Out-of-grade sawn pine: A state-of-the-art review on challenges and new opportunities in Cross Laminated Timber (CLT)

Rebecca Cherry[a,b], Allan Manalo[a], Warna Karunasena[a,*], Geoff Stringer[b]

[a] Centre for Future Materials, University of Southern Queensland, Toowoomba, QLD 4350, Australia
[b] Hyne & Son Pty Ltd, Kent Street, Maryborough QLD 4650, Australia

* Corresponding authors.
E-mail address: Karu.Karunasena@usq.edu.au (W. Karunasena).

Abstract

Plantation softwood is the future timber material resource for building and construction. However, significant volumes of sawn softwood are considered out-of-grade and sold at a loss. New approaches and methods need to be implemented to value-add out-of-grade timber and increase structural yield from existing plantations. This paper provides a critical review of out-of-grade characteristics of pine timber to gain an understanding of the strengths and weaknesses of this resource as a structural building material. Methods to incorporate out-of-grade timber into current building systems are presented and building technologies that can facilitate this use are identified. Finally, it discusses developments and important considerations for design of cross laminated timber (CLT) as a prime example of a building system with good capacity to incorporate high volumes of out-of-grade timber. This provides critical information for the maximum utilisation of sawn out-of-grade pine and is anticipated to create new opportunities that can effectively incorporate this renewable and sustainable material resource into innovative building systems and technologies.

Keywords

Out-of-grade timber, low grade timber, Cross laminated timber, CLT, timber defects, building technology, building systems

1. Introduction

Timber is a well-used and familiar material, which possesses many excellent attributes for construction, is renewable, adaptable, diverse, has a range of good mechanical properties, has low relative embodied energy, low carbon impact and where sustainable practices are used through forestry and harvesting, it will be available indefinitely [1]. Timber stores carbon during all stages of the life cycle with 171 million, 103 million and 123 million tonnes of carbon stored in plantations, timber and timber products in service and landfill respectively in Australia in 2010 [2]. Ramage et al. [3] stated that cultural and engineering practice play a large role in the influences of timber use in many regions around the world. In Australia, local government associations and councils are seeing the benefits of timber and encouraging its use in building and construction.

Australia has over 1.9 million hectares of tree plantations [4], of which 1.036 million hectares are softwood [2]. Of these softwood plantations, 97.7% are managed to supply the Australian housing market with sawlogs [5] and structural framing products [6]. Pine timber from sustainable softwood plantations is the foreseeable future of timber construction. However, it is well known that significant volumes of sawn Australian softwood do not meet the Machine Graded Pine (MGP) structural framing requirements [7] of AS1748 [8] and AS1720.1 [9], and are considered out-of-grade. Cown et al. [10] found up to 27.5% of total boards were rejected in a validation study for 27 to 33 year old radiata pine. Based on sawmill recovery trials discussed by Harding [7], up to 57.5% of sawn board volume from 28-year old southern pines are failing structural framing requirements. With a volume of 4.4 million m^3 of sawn Australian softwood in 2015/16 presented by ABARES [2] and the more conservative 27.5% out-of-grade estimation, at least 1.2 million m^3 of sawn timber fell into out-of-grade for structural framing products. Predictions of increased demand and available resource in coming years [2] will lead to increased volumes of out-of-grade timber, and for sawyers these out-of-grade products have limited market opportunities and are often sold at a loss [11]. Therefore, the development of new and innovative building technologies from out-of-grade sawn pine will value-add and maximise utilisation of this timber resource.

Out-of-grade timber is a highly variable resource containing equally variable structural properties and to randomly include all out-of-grade timber into a building system irrespective of this, will likely result in unpredictable and poor performance and the opportunity for optimisation will be missed. A number of studies indicated that characteristics of out-of-grade timber still possess some good structural properties [1,3,12-18] that could be utilised to supplement the more expensive and highly sought after in-grade resource. In the context of structural grading aimed at ensuring a single piece of timber performs satisfactorily in a yet unknown application, out-of-grade timber is rejected for good reason. However, a good portion of this timber could be used where its structural properties can be matched to the demands of a known structural application. By matching the properties of timber to the expectations of the end user, optimisation is possible and the image and profitability of the timber will improve [19]. It is critical therefore to have a detailed understanding of the out-of-grade characteristics of timber as this is key to making an informed decision about what roles this material resource can play in a building system.

Despite the enduring abundance of out-of-grade timber, it remains an underutilised and arguably underestimated resource. Other research found in the literature rarely looks to exploit the good qualities of out-of-grade characteristics. These are primary drivers for this review paper whereby a targeted approach will be taken to investigate a range of important out-of-grade pine timber characteristics, looking for their strength and weaknesses in order to find ways in which building systems can effectively incorporate this renewable and sustainable material resource. It primarily contributes to the literature by critically reviewing the out-of-grade characteristics and in providing suggestions and an example of identifying building design methods and technologies which enable out-of-grade to be substituted in place of in-grade timber and in some cases may identify out-of-grade timber characteristics as superior. It will focus on the recent developments on cross-laminated timber (CLT) and identify demands in their design. Finally, effective ways in which this emerging building technology can incorporate the out-of-grade timber resource will be identified. This state-of-the-art review paper provides valuable information in addressing the long standing challenge of value adding loss generating out-of-grade sawn pine timber.

2. Characteristics of out-of-grade timber

Timber that does not meet the requirements of the selected grading rules is considered out-of-grade. Timber grading is a sorting method that requires grading rules, an assessment process and an identification system that communicates an estimate of timber properties to the designer including appearance, geometry, durability and structural properties. Large softwood mills in Australia produce structural framing and truss timbers for which the most important characteristics are stiffness, strength and stability [7].

Out-of-grade timber characteristics occur during the natural growth of a tree or are inflicted during processing and handling; these are not always exclusive of each other. Machine Grade Pine (MGP) is the base grade for structural pine in Australia [7] for which minimum strength and stiffness properties are set in AS1720.1 [9]. AS/NZS1748 [8,20] are the grading rules relevant where machine stress grading is used and this standard places restrictions on knots, resin defects, splits, distortion, wane, moisture content, dimensional variance and machine skip. Therefore, in addition to clear wood with low stiffness and strength properties, an out-of-grade timber population using this grading system would contain these characteristics. The following sections describe the naturally occurring out-of-grade timber features and identify their strength and weaknesses in order to overcome these limitations for their possible use as a new material resource for construction and building applications.

2.1 Low longitudinal bending stiffness

The Australian MGP standards [8] require at least 10 GPa mean Modulus of Elasticity (MOE) for a batch population of MGP10 timber. Low longitudinal MOE is often associated with juvenile wood, which develops in the first 10 to 20 years of a trees life during early growth and in the crown of maturing trees [21]. It grows in a cylindrical shape around the pith along the entire length of the tree [12]. Pith is a thin non-straight cylinder of encapsulated dead low quality cork like cells.

Juvenile wood contains a high proportion of early wood [22], compression wood [23] and has a high microfibril angle [21]. Early wood is less dense and less stiff compared to late wood [22]. Compression wood [12,23] has densities up to 50% greater than normal wood but does not possess the normally associated increased mechanical properties and has unfavourable cell geometry leading to distortion issues [21]. Compression wood has lower longitudinal to grain tensile strength and longitudinal MOE than normal wood [12]. Microfibril angle and density can explain 90% of the wood stiffness variation in juvenile wood [24]. Compression and juvenile wood have a high microfibril angle in the S2 cell wall layer which is correlated with low longitudinal stiffness and high shrinkage [1,21].

Nevertheless, compression wood has higher bending and compression parallel to grain strengths than normal wood [12] and while high microfibril angle decreases longitudinal stiffness, it increases durability and is important for transverse direction mechanical properties [3]. Xavier et al. [13] found perpendicular to grain stiffness and longitudinal shear stiffness both decreased at mid-radius but increased again toward the pith where microfibril angle is high. A model developed by Astley et al. [14] showed longitudinal shear stiffness increases significantly with increasing microfibril angle, rolling shear stiffness, radial and tangential to grain stiffness had minimal change. Rolling shear is the shear stress applied in the radial – tangential plane of timber and is experienced by the perpendicular layers in CLT. Aicher et al. [16] and Aicher and Dill-Langer [15] found no reduction in rolling shear stiffness for boards that contained pith whereas Erhart et al. [25] found it increased. These findings mean that the linear relationships of perpendicular to grain stiffness ($E_{90}=E_0/30$), longitudinal shear stiffness ($G_0= E_0/16$) and rolling shear stiffness ($G_{90}= E_0/160$) given in the CLT handbook [26] for the shear analogy method may be under predicting performance of low stiffness juvenile wood. Moreover, Denzler and Glos [27] found that although boards containing pith had lower densities, they did not reduce in longitudinal shear strength. Erhart et al. [25] found rolling shear strengths were just as high near the pith as they were at a radial distance 100mm from the pith, suggesting their possible use for structural applications.

