theory and Shear Analogy Method) were applied to determine the flexural properties for an out-of-plane loading of the DCLT. Scots pine and Pau-roxo were used for the lamellae and dowels respectively in three-layer and five-layer DCLT. Three-point bending tests on the DCLT were carried out to determine their flexural properties. By comparing the deflection curves and stiffness, both the Mechanically Jointed Beams Theory and the Shear Analogy Method were experimentally validated. When the number of lamella layers was increased from 3 to 5, the longitudinal bending stiffness increased from 727 to 1353 kN/m^2 while the bending strength decreased from 20.4 to 16.7 MPa. It was also stated that the stiffness of three-layer DCLT panel was 30% lower than that of the equivalent CLT panel. This value dropped to 75% for the five-layer panels. Because a glued bond-line in CLT is rigid, the deformation of CLT is almost due to the shear deformation of individual lamellae, whereas in DCLT, the deformation consists of both dowel connection slip and the shear deformation of individual lamellae. The overall in-plane shear deformation of DCLT (Figure 9) during the bending tests was therefore much greater than that of the equivalent CLT. Since there were more dowel layers in the five-layer DCLT panel, there was an accumulation of deformations as there are proportionally more slips in the five-layer DCLT panel than in the three-layer panel.



(a)



(b)

Figure 9. Three-point bending tests of a DCLT: (**a**) longitudinal bending test, and (**b**) interlayer in-plane slip movement, shear and bending forces in the panel [92].

Ogunrinde [79] investigated the influence of dowel swelling on the pull-out resistance of dowelled joints and showed a clear linear relationship between the pull-out resistance and the initial MC of the dowel. A lower initial MC of the dowel increases the possibility to achieve a tighter connection in the DLT. Ogunrinde also carried out four-point bending tests to evaluate the flexural properties of full-scale seven-layer DLT beams with lamellae and dowels of spruce and hickory, respectively. GLT beams with the same dimension were manufactured and tested for comparison. The GLT beams exhibited a higher stiffness and strength than DLT beams. The larger adhesive bond-lines area in the GLT beams helped the load transmission and held the lamellae together, in contrast to the DLT beams in which the load was transferred mainly through the dowels with a small cross-section area. The pre-drilled holes in the DLTs may also contribute to the propagation of cracks under loading reducing the mechanical properties [63].

Dourado et al. [80] manufactured two-layer DLT beams of maritime pine lamellae with European beech dowels, using an epoxy adhesive to join the dowels to the lamellae with different dowel insertion angles (30°, 45°, 60°, and 90°). GLT beams of the same dimension were tested for comparison. Among the DLT beams, the highest bending stiffness and failure load were achieved with a 45° dowel insertion angle. The bending stiffness of DLT with a 45° dowel insertion angle was about 50% of that of the equivalent GLT beam, while its failure load was 20% lower than that of the equivalent GLT beam. As shown in Figure 10, the dowel can be subject to, e.g., pure shear, shear with tension, and shear with compression depending on the insertion angle of the dowels. A joint with a 90° insertion angle deforms under a pure shear stress (Figure 10a), whereas the joint with a 45° insertion angle is subjected to a combination of much lower shear and tensive stresses (Figure 10b); and the dowels were thus slightly deformed. When the insertion angle is less than 90°, a tighter joining of the lamellae is achieved under load, but when the insertion angle exceeds 90° (Figure 10c), the lamellae tend to separate under a load [98,99]. Overall, the joint with an insertion angle of 45° showed the best stiffness and highest maximum failure force of all the tested insertion angles [88].

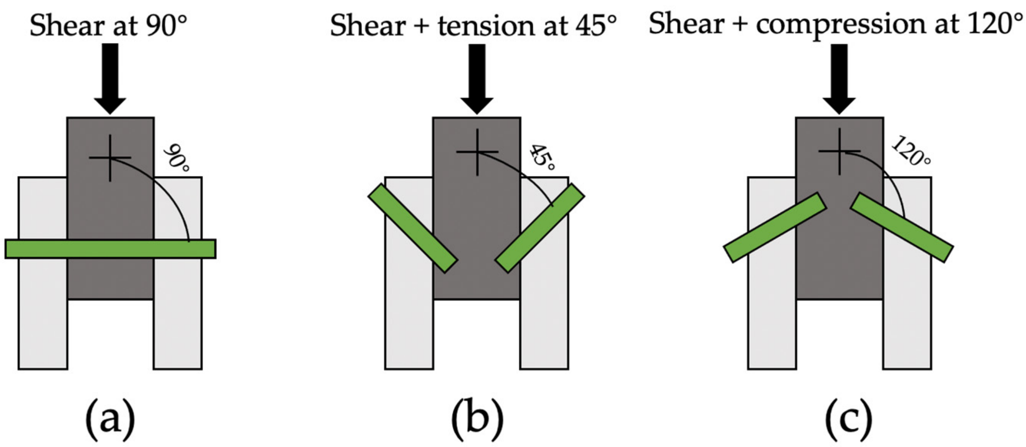


Figure 10. Schematic representation of different dowel insertion directions, and the type of load the dowels are subjected: (**a**) shear, (**b**) shear and tension in combination, and (**c**) shear and compression in combination. Redraw from [88].