2.2 Sloping grain

Ideally timber is cut with all the longitudinally strong fibres running parallel to the length of the piece however, this rarely happens in reality with at least some extent of sloping grain occurring. Causes of sloping grain in sawn timber include grain deviation, spiral grain and cutting pattern. The orientation of fusiform initial cells in the vascular cambium are responsible for the change in grain orientation in wood and are in response to stimuli such as death of a lateral branch, injury, constriction of the stem by a vine, auxin flux through the cambium and mechanical stresses in the wood [28]. It has been proposed that spiral grain develops as a result of wood grain rotating until it is parallel to tensile stresses caused by wind-imposed torques on the tree [28]. An example of the resin and heartwood skeleton of a slash pine showing spiral grain can be seen in Figure 1.

Figure 1 Spiral grain with 1.5 turns over a 4.2 meter length in slash pine.

In a standing tree, grain deviation and spiral grain are of little concern as the longitudinally strong interlocking fibres continuously flow, effectively transferring stresses throughout the tree. However, once sawn through this flow meets an abrupt halt and longitudinal loads can no longer be transferred along the strong axis. Load transfer increasingly occurs perpendicular to grain and through shear depending on severity of grain angle [29] but timber is less stiff and weaker in these directions which leads to a reduction in stiffness and strength. A simplistic example of sloping grain showing weakest and less stiff axis orientation can be seen in Figure 2. Reductions of up to 60% of bending and longitudinal tension strengths and up to 44% compression strength can occur [30].

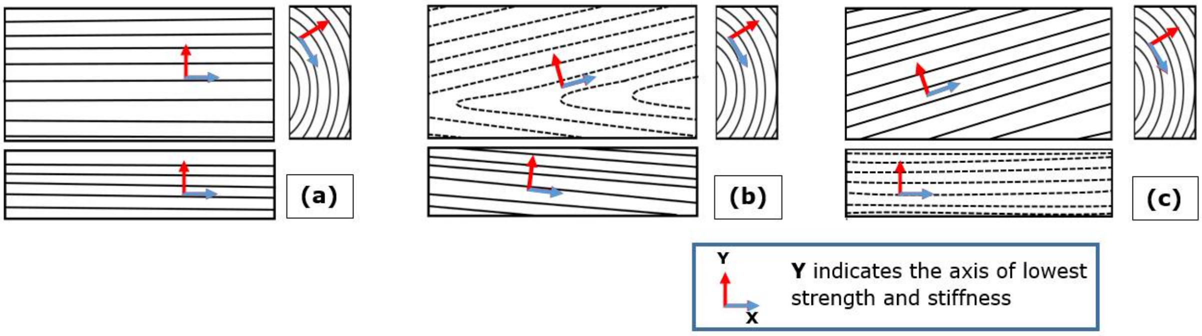

Figure 2 (a) straight grain, (b) sloping grain across edge and (c) sloping grain across face

Nevertheless, where grain deviation takes away from longitudinal strengths and stiffness, the redirected fibres can increase transverse properties. The Hankinson formula provides a method to calculate the change in strength and stiffness properties due to varying grain angle in clear wood [1,17].

2.3 Knots

Knots in sawn timber are the result of branches encased in the trees' stem and although structural grade timber is not free of knots, they are more frequent and larger in out-of-grade timber [31]. Their composition is highly variable and there still remains a lack of understanding around their complex structure and behaviour [32,33]. A knot encompasses both the branch wood and the associated surrounding timber fibre. Knots may contain compression wood, resin streaks [23], grain deviation, grain disruption and drying shrinkage cracks, of which the latter three are of most significance to the longitudinal structural properties [1,23,32,34,35].

The impact of a knot on structural performance is dependent on the combination of all characteristics including size, location, shape and soundness but also on the type of loading it is exposed to [1,36]. The location of a knot across the width and along the length of timber leads to changes in magnification and combinations of tensile, compressive and shear stresses depending on application [37]. An extensive study on radiata pine by Grant et al. [38] looked for relationships between knot area ratio (KAR), knot location and bending stiffness and strength which can be used to improve predictability. They found that using KAR and in some instances knot position gave significantly improved MOR predictions in comparison to using MOE alone. KAR is defined in AS 2858-2008 [39] as the ratio of knot cross-sectional area to that of the piece and places limits on KAR by location.

An encased knot or knot hole does not transfer stresses well through the branch but can be considered more as a 2 dimensional deviation. They have reduced capacity to disperse strain [32]. On the other hand, despite the branch being interconnected, the inter-grown knots have significantly more of the problematic 3 dimensional grain deviation. Where grain deviation effects both faces and edges of a piece of timber the reduction in strength is more significant than in face or edge alone [29]. Therefore encased and inter-grown knots are often considered equivalent for structural performance assessment [1]. Examples of simplistic grain deviation around encased and inter-grown knots are shown in Figure 3. The Y axis indicates the direction of least stiffness and strength. The closer aligned the Y axis is to the direction of load, the lower the structural performance of the piece.

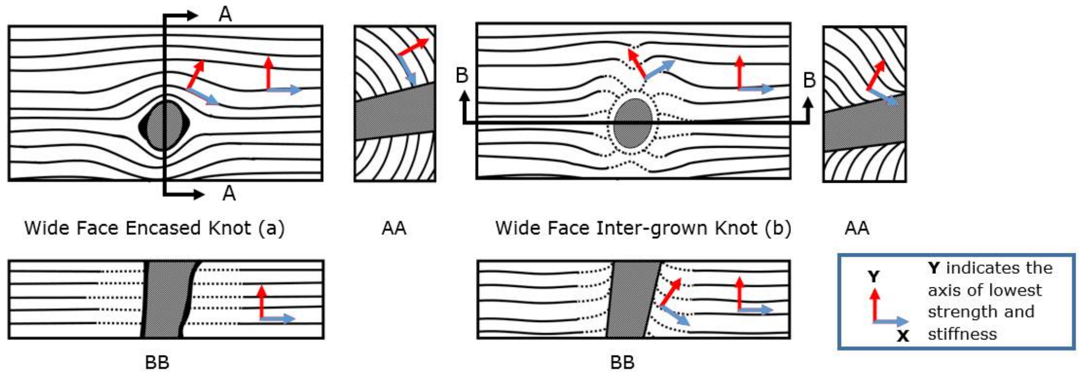

Figure 3 Simplistic example of grain deviation around encased (a) and inter-grown (b) knots

Longitudinal tensile strength, modulus of rupture, longitudinal compressive strength followed by the modulus of elasticity are the order of most negatively impacted by knots [40]. Their impact on longitudinal tensile strength is significant, causing the majority of tensile failures [31] and are believed to be the tensile strength limitation for Australian softwoods [41]. Wang et al. [42] found failure on the tension side of CLT occurred at knots. Under longitudinal loading, edge knots introduce lateral bending stresses [38,43] reducing the capacity more significantly than centrally located knots [44] and grouped knots [31]. This is also the case for tensile transverse loading with edge knots having more negative impact on tensile strength compared to central knots [44]. ASTM International [30] give reductions of bending strength and compressive strength for a 32mm edge knot on a 90mm face width of 53% and 31% respectively while a 44mm knot reduces strengths by 74% and 44% respectively.

The Forest Products Laboratory [1] highlighted that there is potential for an increase in some transverse directional properties in the region around a knot due to strong fibre direction being across the piece. This grain deviation can disperse perpendicular to grain stresses and where branch wood is intact and knots provide reinforcement though a dowelling effect resisting shear [18]. Gupta et al. [45] found knots had no significant effect on longitudinal shear and Jockwer et al. [18] found knots can increase load carrying capacity in notched beams by disrupting and resisting crack propagation. Moreover, knots have less negative impact in flatwise bending stiffness [46,47] and strength [48,49] therefore may be more suitable for flatwise than edgewise applications such as floor panelling.

2.4 Shakes, splits, checks, resin and bark pockets

Shakes, splits, checks, resin pockets and bark pockets are all separations in timber fibres occurring due to wounds during the life of a tree [50] or from the drying process. These characteristics are illustrated in Figure 4. AS/NZS 1748.1 [8] restricts the size of resin pockets and end splits and prohibits other splits while AS/NZS 1748.2 [20] restricts heart-shakes and prohibits cross-shakes. Harding et al. [51] estimate 4 to 5% of sawn timber boards on average are rejected due to shake but state this quantity can be significantly higher. The loss due to resin defect for Queensland alone is estimate to be at least $4 to $5 million per year [51].