Derikvand et al. [81] replaced European oak dowels with tenons made from salvaged (recycled) EWPs such as LVL and plywood in three-layer DLTs made from Norway spruce lamellae, and subjected them to push-out shear and four-point bending tests. The tenons made with salvaged plywood tenons result in DLTs with higher bending stiffness than DLTs made with solid hardwood dowels. It was concluded that the material properties of the salvaged EWPs need to be determined before they can be used as dowels or in other load-bearing applications.

Bouhala et al. [87] modelled the bending creep behaviour of DLT beams assembled with densified wooden dowels and validated the model with experimental three-point bending tests. According to the model analysis, the bending stress was concentrated in the centre of the beam. The creep resistance of the DLT beam compared with that of the massive beam and the layered beam could be increased by using densified wood dowels, especially when the number of dowels increases.

2.2.2. DLTs Assembled with THM-Densified Wooden Dowels

In 2006, Jung et al. [20] reported use of THM densified Japanese cedar dowel connectors in the Japanese traditional post and beam structure, and the effects of cyclic humidity changes. They [100] also evaluated the structural performance of THM-densified wood dowels by carrying out double wood-to-wood shear tests (Figure 11). In the radial direction, densified cedar (70% CR at 130 °C for 30 min.) wooden dowels exhibited a greater stiffness, strength, and ductility than maple dowels with properties very close to those of a steel pin, and dowels with a square cross-section exhibited a higher stiffness and maximum load than dowels with a circular cross-section and similar cross-section area. Jung et al. [20] also reported that densified dowels with the growth rings parallel (0°) to the loading direction exhibited better bending and shear properties than densified dowels with a 90-degree growth-ring orientation with respect to the loading direction (Figure 11). During the double wood-to-wood shear tests, the undensified dowel failed by bending at the centre of the dowel whereas the densified dowel was able to maintain its load-carrying capacity. The ultimate load of the joint increased linearly with increasing density of the base member but increasing density of the base member had a negative influence on the ductility of the joint.

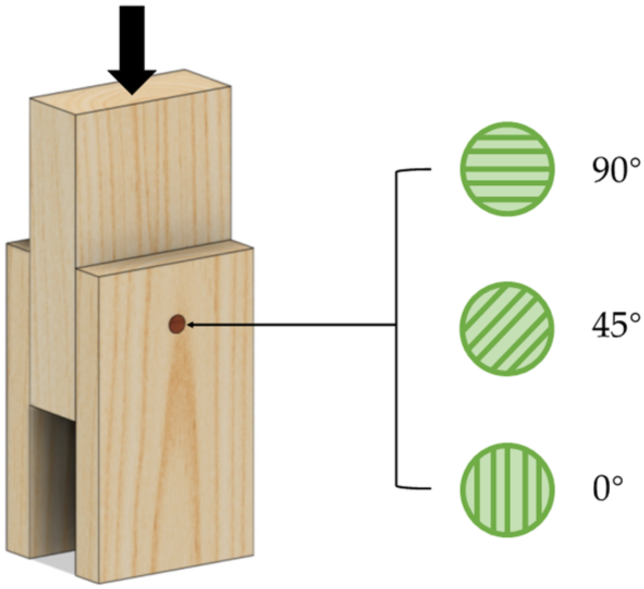


Figure 11. Dowel orientation in relation to the load direction in a double wood-to-wood shear test.

In 2009 and 2010, Jung et al. [101–103] studied densified Japanese cedar as dowels loaded in shear in beam–column, beam–beam, and glued-in-rods systems (Figure 12), and the results showed that the densified dowels exhibited a relatively higher pull-out strength and joint rotation performance than conventional maple dowels. The mechanical properties of the glued-in-rod joints using densified dowels also remained after exposure to cyclic humidity and after soaking for 24 h in cold water and they stated that densified wood could act as a suitable substitute for maple in dowel connections, especially where severe compression or a high shear-stress concentration occurs.