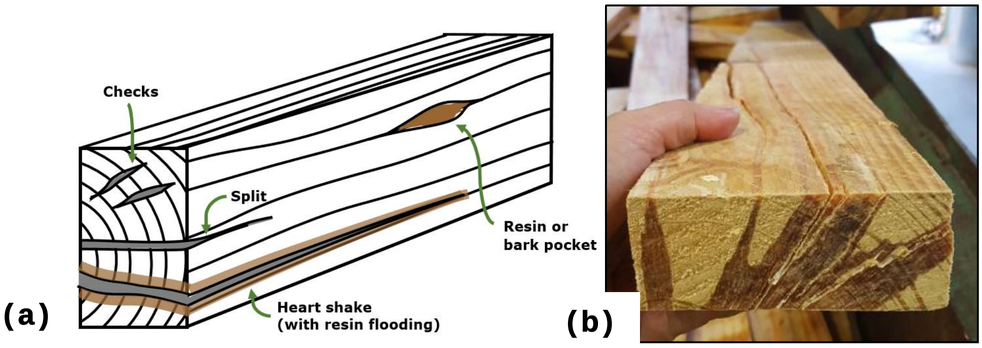

Figure 4 (a) shakes, splits, checks, resin and bark pockets (b) heart shake in pine timber

The fibre separation obstructs the transfer of stresses leading to stress concentrations and a reduction in shear [7,30,52] and perpendicular to grain tensile strength [35]. The width of a shake, its occurrence on two faces, presence with needle trace and with pith are all highly influential in reducing shear strength [52]. Even small shakes acceptable in structural grade timber reduce shear strength as much as 30% [52]. Nevertheless, outside critical areas, bending stiffness and strength [30,35] and axial strength can go unaffected [30]. Depending on the size and orientation of the separation, perpendicular to grain compressive stiffness and strengths should be minimally impacted. Additionally, the separation of fibre may provide opportunity for connection such as a glued shear key although, the impact of resin on gluability where present would need to be investigated.

2.5 Distortion

Distortion in sawn timber occurs as bow, cup, twist and spring and is associated with timber processing and wood properties. Growth stresses develop in wood during cell development and maturation. Both new and matured tree cells are under tangential compression however, as new cells in the outer fibre mature they shrink longitudinally inflicting longitudinal compressive stresses on the inner cells while they themselves remain in tension [21]. Sawing through the wood releases these stresses resulting in strains and distortion [21]. Moreover, as timber dries it shrinks at different rates in the radial, tangential and longitudinal directions and the growth ring orientation of a board can dictate the type of distortion that occurs. Examples of timber distortion are illustrated in Figure 5.

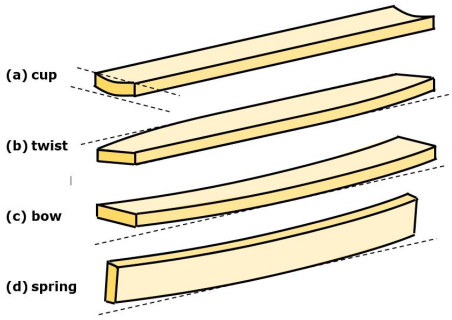

Figure 5 Timber Distortion

Under end loading, a distorted piece of timber experiences both compression and a bending moment, reducing capacity in that application. The distorted shape may cause conflicts with other building systems and components such as sheeting or connections. When used in engineered wood products, if the distortion causes inconsistent bond line thickness, this will result in a weak glued connection [1]. A distorted piece of timber however does not necessarily have low stiffness or strength properties. Further processing such as planing required in preparation for gluing engineered timber products or relief cutting would reduce or eliminate distortion. Also, there is opportunity to use distorted timber in applications requiring specific shapes or as a prestressed member such as bow or spring upwards in a floor element.

3. Building design methods and technologies using out-of-grade timber

Many building systems currently in use have an opportunity to incorporate out-of-grade timber in one or multiple ways by direct substitution for or in combination with in-grade timber. These technologies can be designed, modified or selected to target high performing properties while avoiding or minimising dependence on lower performing properties. A stacked building system (Figure 6) could incorporate out-of-grade timber with high perpendicular to grain compressive properties but low longitudinal properties. Modifying an existing system such as decreasing the angle of the transverse layers [53] or modifying layer thickness [25] in CLT can change the type or magnitude of stresses required to be resisted by the out-of-grade timber content. In addition, selecting engineered timber products and targeting their lower stressed zones or taking advantage of their inherent lamination effect which provides alternative stress paths around lower performing pieces, creates an opportunity for the use of out-of-grade timber [43].

Monizza et al. [54] developed an algorithm to identify low stress regions of complex timber members specifically for the purpose of using lower performing timber.

Figure 6 Stacked timber bricks (Display at KY Wood museum South Korea)

Architectural design using timber visually and structurally provides opportunity to engineer the skeleton of the structure from in-grade timber while the balance of the timber is out-of-grade. Alternatively using computational methods of design allows the design of the building to fit the resource rather than forcing the resource to fit the building. This would lead to interesting, unique and expressive projects.

Building technologies facilitate the use of out-of-grade timber by providing knowledge, enhancement and assistance of structural performance, design, planning and construction. This includes skills, knowledge, tools or materials that can be applied at all stages. During milling and grading the information collected about every board can be extensive. Ionizing radiation computed tomography, thermal imaging, microwave imaging, ultrasonic imaging, acoustic vibrations and dynamic bending techniques can all be used to gather information on the presence, geometry and location of surface and internal defects, knots, grain orientation, density, moisture content, surface roughness and board dimensions [55]. Figure 7 illustrates an example of wood imaging techniques used during the grading process. Out-of-grade timber packs contain highly variable characteristics but this detailed information reduces uncertainty by giving an in-depth understanding of every board and could be used to inform computer aided design (CAD), engineering (CAE) and manufacture (CAM).

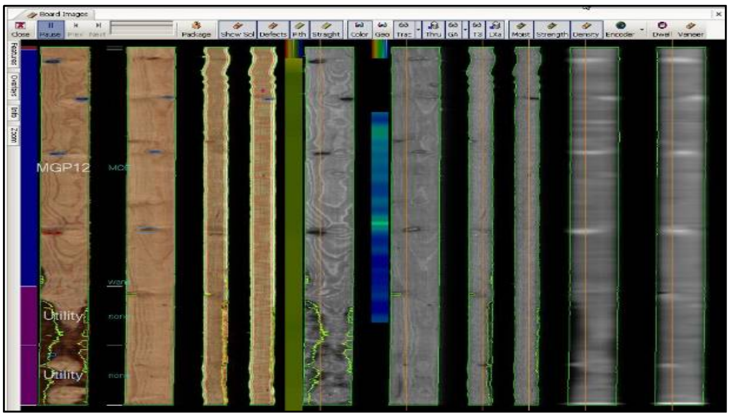

Figure 7 Lucidyne GradeScan® wood imaging

Digital technologies in design, engineering and manufacture continue to advance and with further adaptation could be used to optimise and construct buildings incorporating out-of-grade timber. Fully integrated systems for timber are possible however, information sharing and communication throughout the entire timber and building industries is essential. Lipton et al. [56] developed a system for carpentry which uses CAD for parametric design, finite element method (FEM) for verification, an interface for user customisation and simulation, an algorithm for automated assignment and robots to manufacture parts and complete assembly. Willmann et al. [57] argue that while still in its infancy, robotic timber construction including digital design and automated fabrication provides new possibilities for the future of timber construction but self-evaluation, problem solving and self-adjustment are needed to accommodate the variability of timber [57]. This variability is exasperated in out-of-grade timber packs.

The use of reinforcement can enhance the properties of out-of-grade timber overcoming deficiencies in structural performance. Many reinforcement materials have been successful in enhancing timber performance and could also be used for out-of-grade timber. These include carbon fibre plates [58,59], glass fibre reinforced polymer plates (Figure 8b), woven fabric and pultruded rods [60-63], basalt fibre reinforced polymer sheets [64], steel reinforced plates [59,65], aluminium plates [66], self-tapping screws [67] metal rods [65,68] (Figure 8a), carbon nano tube epoxy coatings [69] and concrete [70]. Pre-stressing FRP tendons, sheet or rods [62], compressed wood inserts [66] and post tensioning of steel bars [71] have been successful in achieving higher flexural strength and stiffness and accomplishing extended spans.

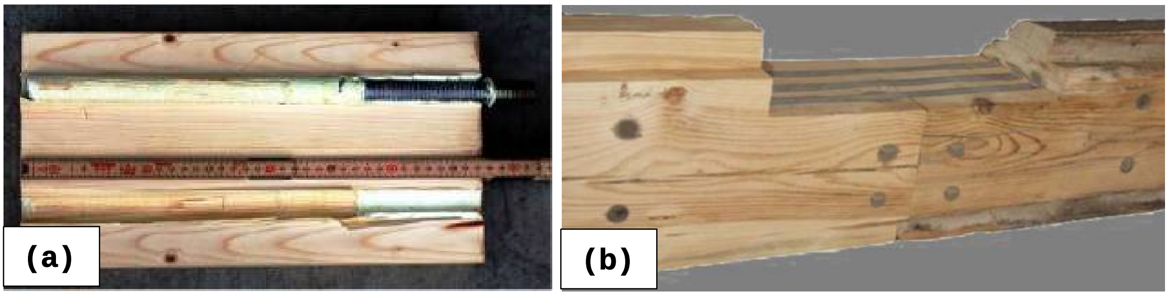

Figure 8 Timber reinforced with (a) metal rods [68], (b) glass fibre reinforced polymer plates [62]

Timber adhesives are fundamental for connection of out-of-grade timber to reinforcing materials and to other timber in engineered timber products. Advancements in adhesive technologies are leading to performance that can overcome challenges associated with out-of-grade timber. Nanomaterials are increasing the mechanical properties of wood adhesives [72]. The more brittle adhesives such as epoxy based or urea formaldehyde adhesives are prone to failure due to the dimensional changes of wood caused by changes in moisture content [59,73] however, the addition of nanomaterials such as graphene or cellulose nanofibrils have proven to increase fracture toughness [72-74]. Moreover, some wood adhesives available change MOE with humidity levels and accommodate the dimensional changes in timber [73]. Furthermore, the use of primers can improve adhesions and shear strength, reducing delamination [75].

Wood modification can increase the strength, stiffness, hardness and dimension stability of timber by using chemical, physical or biological methods to change its properties at the cell wall level [76]. Acetylation [76-78], furfurylation [77,78], wax impregnation[78], resin impregnation, heat modification [76,78], densification [79], and some combinations of these [80,81] are some examples showing positive results. Recently, Song et al. [81] achieved impressive results by boiling timber in a mixture of sodium hydroxide and sodium sulphite then deionized water followed by hot-pressing. Chemical, thermal and impregnations methods of wood modification are increasingly being commercialised today [76,77]. These technologies have demonstrated successful partnerships with timber and open up new and innovative opportunities in exploring new engineering applications to value-add this abundant out-of-grade timber resource.

4. Developments and design of Cross Laminated Timber (CLT)

Cross laminated timber (CLT) is a structural composite which possesses more uniform mechanical properties than solid sawn timber while allowing the use of smaller, lower quality and underutilised timber and residues keeping forest products competitive in the market [43,82]. CLT is a prefabricated engineered timber solution which is efficient, environmentally friendly, sustainable and a great alternative to concrete in urban infill developments for achieving housing targets [83]. Due to its size and extensive possible applications, CLT utilises large volumes of sawn timber and its unique design and intrinsic lamination effect give it good potential to substitute out-of-grade in place of in-grade timber. First developed in the 1990's in Austria and Germany, CLT is increasing in demand worldwide as people begin to see and take advantage of its benefits.

CLT is manufactured with timber boards placed side by side commonly with 3, 5 and 7 layers glued at 90 degrees to the adjacent layer (Figure 9) with panel thicknesses between 60mm and 500mm, in sizes typically 3.5m wide and up to 16m long. Adhesives are often used for timber connection, polyurethane being most common but melamine urea-formaldehyde or phenol-resorcinol-formaldehyde are also used [84]. Mechanical fastening systems such as steel, aluminium or wooden - nails, screws or dowels and timber-to-timber interlocking systems are also used [85]. For a review on the manufacturing and mechanical properties of CLT panels, the readers are directed to Jelec et al. [86].

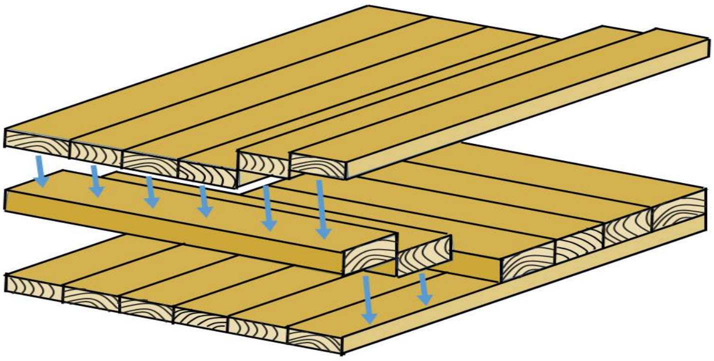

Figure 9 Cross Laminated Timber

The range of timber species that have been investigated for CLT continues to expand. These include spruce [87-90], beech wood [16], southern pines [91,92], radiata pine [93,94], eucalyptus [95] and poplar [96,97]. Draft standards and CLT handbooks specify the use of graded timber to national standards with proprietary grades and wood based panels permitted under certain conditions [26,98-100]. Each layer of a CLT panel is exposed to different loadings depending on its application. Lower timber grades are often used for the inner layers which experience lower stresses. The American National standard specifies a minimum grade No. 2 for parallel and No. 3 for perpendicular layers [100], in Europe, structural grades C24 for outer and C16 or C18 for inner layers for floor elements is common [26,94]. The New Zealand and Australian CLT manufacturer use lower stiffness timber for inner layers [101].

Researchers continue to investigate the effect of different designs and materials for these inner layers. Buck et al. [53] achieved higher structural performance in CLT by altering the angle of the transverse layers while other researchers looked for performance using oriented strand lumber, laminated strand lumber [42,102] laminated veneer lumber [103] and also mixing different timber species [97,104]. As with these examples, the structural performance of characteristics of out-of-grade timber can be matched to the structural demands of the various layers within CLT. Moreover, the effective manufacture of CLT requires a good understanding of a number of design parameters.

The design of CLT panels is usually serviceability governed [26] of which deflection is a major criteria. The Shear Analogy Method by Kreuzinger [105] can be used to determine the stiffness and deflection of a panel under bending and the axial and shear stresses throughout its layers. It is one of a number of analytical models that have been adopted in CLT standards and design guides and is argued to be the most accurate [26]. Using the relationships for timber properties specified in Gagnon and Popovski [26] (Table 1), the axial stresses throughout the depth of a 5 layer panel with longitudinal stiffness (E_0) of 11GPa can be seen in Figure 10. The span used is the longest allowable under a span/400 deflection limit. The impact on stress distribution and allowable span of changing layer stiffness can be determined and the stresses in each layer can be matched to the strength capacity of out-of-grade timber.

Table 1 Layer Mechanical Property Assumptions

Longitudinal to grain MOE	E_0 (GPa)	Relationship to E_0	11 GPa
Perpendicular to grain MOE	E_{90} (GPa)	$E_0/30$	0.367
Longitudinal shear modulus	G_L (MPa)	$E_0/16$	687.5
Rolling shear modulus	G_R (MPa)	$E_0/160$	68.75

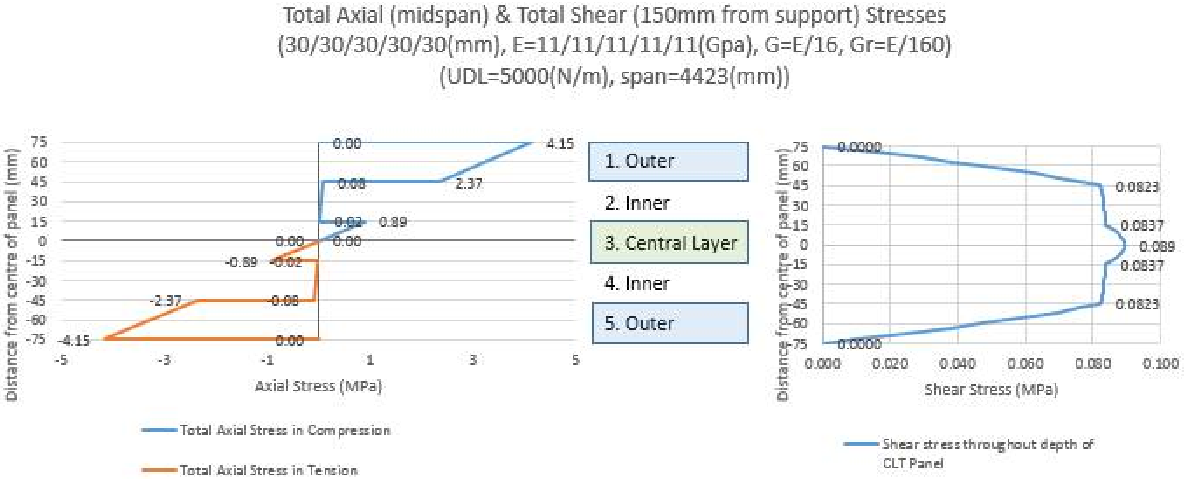

Figure 10 Total Axial Stresses at mid-span and Shear Stress at Distance 150mm from Support

The percentage contribution of bending, longitudinal shear and rolling shear to total panel deflection and the deflection design limit can be seen over a range of panel span/depth ratios in Figure 11. The larger span/depth ratio panels are more likely to fail due to deflection limits and hence, bending deflection becomes the more critical.