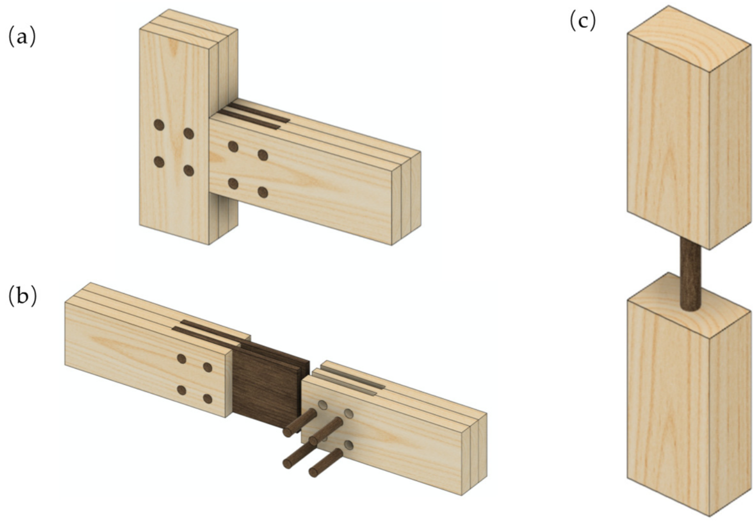


Figure 12. Examples of applications using the densified wood as connection materials: (**a**) beam–column connection, (**b**) beam–beam connection, and (**c**) glued-in-rod joint.

Chang et al. [18] studied glued-in-rod connections with densified wood dowels and found that the average push-out resistance decreased with time after fabrication. The push-out force for densified wood dowels measured 2 days and 90 days after fabrication was 22% and 27% lower than the force measured 2 h after fabrication. During bending, a beam assembled with densified dowels normally failed in a ductile manner, which is favoured in structural applications to avoid a catastrophic brittle collapse. After achieving the maximum bending force, the dowel made from densified wood still provided about half the moment capacity by its set-recovery-swelling-induced frictional resistance. It was also reported that dowels with a high density resulted in brittle failure. Densified dowels with a density higher than 700 kg/m^3 were not able to form hinges to provide residual frictional resistance in the early stages of deformation.

Xu et al. [104] explored the possibility of using densified low-density poplar dowels as a replacement, in timber constructions, for steel dowels to connect timber members. The results of double timber-to-timber shear tests showed that joints with densified poplar dowels exhibited favourable load-carrying capacity and ductility values compared with grade 4.8 steel dowel calculated according to Eurocode 5. Xu et al. [104] reported that densified dowels with growth rings perpendicular (90°) to or at an angle of 45° to the loading direction exhibited higher ultimate load and ductility than the densified dowels with growth rings parallel (0°) to the loading direction. The same group [105,106] studied the mechanical properties of wooden dowels densified by a two-step densification process starting with an alkali pre-treatment to remove the hemicellulose and lignin from wood. The results showed that the density, MOE, MOR, and dimension stability of poplar were significantly increased after delignification and densification. The timber-to-timber joints assembled with this type of densified dowel exhibited a load capacity, stiffness, and ductility similar or even higher than those of hardwoods such as beech, maple, and oak. The tight fit of densified wood dowels due to their set-recovery significantly increases the ultimate load-carrying capacity of timber joints. Xu et al. [93] showed in three-layer DCLTs assembled by densified wooden dowels that, although the bending stiffness and strength of DCLTs were only 20% and 30%, respectively, to the values of CLT, the DCLT was a significantly more ductile.

More recently, an adhesive-free timber building (AFTB) project [107] using THM-densified wood dowels reported some interesting findings:

(1) Namari et al. [108] carried compression, tension, bending, embedment, yield moment, push-out shear, and impact tests to evaluate the mechanical properties of THM-densified wood and the results provide important information which engineers can

use for further application of THM-densified wood in load-bearing elements and wood-based connectors for use in timber structures. THM-densification significantly improved the strength and stiffness properties of low-density softwoods such as pine and spruce. Densified wood dowels showed a higher yield moment capacity than beech or oak dowels.

(2) Timber–connection applications (beam–beam, beam–column connections) made from GLT, or DLT fastened by steel or densified wooden dowels and reinforcement plates were tested [109–112]. The mean failure load and rotational stiffness of the densified dowel connections was about 20% lower than the values for equivalent steel connections, but compared to un-densified wooden dowels and plates, this was a high-strength performance. Thanks to the high shear strength of densified wooden dowels, and the improved bending and embedment properties of the reinforcement plate compared to those of the undensified wood, the test results indicated that increasing number of densified dowels and increasing the thickness of the densified reinforcement plates increases the moment-carrying capacity but leads to brittle failure of the joint.

(3) El-Houjeyri et al. [94] manufactured three-layer DLT beams of Norway spruce lamellae with undensified European oak or densified Norway spruce dowels. Densified wooden dowels showed a greater strength, stiffness, and ductility than the un-densified oak dowels during monotonic push-out shear tests. Under four-point bending, reference GLT beams exhibited twice the stiffness and a 30% higher load-carrying capacity than the DLT beams. Nevertheless, the DLT beams exhibited higher ductility than the GLT beams because of the dowel shearing which involves high-energy dissipation.