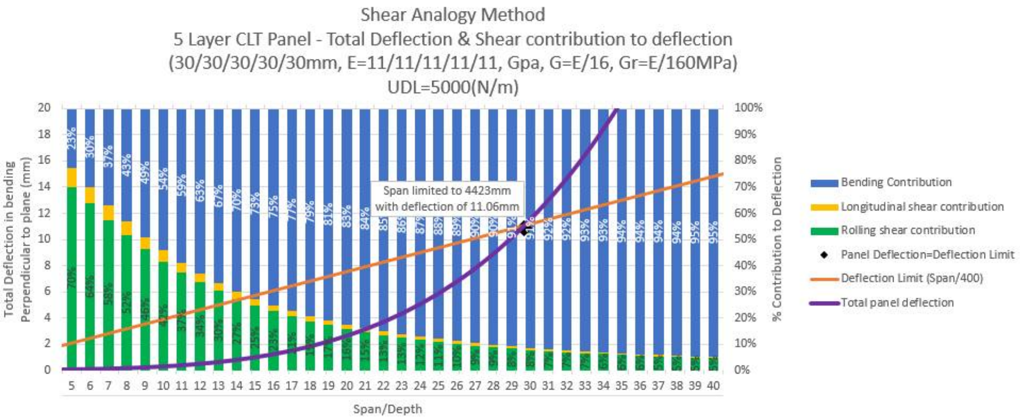

Figure 11 5 Layer CLT Panel Deflection at Mid span

These findings raise the question of whether shear stiffness and specifically rolling shear stiffness is important to CLT design. Rolling shear (Figure 12) accounts for at least 90% of shear deflection (Figure 11). Mestek et al. [106] state that shear deflection is only important up to span/depth of 20 whereas, Gagnon and Popovski [26] argue it should be considered up to span/depth of 30. Niederwestberg and Chui [87] found that the shear analogy method overestimated the bending stiffness of CLT in span/depth ratio of 10 and attributed this to shear deflection. The lower the rolling shear stiffness of the timber, the shorter the allowable span and the more important rolling shear stiffness becomes. Therefore, shear deflection is considered important for panel design for low stiffness out-of-grade timber.

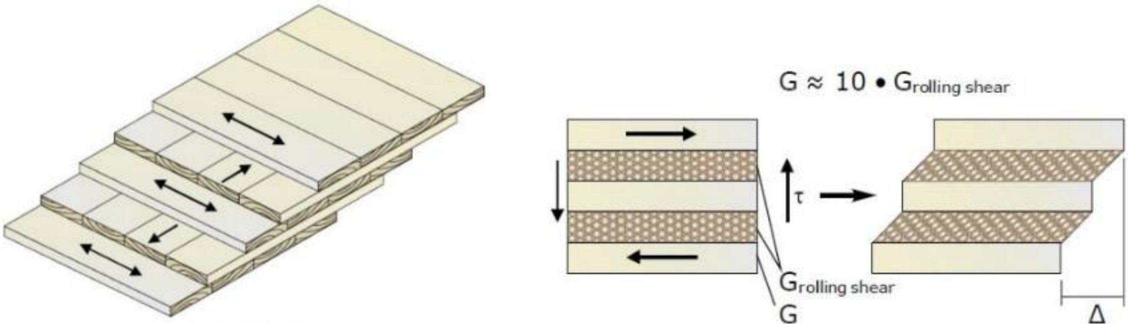

Figure 12 Shear deformation of a CLT-element [106]

Rolling shear is a common failure mode when testing CLT [16,93,107] however, more information on rolling shear properties of timber are required. A number of researchers have looked at the rolling shear properties of various species and found that grain orientation has an effect on rolling shear capacity of timber [1,16,25,89,91,108]. Erhart et al. [25] compared rolling shear of spruce, birch, ash, poplar, beech and pine and found average stiffness between 100 to 401 MPa and average strengths between 1.88 to 5.57 MPa. Forest Products Laboratory [1] presents values of rolling shear stiffness for loblolly pine at 15.2% and slash at 18.2% of their longitudinal shear modulus and state rolling shear strengths are commonly between 18% and 28% of the longitudinal shear strength. For CLT design, rolling shear stiffness values of 10% of longitudinal shear stiffness are often used [26,106].

5. Opportunities for out-of-grade timber in CLT

Although initially developed to value add to sawn side boards, CLT's potential in markets not previously serviced by timber are driving demand worldwide [109].

This is driving research into optimisation and additional feedstock options for which out-of-grade timber may be one possible solution.

Given the average stiffness and characteristic strength requirements set out for MGP grades in AS1720.1 [9], it is anticipated that some portion of both strength and stiffness limited out-of-grade timber will satisfy the demands of layers within CLT panels. Moreover, if smaller span/depth ratios are acceptable, very low stiffness timber can be used especially in the centre layers, but the importance of rolling shear stiffness will increase. The typical European CLT panel has outer E_0=11GPa and inner and central E_0=8GPa layers [26] which reduce the allowable span by only 1.3% and 1.2% compared to a panel with E_0=11GPa for all layers. Panels made from 100% out-of-grade timber due to low stiffness with E_0=6GPa outer and E_0=4GPa inner layers, still achieve 80% of the original E_0=11GPa panel span despite containing timber equal to or less than 55% of the original stiffness values.

Sigrist and Lehmann [94] investigated the use of non-structural radiata pine in CLT panels finding some achieved satisfactory performance. They found that with some coarse grading and placement within specific layers, they were able to increase the structural properties of the CLT panel by up to 40%. This research did not single out specific out-of-grade timber characteristics or investigate their structural properties therefore, no conclusions could be made about their individual performance and suitability. However, it did demonstrate that out-of-grade timber has potential to perform in the structural application of CLT. Nonetheless, CLT has many possible applications such as walls, roofs, on edge beams, floors and can be prestressed and/or part of a composite system. All of these applications place many different demands on the timber used in its manufacture and therefore it is essential to investigate every out-of-grade timber characteristic for its potential in each CLT application. Thorough investigation needs to look at not only all of its mechanical properties but also gluability and fire performance. Although the work involved in such research would be extensive, out-of-grade timber continues to be produced in abundance worldwide and CLT could offer a solution to utilise and value add significant portions of this. Table 2 matches the out-of-grade characteristics discussed in section 2 with their potential for layers within CLT under bending.

Table 2 Out-of-grade characteristics potential for layers within CLT

Out-of-grade characteristic	**Potential for CLT layers**
Low longitudinal stiffness	• Transverse layers • Central layer
Sloping grain	• Transverse layers • Central layer
Knots	• Top layer under compression • Transverse layers • Central layer
Shakes, splits, checks, resin and back pockets	• Top layer • Depending on extent and orientation of separation - transverse or central layers • Bottom layer
Distortion	• All layers- where distortion can be reduced to within acceptable limits through preparation for gluing

A better understanding and knowledge about CLT and more available technical information will increase its adoption [85,110-114] and increase confidence in its usage [115]. Jones et al. [112] argued that historic objectives in construction focus on reduced costs and risk leading to a lack of commercial opportunity to adopt options perceived to be more expensive or to bring higher risk. The recent changes made by the Australian Building Codes Board to the National Construction Code in 2016, which allows construction of timber buildings up to 25 metres in height under the deemed-to-satisfy provisions, provides potential for future development and innovation. These represent positive steps toward adoption of timber products such as CLT as incompatibility with building codes is a significant barrier [115]. More importantly, forestry, logging and wood manufacturing employed an estimated 64,300 people in 2015/16 in Australia and contributed 0.5% to GDP [2], thus manufacturing CLT from out-of-grade timber creates additional employment and promotes economic growth.

It can be argued that research into the use of out-of-grade timber in CLT will provide a greater understanding of CLT, provide potential for design improvement, reduce perceived risk, reduce pricing and increased competition which will in turn also give financiers more confidence in funding CTL projects. Furthermore, it will inform manufacturers on the feasibility of out-of-grade timber in CLT and under favourable results would assist in the adoption of this resource into CLT. It would provide valuable information on the mechanical properties and gluability of the out-of-grade pine resource which is also translatable to other engineered timber products. Moreover, it will inform sawyers worldwide on the potential for another avenue for the long standing challenge of value adding loss generating out-of-grade sawn timber.

6. Conclusion

Significant volumes of sawn pine are considered out-of-grade and sold at a loss. This paper provides a critical review of out-of-grade timber characteristics and of building design methods and technologies which can successfully incorporate this out-of-grade timber. It looks at some design requirements for cross-laminated timber (CLT) as a prime example of a building system with good capacity to incorporate high volumes of out-of-grade timber. Based on a comprehensive state-of-the-art review, the following conclusions have been drawn with the aim of value-adding to out-of-grade timber and creating new opportunities for maximising the use of this renewable and sustainable material resource into building and construction:

- Out-of-grade sawn pine is an abundant resource that despite being rejected by structural grading rules would perform well in specific structural applications and lead to benefits for the environment, plantations mangers, sawyers, designers, builders and customers.
- Low longitudinal bending stiffness, sloping grain, knots, distortion, resin shakes, splits and checks were the main characteristics of sawn out-of-grade timber. These perceived unfavourable properties can be overcome with a good understanding of their strengths, and through targeted placement in manufacturing building systems and utilisation of building technologies.
- Fully integrated digital systems to make the use of out-of-grade timber easier and more efficient are possible. Data collected at every stage from milling to construction can be used to inform subsequent stages but this requires a high level of information sharing and communication throughout the entire timber and building industries.
- CLT's unique design and intrinsic lamination effect give it good potential to substitute out-of-grade in place of in-grade timber however, significant research is still needed to confirm the suitability of each out-of-grade characteristic in all possible applications of CLT. It is argued that the work

required for this research is warranted given the potential to utilise very large volumes of out-of-grade sawn timber in CLT.

- CLT made from very low stiffness timber can still achieve spans 80% of the equivalent CLT made from in-grade timber. The rolling shear however is an important design consideration for CLT when using low stiffness out-of-grade timber due to the smaller span-to-depth ratios achievable.
-

Acknowledgement

The first author greatly acknowledges the funding support from the Queensland Government in the form of an Advance Queensland award, and USQ through a Research Training Program scholarship toward her PhD project.

References

[1] Forest Products Laboratory, *Wood Handbook - Wood as an engineering material. General Technical Report FPL-GTR-190*. 2010, Madison WI,: Department of Agriculture, Forest Service, Forest Products Laboratory,.
[2] ABARES, *Australia's Forests at a Glance 2017*, Department of Agriculture Fisheries and Forestry, Editor. 2017: Canberra.
[3] Ramage, M.H., H. Burridge, M. Busse-Wicher, G. Fereday, T. REynolds, D.U. Shah, G. Wu, L. Yu, P. Fleming, D. Densley-Tingley, J. Allwood, P. Dupree, P.F. Linden, and O. scherman, *The wood from the trees: The use of timber in construction.* Renewable and Sustainable Energy Reviews, 2017. 68: p. 333-359. http://dx.doi.org/10.1016/j.rser.2016.09.107.
[4] ABARES, *Australian Forest and wood products statistics September and December quarters 2016*, Department of Agriculture Fisheries and Forestry, Editor. 2017: Canberra.
[5] ABARES, *Australian Plantation Statistics 2016*, Australian Bureau of Agricultural Resource Economics and Sciences, Editor. 2016: Canberra.
[6] Harding, K.J., M.R. Nester, M.J. Dieters, A. Zbonak, and T.R. Copley, *Managing subtropical exotic pine plantations for improved wood production*. 2010, Forest and Wood Products Australia Ltd.
[7] Harding, K., *Review of wood quality studies in Queensland and northern New South Wales exotic pine plantations*. 2008.
[8] Standards Australia/New Zealand Standards, *AS/NZS 1748.1 Timber - Solid - Stress-graded for structural purposes, Part 1: General Requirements*. 2011: Retrieved from Standards On-line Premium database.
[9] Standards Australia, *AS 1720.1 - 2010 Australian Standard, Timber structures, Part 1: Design methods*. 2010, SAI Global Limited: Sydney NSW.
[10] Cown, D.J., A.N. Haslett, M.O. Kimberly, and D.L. McConchie, *The influence of wood quality on lumber drying distortion.* Annuals of Forest Science, 1996. 53(6): p. 1177-1188. https://doi.org/10.1051/forest:19960611.
[11] Dewbury, M., *Improving Thermal Efficiency in Lightweight Construction: Mass timber as thermal mass, Project number: PNA289-1213a*. 2016, Forest & Wood Products Australia.
[12] Hakkila, P., *Utilization of Residual Forest Biomass*. 2012, Berlin Heigelberg: Springer.
[13] Xavier, J., S. Avril, F. Pierron, and J. Morais, *Variation of transverse and shear stiffness properties of wood in a tree.* Composites: Part A, 2009. 40: p. 1953-1960. http://dx.doi.org/10.1016/j.compositesa.2009.09.023.

[14] Astley, R.J., K.A. Stol, and J.J. Harrington, *Modelling the elastic properties of softwood.* Holz als Roh- und Wekstoff, 1998. 56: p. 43-50. https://doi.org/10.1007/s001070050262.
[15] Aicher, S. and G. Dill-Langer, *Basic Considerations to rolling shear modulus in wooden boards.* Otto-Graf-Journal, 2000. 11: p. 157-166.
[16] Aicher, S., Z. Christian, and M. Hirsch, *Rolling shear modulus and strength of beech wood laminations.* De Gruyter, 2016. 70(8): p. 773-781. https://doi.org/10.1515/hf-2015-0229.
[17] Green, D.W., *Wood: Strength and Stiffness*. Second ed. Encyclopedia of Materials: Science and Technology. 2001, Oxford: Elsevier Science Ltd. 9732-9736.
[18] Jockwer, R., E. Serrano, P.J. Gustafsson, and R. Steiger, *Impact of knots on the fracture propagating along grain in timber beams.* International Wood Products Journal, 2017. 8(1): p. 39-44. https://doi.org/10.1080/20426445.2016.1275093.
[19] Johansson, G., R. Kliger, and M. Perstorper, *Quality of structural timber-product specification system required by end-users.* Holz als Roh- und Wekstoff, 1994. 52(1): p. 42-48. https://doi.org/10.1007/BF02615017.
[20] Standards Australia/New Zealand Standards, *AS/NZS 1748.2 Timber - Solid - Stress-graded for structural purposes, Part 2: Qualification of grading method*. 2011: Retrieved from Standards On-line Premium database.
[21] Plomion, C., G. Leprovost, and A. Stokes, *Wood Formation in Trees.* Plant Physiology, 2001. 127(4): p. 1513-1523. https://doi.org/10.1104/pp.010816.
[22] Mead, D., *Sustainable management of Pinus radiata plantations*, Food and Agriculture Organization of The United Nations, Editor. 2013, Food and Agriculture Organization of The United Nations: Rome.
[23] Koch, P., *Utilization of the Southern Pines - Volume 1. Agricultural Handbook SFES-AH-420*. 1972, Washington: U.S. Dept. of Agriculture forest Service, Southern Forest Experiment Station.
[24] Malan, F.S., *Family variation in diameter growth and acoustic velocity in three 5-year-old South African-grown Pinus elliottii x Pinus caribaea progeny trials established on three diverse sites.* Southern Forests: a Journal of Forest Science, 2015. 77(4): p. 269-276. https://doi.org/10.2989/20702620.2015.1108621.
[25] Erhart, T., R. Bradner, G. Schickhofer, and A. Frangi, *Rolling Shear Properties of some European Timber Species with Focus on Cross Laminated Timber (CLT): Test Configuration and Parameter Study*, in *48th Meeting of the International Network on Timber Engineering Research (INTER2015)*. 2015: Sibenik Croatia.
[26] Gagnon, S. and M. Popovski, *Chapter 3: Structural design of cross-laminated timber elements*, in *FPInnovations CLT Handbook*. 2011.
[27] Denzler, J.K. and P. Glos, *Determination of shear strength values according to EN 408.* Materials and Structures, 2007. 40: p. 79-86. https://doi.org/10.1617/s11527-006-9199-4.
[28] Kramer, E., *Wood Grain Pattern Formation: A brief review.* Journal of Plant Growth Regulation, 2006. 25: p. 290-301. https://doi.org/10.1007/s00344-006-0065-y.
[29] Guindos, P. and M. Guaita, *A three-dimensional wood material model to simulate the behavior of wood with any type of knot at the macro-scale.* Wood Science and Technology, 2013. 47(3): p. 585-599. https://doi.org/10.1007/s00226-012-0517-4.

[30] ASTM International, *ASTM D245-06(2011): Standard Practice for Establishing Structural Grades and Related Allowable Properties for Visual Graded Lumber*. 2011, ASTM West Conshohocken PA, US.
[31] Takeda, T. and T. Hashizue, *Differences of tensile strength distribution between mechanically high-grade and low-grade Japanese larch lumber II: Effect of knots on tensile strength distribution.* Journal of Wood Science, 1999. 45: p. 207-212. https://doi.org/10.1007/BF01177727.
[32] Buksnowitz, C., C. Hackspiel, K. Hofstetter, U. Muller, W. Gindl, A. Teischinger, and J. Konnerth, *Knots in trees: strain distribution in a naturally optimised structure.* Wood Science and Technology, 2010. 44: p. 389-398. https://doi.org/10.1007/s00226-010-0352-4.
[33] Nagai, H., K. Murata, and T. Nakano, *Strain analysis of lumber containing a knot during tensile failure.* Journal of Wood Science, 2011. 57: p. 114-118. https://doi.org/10.1007/s10086-010-1154-x.
[34] Dundar, T., U. Buyuksari, and N. AS, *Effects of Knots on the Physical and Mechanical Properties of Wood.* Journal of the Faculty of Forestry Instanbul University Series B, 2008. 58(2): p. 1-13.
[35] Thelandersson, S., *Timber engineering: Introduction: Wood as a Construction Material*. 2003, England: John Wiley & Sons Ltd.
[36] Steffan, A., C. Johansson, and E. Wormuth, *Study of the relationship between flatwise and edgewise moduli of elasticity of sawn timber as a means to improve mechanical strength grading technology.* Holz als Roh- und Wekstoff, 1997. 55: p. 245-253. https://doi.org/10.1007/BF02990556.
[37] Guindos, P. and M. Guaita, *The analytical influence of all types of knots on bending.* Wood Science and Technology, 2014. 48: p. 533-552. https://doi.org/10.1007/s00226-014-0621-8.
[38] Grant, D.J., A. Anton, and P. Lind, *Bending Strength, Stiffness, and Stress-grade of Structural Pinus Radiata.* New Zealand Journal of Forestry Science, 1984. 14(3): p. 331-348.
[39] Standards Australia, *AS 2858 - 2008 Australian Standard, Timber - Softwood - Visually stress-graded for structural purposes*. 2008, SAI Global Limited: Sydney NSW.
[40] Phillips, G., J. Bodig, and J. Goodman, *Flow-grain analogy.* Wood Science, 1981. 14: p. 55-64.
[41] Adam, C. and H. Milner, *Glulam design based on lamination grades and the use of mill shorts*. 2012, Forest and Wood Products Australia Limited.
[42] Wang, Z., M. Gong, and Y.-H. Chui, *Mechanical properties of laminated strand lumber and hybrid cross-laminated timber.* Construction and Building Materials, 2015. 101: p. 622-627. https://doi.org/10.1016/j.conbuildmat.2015.10.035.
[43] Falk, R.H. and F. Colling, *Laminating Effects in Glue-Laminated Timber Beams.* Journal of Structural Engineering, 1995. 121(12): p. 1857-1863. https://doi.org/10.1061/(ASCE)0733-9445(1995)121:12(1857).
[44] Cramer, S. and J. Goodman, *Model for stress analysis and strength prediction of lumber.* Wood and Fiber Science, 1982. 15(4): p. 338-349. https://doi.org/10.1061/(ASCE)0733-9445(1990)116%3A10(2729).
[45] Gupta, R., C. Basta, and S.M. Kent, *Effect of knots on longitudinal shear strength of Douglas-fir using shear blocks.* Forest Products Journal, 2004. 54(11): p. 77-83.
[46] Samson, M. and L. Blanchet, *Effect of knots on the flatwise bending stiffness of lumber members.* European Journal of Wood and Wood Products, 1992. 50(4): p. 148-152. https://doi.org/10.1007/BF02663256.