(4) Sotayo et al. [86] tested DLT beams and DCLT made of Scots pine lamellae with densified Norway spruce, Scots pine, or European beech dowels. In the four-point bending test, there were various failure modes of DLT beams and DCLT including tensile failure in the bottom layer, fractures around inherent knots, and the propagation of damage along the pre-drilled holes. No visible damage to the dowels themselves was observed. The stiffness and strength of DLT beams and DCLT were significantly lower than those of reference GLT beams and CLT, but greater ductility of DLT beams and DCLT was reported. Dowel-insertion angle, and dowel species had no significant influence on the stiffness of DLT beams and DCLT. The larger diameter of the densified dowels and the greater number of dowels per unit area resulted in an increased stiffness of the DLT beams and of the DCLT.

(5) Bai et al. [95] studied DLT beams and CDLT made of European oak lamellae with densified Norway spruce dowels to evaluate the vibrational serviceability comfort and they found that DLT panels exhibited a satisfactory vibrational performance compared to the Eurocode 5 vibrational serviceability design requirements.

(6) Mehra et al. [84] investigated the influence of accelerated ageing under cyclic dry and moist climate conditions on the pull-out resistance of densified Scots pine and undensified European beech dowel-type fasteners, and showed that the shape-recovery of the densified dowels increased the pull-out strength and improved the long-term performance of the dowel-to-lamellae connection (Figure 13).

(7) Tran et al. [96,97] developed models to predict the thermomechanical behaviour during a fire resistance test of wood components assembled with THM-densified Norway spruce dowels and showed that the THM-densification of dowels leads to an increase in the thermal conductivity coefficient, the heat release rate, the thermal inertia while reducing charring rate and the mass loss compared to undensified wood.

(8) Several studies have focused on optimising DLT performance by studying the influence of the mechanical properties of dowels and layers, the thickness of the assembled layers, the spacing of dowels (or the number of rows of dowels), the diameter of dowels through both experimental testing and finite element (FE) models, on the mechanical performance of the assembly [82,83,85,112,113]. Typically, increasing the

number of dowels per unit area (reducing dowel spacing) leads to an increase in stiffness of the DLT, whereas a larger dowel diameter (pre-drilled hole diameter) results in a reduction in the net area of lamellae to resist a tensile force under bending and reduces the load-carrying capacity of the DLT. Higher stiffness and strength of DLT were achieved when a smaller number of lamellae were used, leading to fewer interlayer partial composite actions.

Figure 13. Set-recovery of a dowel made of densified Scots pine (left), and swelling of a non-modified European beech dowel after accelerated ageing [84].

2.2.3. DLT Assembled by Rotary-Welded Wooden Dowels

Bocquet [114] reported that in suspended flooring elements assembled by rotary-welded dowels, the displacement of the loaded floor was low and its vibration frequency high. The displacement of the floor under a static load satisfied the requirements of Eurocode 5. Scaling-up of the rotary welding technique for wooden dowels is feasible. Bocquet et al. [88] assembled two-layer European beech and Norway spruce DLT beams with European beech dowels with a diameter of 8 mm by rotational welding. The dowels were inserted in a single row at an angle of 30° to the longitudinal direction of the lamellae, of intervals of 28 mm along the beam. Beams of the same dimensions joined by (1) dowels bonded with PVAc adhesive, and (2) ordinary steel nails were also prepared, and the results showed that the welded-dowel beam was stiffer in bending than both the nailed and PVA-bonded dowel beams, but that the maximum failure force in bending was not significantly difference. Due to the better mechanical properties of beech lamellae, the failure force and stiffness in bending of the beech beam were much higher than those of the spruce beam.

O'Loinsigh et al. [66] assembled four-layer Norway spruce DLT beams with European beech dowels by rotational welding, the dowels being inserted in a single row at an angle of 60° to the longitudinal direction of the lamellae and studied the effect on the bending performance of varying the number of dowels. Lamellae of the same dimension without adhesive or dowels were prepared for comparison. The results showed that the bending stiffness of the welded dowel beams was about three times higher than that of reference beams and that the difference in bending strength of welded beams and reference beams was approx. 14%. The 3D stress analysis of the multi-layered wooden beams made with welded-through wooden dowels indicated that the bending stiffness of welded-dowel beams could be increased by (a) increasing the mechanical properties of the dowels and of the top and bottom lamellae, (b) increasing the number of dowels, and (c) increasing the thickness of the lamella in the neutral plane [89,91].

Figure 14 shows edge-wise joining of two pieces of sawn timber by rotary-welded dowels in a zig-zag configuration [115]. Tests showed that this joint could resist accelerate d of ageing through immersion in boiling water and subsequent oven drying at a temperature of 103 °C. Rodrigues et al. [48] also reported that welded-dowel joints showed greater tensile strength after exposure to water than PVAc-glued dowel joints, although this type of joint could not meet the requirements of exterior-grade standards for structural application [116].