[47] Courchene, T., F. Lam, and J. Barrett, *The effect of edge knots on the strength of SPF MSR lumber.* Forest Products Journal, 1998. 48(4): p. 75-82.
[48] Nowak, A., P. Stankiewicz, and M. Ritter, *Bending tests of bridge deck planks.* Construction and Building Materials, 1999. 13(4): p. 221-228. https://doi.org/10.1016/S0950-0618(99)00012-4.
[49] Stringer, J., A. Dakin, and D. Fernando, *The use of flatwise structural properties in the design of timber-framed residential buildings*, in *World Conference on Timber Engineering 2016*. 2016: Vienna, Austria.
[50] Crown, D., L. Donaldson, and G. Downes, *A review of resin features in radiata pine.* New Zealand Timber Design Journal, 2011. 41: p. 41-60.
[51] Harding, K., J. Davis, T. Copley, A. Selleck, and T. Haslett, *Resin defect impacts on the value of graded recovery and evaluation of technologies for internal defect detection in slash pine logs*, Horticulture and Forestry Science - Department of Agriculture and Fisheries, Editor. 2007: Indooroopilly QLD.
[52] Laveielle, L., O. Gibier, and G. Stringer, *A shear strength assessment of resin shakes in Australian grown slash pine*, in *25th Forests Products Research Conference*. 1996: Victoria Australia.
[53] Buck, D., X. Wang, O. Hagman, and A. Gustafsson, *Further Development of Cross-Laminated Timber (CLT) Mechanical tests on 45º Alternating Layers*, in *World Conference on Timber Engineering*. 2016: Vienna, Austria.
[54] Monizza, G.P., C. Bendetti, and D.T. Matt, *Parametric and generative design techniques in mass-production environments as effective enablers of Industry 4.0 approaches in the building industry.* Automation in construction, 2018. 92: p. 270-285. http://dx.doi.org/10.1016/j.autcon.2018.02.027.
[55] Bucur, V., *Nondestructive Characterization and Imaging of Wood*. 2013: Springer Berlin Heidelberg.
[56] Lipton, J.I., A. Schulz, A. Spielberg, L. Trueba, W. Matusik, and D. Rus, *Robot assisted carpentry for mass customization*, in *International Conference on Robotics and Automation (ICRA)*. 2018: Brisbane, Australia.
[57] Willmann, J., M. Knauss, T. Bonwetsch, A.A. Apolinarska, F. Gramazio, and M. Kohler, *Robotic timber construction - Expanding additive fabrication to new dimensions.* Automation in construction, 2015. 61: p. 16-23. https://doi.org/10.1016/j.autcon.2015.09.011.
[58] Neubauerova, P., *Timber beams strengthened by carbon-fiber reinforced lamellas.* Procedia Engineering, 2012. 40: p. 292-297. https://doi.org/10.1016/j.proeng.2012.07.097.
[59] Issa, C. and Z. Kmeid, *Advanced wood engineering: glulam beams.* Construction and Building Materials, 2004. 19: p. 99-106. https://doi.org/10.1016/j.conbuildmat.2004.05.013.
[60] Basterra, L.A., J.A. Balmori, L. Morillas, L. Acuna, and M. Casado, *Internal reinforcement of laminated duo beams of low-grade timber with GFRP sheets.* Construction and Building Materials, 2017. 154: p. 914-920. https://doi.org/10.1016/j.conbuildmat.2017.08.007.
[61] Raftery, G. and P.D. Rodd, *FRP reinforcement of low-grade glulam timber bonded with wood adhesive.* Construction and Building Materials, 2015. 91: p. 116-125. https://doi.org/10.1016/j.conbuildmat.2015.05.026.
[62] Schober, K.-U., A.M. Harte, R. Kliger, R. Jockwer, Q. Xu, and J.-F. Chen, *FRP reinforcement of timber structures.* Construction and Building Materials, 2015. 97: p. 106-118. https://doi.org/10.1016/j.conbuildmat.2015.06.020.
[63] Raftery, G.M. and A.M. Harte, *Low-grade glued laminated timber reinforced with FRP plate.* Composites: Part B, 2011. 42: p. 724-735. https://doi.org/10.1016/j.compositesb.2011.01.029.

[64] Zhang, P. and S. Shen, *Strengthening mechanical properties of glulam with basalt Fiber.* Advances in Natural Science, 2011. 4(2): p. 130-133. http://dx.doi.org/10.3968/j.ans.1715787020110402.137.
[65] Broughton, J.G. and A.R. Hutchinson, *Adhesive systems for structural connections in timber.* International Journal of Adhesion & Adhesives, 2001. 21: p. 177-186. https://doi.org/10.1016/S0143-7496(00)00049-X.
[66] Anshari, B., Z.W. Guan, A. Kitamori, K. Jung, and K. Komatsu, *Structural behavior of glued laminated timber beams pre-stressed by compressed wood.* Construction and Building Materials, 2012. 29: p. 24-32. https://doi.org/10.1016/j.conbuildmat.2011.10.002.
[67] Dietsch, P. and R. Brandner, *Self-tapping screws and threaded rods as reinforcement for structural timber elements - A state-of-the-art report.* Construction and Building Materials, 2015. 97: p. 78-89. https://doi.org/10.1016/j.conbuildmat.2015.04.028.
[68] Steiger, R., E. Serrano, M. Stepinac, V. Rajcic, C. O'Neill, D. McPollin, and R. Widmann, *Strengthening of timber structures with glued-in rods.* Construction and Building Materials, 2015. 97: p. 90-105. https://doi.org/10.1016/j.conbuildmat.2015.03.097.
[69] Marzi, T., *Nanostructured materials for protection and reinforcement of timber structures: A review and future challenges.* Construction and Building Materials, 2015. 97: p. 119-130. https://doi.org/10.1016/j.conbuildmat.2015.07.016.
[70] Ceccotti, A., *Composite concrete-timber structures.* Progress in Structural Engineering Materials, 2002. 4(3): p. 264-275. https://doi.org/10.1002/pse.126.
[71] Buchanan, A., B. Deam, M. Fragiacomo, S. Pampanin, and A. Palermo, *Multi-storey prestressed timber buildings in New Zealand.* Structural Engineering International, 2018. 18(2): p. 166-173. https://doi.org/10.2749/101686608784218635.
[72] Jiang, W., L. Tomppo, T. Pakarinen, J.A. Sirvio, and H. Liiatainen, *Effect of cellulose nanofibrils on the bond strength of polyvinyl acetate and starch adhesives for wood.* BioResources, 2018. 13(2): p. 2283-2292.
[73] Stoeckel, F., J. Konnerth, and W. Gindl-Altmutter, *Mechanical properties of adhesives for bonding wood - A review.* International Journal of Adhesion & Adhesives, 2013. 45: p. 32-41. https://doi.org/10.1016/j.ijadhadh.2013.03.013.
[74] Saleem, H., A. Edathil, T. Ncube, J. Pokhrel, S. Khoori, A. Abraham, and V. Mittal, *Mechanical and thermal properties of thermoset-graphene nanocomposites.* Macromolecular Materials and Engineering, 2016. 301: p. 231-259. https://doi.org/10.1002/mame.201500335.
[75] Amen-Chen, C. and J. Gabriel, *Wet adhesion durability improvement of polyurethane wood adhesives with primer.* European Journal of Wood and Wood Products, 2014. 73: p. 697-700. https://doi.org/10.1007/s00107-015-0942-9.
[76] Hill, C., *Wood Modification: Chemical, Thermal and other Processes*, ed. D.o.O.C. Christian V Stevens, Ghent University, Belgium. 2006, West Sussex, England: John Wiley & Sons Ltd.
[77] Mantanis, G.I., *Chemical modification of wood by acetylation or furfurylation: A review of the present scaled-up technologies.* BioResources, 2017. 12(2): p. 4478-4489.
[78] Xie, Y., Q. Fu, Q. Wang, Z. Xiao, and H. Militz, *Effects of chemical modification on the mechanical properties of wood.* European Journal of Wood