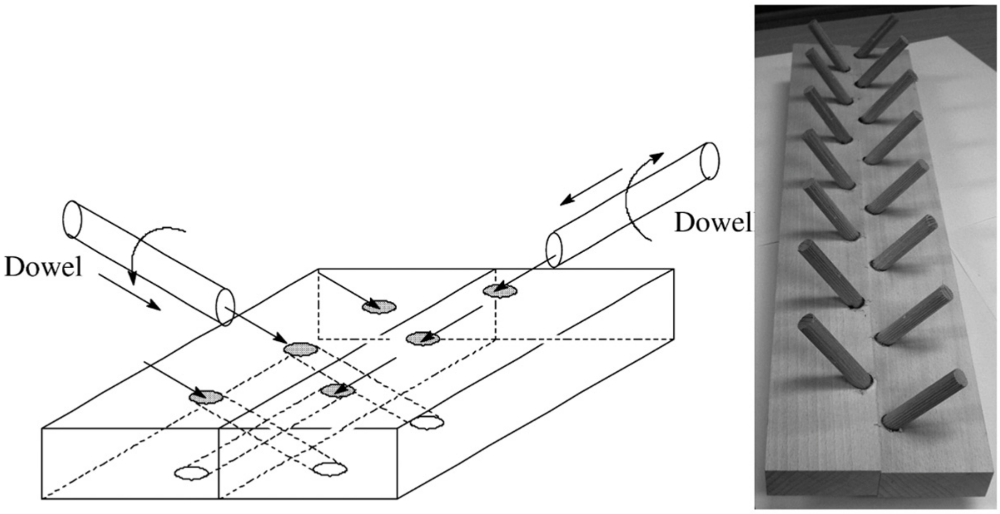


Figure 14. A joint of two pieces of wood edge-wise joined by rotary-welded wooden dowels in a zig-zag pattern [115].

Belleville et al. [90] tested birch and maple panels joined edge-wise with either PVA adhesive or rotary-welded dowels. A three-point bending test showed that the adhesive-bonded panels were about four times stiffer and stronger than the dowel-welded panels, and that failure of adhesive-bonded panels under bending was brittle whereas the dowel-welded panel showed a ductile failure. In all cases, the dowel-welded panels showed failure in the dowels at the midspan of the panel or adjacent lamella, without slippage along the welded interface. The swelling of the dowels under moist climate conditions resulted in a tighter connection between the dowel and the surrounding wood and improved the bending properties of the panel.

2.3. Design Rules

The strength, deformation behaviour, internal force distribution, durability, and fire resistance of DLT are highly related to the strength and stiffness of the connections within DLT. A dowel-type connection is commonly used in timber construction, but the literature relating to the use of non-metallic connections within timber constructions is comparatively limited and the analysis of connections made with non-metallic fasteners typically follows the methods accepted for metal fasteners.

According to Eurocode 5 [117] and the National Design Specifications for Wood Construction [118], the calculation of timber-dowel connections is based upon Johansen's pin-joint theory, which is also referred to as the European Yield Model (EYM) [117–119]. This model is, however, suitable only when the connection fails in a ductile mode and it does not apply to wooden dowel yielding plastically in bending due to the shear loads. In EYM, the failure modes of a dowel joint are classified as Modes I, II, III, and IV to calculate the ultimate load-carrying capacity of a timber-to-timber joint under a double shear load (Figure 15). Modes I and II involve an embedment failure of the connected lateral timber or central timber without any yielding of the fastener. Mode III occurs when the dowel develops a plastic hinge in bending, while simultaneously crushing the connected material. Mode IV represents a combination of embedment failure of the connected material and multiple yield failures of the fastener, which occur when plastic hinges form in both the main and side members in combination with base material crushing. Wood-to-wood connections exhibit a load-bearing behaviour different from that of metal connections. As a result, an additional "Yield Mode V" was introduced, which is a combination of bearing, bending, and shear perpendicular to the grain of the dowel [120].

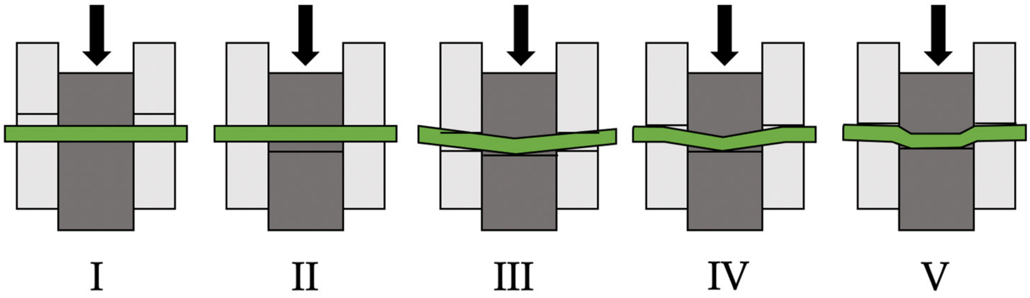


Figure 15. Failure modes of timber-to-timber joints with wooden dowels. Redraw from [117].

2.4. Manufacturers of DLT

In 2022, there were approximately 20 manufacturers in Europe producing DLT (Table 3) for structural walls, composite flooring, ceilings, and roof systems. DLT production requires a relatively small initial capital investment, and it has a potential for both small and medium enterprises (SMEs) as well as multinational companies. Because there is very little that can be referenced from the standards worldwide, the manufacturers normally provide design guidelines and technical information for their DLT themselves, and are approved by a building authority, such as the European Technical Assessment (ETA), on a case-by-case basis.

Table 3. Existing DLT manufacturers, 2022.

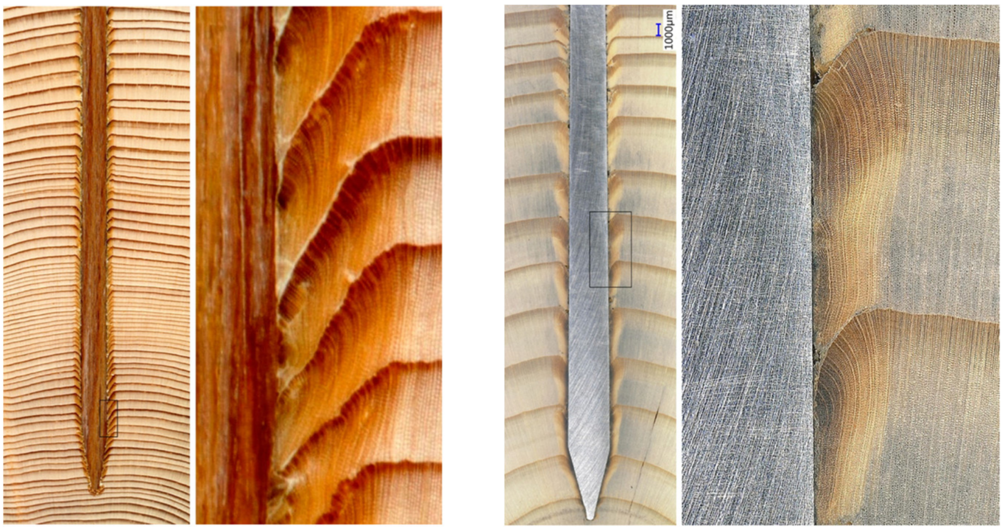
Manufacturers	Technical Assessment	Website
Biohabitat Service srl	ETA 13/0226 (2015)	https://www.biohabitat.it/
Ekobustas	/	https://www.ecobustas.lt/production/technology/brettstapel
Holzbau Willibals Longin GmbH	EAT-20/0403 (2020) and ETA-21/0835 (2022)	https://www.longin.at/holzbau-mit-system/londyb
IQWood	ETA 14/0334 (2014)	https://www.iqwood.com/
Kaufmann Massivholz GmbH	/	https://www.kaufmannbau.com/bauwissen/duebelholz/
Kaufmann Oberholzer AG	/	https://www.kaufmann-oberholzer.ch/bauen-engineering/holzleimbau-optiholzr.html
Kueng Holzbau AG	/	https://www.kueng-holz.ch/de
Nägeli Holzbau AG	/	https://www.naegeli-holzbau.ch/home.html
Rombach (Nur Holz)	ETA-11/0338 (2015)	https://www.rombach-nurholz.de/en.html
Sägerei Sidler AG		https://www.sidlerholz.ch/de/
Sohm Holzbautechnik GmbH	ETA-16/0480 (2016)	https://www.sohm-holzbau.at/diagonalduebelholz
StructureCraft	ICC-ES report (ESR-4069)	https://structurecraft.com/materials/mass-timber/dlt-dowel-laminated-timber
Suttner Massivholzelemente GmbH	/	https://www.holz-suttner.de/
Thoma Holz GmbH	ETA-11/0338 (2011) and ETA-13/0785 (2013)	http://www.thoma.at
Truber Holz AG	/	https://www.truberholz.ch/
Tschopp Holzbau AG	/	https://www.tschopp-holzbau.ch/1/BRESTA
Ulrich Zeh GmbH	/	https://www.ulrichzeh.de/
Weihele Holzbau GmbH	ETA-18/0960 (2018)	https://www.weihele-holz.de/leistung

Bell [121] carried out a detailed investigation into the engineering properties, barriers and drivers for the implementation of DLT on the domestic UK construction market, and pointed out that the successful implementation of DLT requires an awareness of perception criteria (appearance, availability, cost, structural performance, workability); suitability for purpose (flooring, roof, wall); relative advantages compared with existing products, and consumer understanding. The most obvious advantages of DLT products are low embodied energy, low VOCs emission, low thermal conductivity, and offsite construction speed. These benefits are however subservient to the safety and structural adequacy of the product in the situations in which they are used.

3. Other Adhesive-Free Assembling Techniques

3.1. Wooden Nail

A disadvantage of a wooden-dowel connection system is its necessity for pre-drill holes before insertion of the dowels. The connector can however be successfully inserted without pre-drilling holes if the connector resists the insertion process [122], as when elements are jointed with metal nails as the most popular solution for adhesive-free timber joints. Hand-operated hammer and pneumatic nail guns are widely used to drive nails into wood, at a speed of the nail of about 30 m/s with a conventional pneumatic nailing gun. This has been widely used in the past, particularly in shipbuilding and construction. The friction between the nail and the surrounding surfaces heats the interface to the glass-transition temperature and softens the cell-wall lignin. Solidification of the softened lignin when the temperature drops results in joining the wood members (Figure 16) [123]. Wooden nails ensure a firm fixing of the elements as they expand when exposed to moisture like wood dowels. However, the capacity increase only appears after the first moisture cycle while repeated moisture cycling of wooden nails results in a gradual loss of stiffness [124].



(**a**) (**b**)

Figure 16. Two types of nails radially inserted into Norway spruce: (**a**) a beech nail, and (**b**) a steel nail, shot with an air nail gun at 6 bar pneumatic pressure. A small darker region of melted and re-solidified lignin can be seen around the nails [123].

The high conductivity of metal fasteners affects the thermal performance and energy requirements of structures during service life, but the machinability of components joined with metal fasteners is extremely limited during both construction and end-of-life transformation. In contrast, as proposed by Hasan et al. [125] suggested that wooden nails could be used in a robotic fabrication process of nailed laminated timber.

Currently, the wooden-nail assembling technology is combined with other wood-modification technologies such as resin impregnation and wood densification. Riggio et al. [126,127] carried out compression-resistance tests and push-out shear-resistance tests on densified hardwood nails made from Black locust, European ash, European aspen, and European beech and they showed that the average shearing load-carrying capacity of timber-to-timber joints assembled by densified beech with 60% CR was about 550 MPa. Therefore, densified wooden nails are appropriate as connectors in standard timber assemblies. The authors mentioned that the densified wood nail was in some cases found to be damaged at the end because of excessive loading. The dynamic loading necessary to insert a wooden nail result in extensive buckling of the peg/nail column, and this may lead to fracture during nail insertion. Another damaging factor was a compressive stress concentration at the tip of the nail limiting the penetration into the wood components to be joined. This technology was therefore recommended for joining wood with medium density and without features such as knots. Otherwise, it is necessary to use densified wood together with a resin-impregnated composite [128]. It was also reported that both shear failure of the wooden nails and ductile failure of the timber-to-timber joints were observed, and this leads to a significant variability in the load-slip curves. It was concluded that further work is required to develop a procedure for densified-nail insertion and for design of joint geometry. Ruan et al. [99] explored the load-bearing capacity, slip modulus, and failure modes of connections with wooden nails, focusing on nail dimensions, orientations, and geometrical design. A typical three-member push-out shear-test setup was adopted, and they showed that the nail insert orientation which is exposed to both shear and tensile forces leads to a higher load-bearing capacity and a higher slip modulus. Typical failure modes of inclined nail joints were tensile failure of the wooden nails and pull-out failure.

The first market implementation of the wooden-nail technique was achieved by the LIGNOLOC® company [129] with a product in which thin hardwood (usually beech) slices are impregnated with a resin and joined to form a multilayer bio-composite made of sharpened cylindrical dowels with different diameters (Figure 17). The geometry of the wooden nail is optimised depending on the application and specific requirements. The declared application of this technology is a future-oriented industrial production and timber construction, with different types of EWPs such as LIGNOLOC® cross-laminated timber, and nail-laminated timber (NLT). The mechanical properties of the wooden nails currently available on the market allow their insertion into solid wood and wood-based materials without predrilling [125].

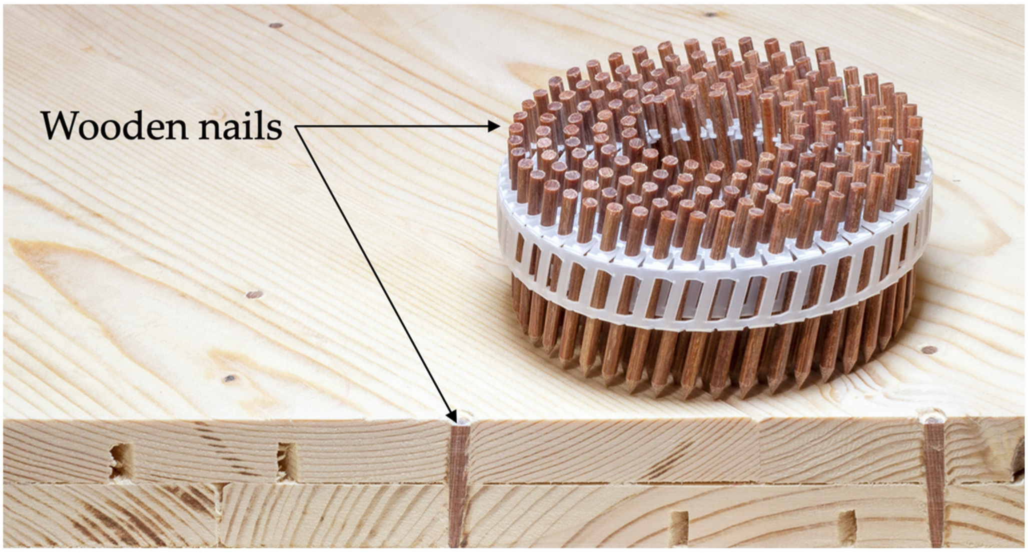


Figure 17. LIGNOLOC® wooden nails [129].

3.2. Dovetailed Panels

Traditional wooden fasteners are uncompetitive due to their high skill requirement and labour costs, but today, with the assistance of emerging digital fabrication and computer-numerical-controlled (CNC) machinery, it is possible to apply traditional wooden fasteners as a cost-competitive alternative to adhesives and metal fasteners for joining modern structures [130,131]. The European DoMWoB project investigated the development of dovetailed wooden panel (Figure 18) for multi-story buildings as a replacement for conventional EWPs [132], involving the design, manufacture, testing (fire resistance, airborne sound insulation, four-point bending, humidity behaviour and air-tightness), and market analysis for dovetailed wooden panels [133,134].

Figure 18. Prototype of a dovetailed wooden panel [133,134].

Another design of a dovetailed wooden panel is shown in Figure 19, where the two slab-panels oriented in a longitudinal direction are held together by wooden dovetail connectors oriented in a perpendicular direction [135]. Unlike CLT and other interlocked panels, there are gaps in the central layer to facilitate the introduction of ducts and electrical installation. Experimental bending tests showed that the stiffness and failure loads were influenced by the separation of the dovetail connectors. The observed failure mode was initiated by a rolling-shear failure on the dovetail connector, followed by a tensile failure in the bottom-layer region. Moltini and Baño [136] found that the bending deflection and shear stress on the connectors decreased with increasing height and width of the connectors.

Figure 19. Dovetailed wooden panel for use as a structural element in buildings [135].

3.3. Linear Wood-Welding Technology

Haha [137,138] produced several prototypes of CLT, multi-layered beams, and ceiling elements by linear wood-welding techniques, and Ganne-Chedeville et al. [49] applied those techniques for joining several kinds of EWPs, such as MDF, OSB, particleboard, and plywood (Figure 20). The mechanical properties of the linear frictional welding connections can be comparable to or even be superior to connections glued with conventional adhesives like PVAs. However, the performance is highly related to the applied manufacture parameters and assembles wood properties. Furthermore, unlike rotary welding joints with outstanding water resistance even in long-term, the linear welding joints are sensitive to moisture content change thus are limited for indoor use [43,44,139].

Figure 20. Potential industrial applications of the linear friction-welding technique in the form of multi-layered beams (**left**) and CLT (**right**) [137].

4. Conclusions and Future Research Directions

The main aim of this review paper has been to introduce a number of emerging adhesive-free techniques, especially wooden-dowel connections, for joining multi-layer panels into EWPs, considering their respective advantages and shortcomings, their technical difficulty, and their mechanical performance.

In general, the DLT and DCLT assembled by high density beech, oak, maple, and THM-densified pine and spruce dowels can provide sufficient load-bearing capacity compared to equivalent size GLT and CLT, but their relatively low stiffness under bending, normally 10 to 20% of equivalent size GLT and CLT, limits their application as structural elements. In addition, wood-viscoelasticity-induced strength loss, stress relaxation, and creep deformation may loosen connections during their service life. The use of THM-densified wood as a dowel in friction-locked joints is a solution to overcome such long-term performance problems and improve the mechanical properties of the whole DLT and DCLT systems. An in-depth characterisation and the development of a comprehensive non-linear model for predicting swelling behaviour would be useful. Since standards for densified wood are lacking, further research to establish guidelines for the production of densified wooden materials is also necessary. The optimised design of wood-densification processes will benefit by utilising the set-recovery and swelling behaviour of dowels. The rotary-welding technology could also enhance the strength and long-term performance of wooden-dowel joints, but its poor water resistance needs further investigation.

In term of DLT products, further research and development should be focused on the materials available, and a certification process is needed in order to bring a construction product onto the market. Technical guidelines for specification in accordance with national design codes are important for the manufacturers, designers, and contractors. Therefore, detailed research and development including, but not limited to, dimensional stability, fire resistance, vibration response, creep behaviour over time, out-door performance under biodegradation and weathering, thermal conductivity, acoustic properties, and environmental life-cycle impact assessment (LCA) need to be undertaken. The review on other emerging adhesive-free assembling techniques such as wood welding, wood nails, and dovetailed connections inspire the possibility to apply advanced wood-modification technology and machining technology to rejuvenate traditional wood-joining methods.

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