and Wood Products, 2013. 71: p. 401-416. https://doi.org/10.1007/s00107-013-0693-4.
[79] Fang, C.-H., N. Mariotti, A. Cloutier, A. Koubaa, and P. Blanchet, *Densification of wood veneers by compression combined with heat and steam.* European Journal of Wood and Wood Products, 2012. 70: p. 155-163. https://doi.org/10.1007/s00107-011-0524-4.
[80] Yano, H., A. Hirose, and S. Inaba, *High-strength wood-based materials.* Journal of materials science letters, 1997. 16: p. 1906-1909. https://doi.org/10.1023/A:1018578431873.
[81] Song, J., C. Chen, S. Zhu, M. Zhu, J. Dai, U. Ray, Y. Li, Y. Kuang, Y. Li, N. Quispe, Y. Yao, A. Gong, U.H. Leiste, H.A. Bruck, J.Y. Zhu, A. Vellore, H. Li, M.L. Minus, Z. Jia, A. Martini, T. Li, and L. Hu, *Processing bulk natural wood into a high-performance structural material.* Nature, 2018. 554: p. 224.
[82] Lam, F., *Modern structural wood products.* Progress in Structural Engineering and Materials, 2001. 3: p. 238-245. https://doi.org/10.1002/pse.79.
[83] Lehmann, S., A. Reinschmidt, and L. Mustillo, *Transition strategies: Accelerating social acceptance and removing the barriers to prefabricated multi-storey timber urban infill developments in Australia using CLT construction systems. PNE293-1213*. 2012, Forest & Wood Products Australia: Melbourne Vic.
[84] Crespell, P. and S. Gagnon, *Cross laminated timber: a primer. Special Publication 52*. 2010.
[85] Smith, R.E., *Interlocking Cross-Laminated Timber*, in *Building Technology Educators Conference 2011*. 2011: Toronto, Ontario, Canada.
[86] Jelec, M., V. Varevac, and V. Rajcic, *Cross-laminated timber (CLT) - A state of the art report.* Gradevinar, 2018. 70(2): p. 75-95. https://doi.org/10.14256/JCE.2071.2017.
[87] Niederwestberg, J. and Y.H. Chui, *Characterizing influence of laminate characteristics on elastic properties of cross laminated timber*, in *World Conference on Timber Engineering (WCTE 2014)*. 2014: Quebec City Canada.
[88] Sikora, K.S., D.O. McPolin, and A.M. Harte, *Effects of the thickness of cross-laminated timber (CLT) panels made from Irish Sitka spruce on mechanical performance in bending and shear.* Construction and Building Materials, 2016. 116: p. 141-150. https://doi.org/10.1016/j.conbuildmat.2016.04.145.
[89] Zhou, Q., M. Gong, T.H. Chui, and M. Mohamma, *Measurement of rolling shear modulus and strength of cross laminated timber fabricated with black spruce.* Construction and Building Materials, 2014. 64: p. 379-386. https://doi.org/10.1016/j.conbuildmat.2014.04.039.
[90] Crawford, D., R. Hairstans, and R. Smith, *Feasibility of cross-laminated timber production from UK Sitka spruce*, in *European Conference on Cross Laminated Timber (CLT): COST Action FP1004 with TU Graz: Focus Solid Timber Solutions*. 2014, University of Bath: Graz University of Technology, Austria.
[91] Mengzhe, G. and P. Weichaiang, *Rolling Shear Strengths of Southern Pine Cross Laminated Timber.* Journal of Contemporary Wood Engineering, 2016. 26(1): p. 25-34. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001203.
[92] Hindman, D.P. and J.C. Bouldin, *Mechanical Properties of Southern Pine Cross Laminated Timber.* Journal of Materials in Civil Engineering, 2014. 27(9). https://doi.org/10.1061/(ASCE)MT.1943-5533.0001203.
[93] Fortune, A. and P. Quenneville, *Feasibility study of New Zealand Radiata Pine Cross Laminated Timber.* New Zealand Timber Design Journal 2011. 19(3): p. 3-7.

[94] Sigrist, C. and M. Lehmann, *Potential of CLT produced from Non-Structural Grade Australian Pinus Radiata*, in *World Conference on Timber Engineering 2014*. 2014: Quebec City Canada.
[95] Liao, Y., D. Tu, J. Zhou, H. Zhou, H. Yun, J. Gu, and C. Hu, *Feasibility of manufacturing cross-laminated timber using fast-grown small diameter eucalyptus lumbers.* Construction and Building Materials, 2017. 132: p. 508-515. https://doi.org/10.1016/j.conbuildmat.2016.12.027.
[96] Karmar, A., A.R. Barbosa, and S. Sinha, *Viability of Hybrid Poplar in ANSI approved cross-laminated timber applications.* Journal of Materials in Civil Engineering, 2013. 26(7). https://doi.org/10.1061/(ASCE)MT.1943-5533.0000936.
[97] Wang, Z., H. Fu, Y.-H. Chui, and M. Gong, *Feasibility of Using Poplar as Cross Layer to Fabricate Cross-Laminated Timber*, in *World Conference on Timber Engineering*. 2014: Quebec City Canada.
[98] International Standards, *ISO/DIS 16696-1 Draft International Standard: Timber Structures - Cross Laminated Timber - Part 1: Component performance and production requirements*. 2017: Switzerland.
[99] European Committee for Standardization, *BS EN 16351 Timber Structures - Cross laminated timber - Requirements*. 2015: Brussels.
[100] ANSI/APA, *ANSI/APA PRG 320-2012 American National Standard - Standard for Performance-Rated Cross-Laminated Timber*. 2012: Tacoma WA.
[101] XLam NZ Limited. *Designing with XLam Cross Laminated Timber Version 2.2*. 2017; Available from: https://www.xlam.co.nz/contact.html#contact-design-guide.
[102] Davids, W., N. Willey, R. Lopez-Anido, S. Shaler, D. Gardner, R. Edgar, and M. Tajvidi, *Structural performance of hybrid SPFz-LSL cross-laminated timber panels.* Construction and Building Materials, 2017. 149: p. 156-163. https://doi.org/10.1016/j.conbuildmat.2017.05.131.
[103] Wang, Z., H. Fu, M. Gong, J. Luo, W. Dong, T. Wang, and T.H. Chui, *Planar shear and bending properties of hybrid CT fabricated with lumber and LVL.* Construction and Building Materials, 2017. 151: p. 172-177. https://doi.org/10.1016/j.conbuildmat.2017.04.205.
[104] Aicher, S., M. Hirsch, and Z. Christian, *Hybrid cross-laminated timber plates with beech wood cross-layers.* Construction and Building Materials, 2016. 124: p. 1007-1018. https://doi.org/10.1016/j.conbuildmat.2016.08.051.
[105] Kreuzinger, H., *Flächentragwerke – Platten, Scheiben und Schalen – ein Berechnungsmodell für gängige Statikprogramme.* Bauen mit Holz, 1999. 01/1999: p. 34-39.
[106] Mestek, P., H. Kreuzinger, and W. Stefan, *Design of Cross Laminated Timber (CLT)*, in *10th World Conference on Timber Engineering (WCTE 2008)*. 2008: Miyazaki Japan.
[107] Kim, H.-K., J.-K. Oh, G.-Y. Jeong, H.-M. Yeo, and J.-J. Lee, *Shear Performance of PUR Adhesive in Cross Laminating of Red Pine.* Journal of the Korean Wood Science and Technology, 2013: p. 158-163.
[108] Zhou, Q., M. Gong, Y.H. Chui, and M. Mohammand, *Measurement of Rolling Shear Modulus of Cross Laminated Timber: Exploratory study using downscaled specimens under variable span bending test*, in *International Conference on Biobase Material Science and Engineering*. 2012: Changsha China.
[109] Brandner, R., G. Flatscher, A. Ringhofer, G. Schickhofer, and A. Thiel, *Cross laminated timber (CLT): overview and development.* European Journal of

Wood and Wood Products, 2016. 74(3): p. 331-351. https://doi.org/10.1007/s00107-015-0999-5.
[110] Green, M.C., *Tall Wood*. 2012.
[111] Johnson, O., *Architects embrace "the beginning of the timber age"*, in *dezeen*, A. Frearson, Editor. 2015.
[112] Jones, K., P. Stegemann, J. Sykes, and P. Winslow, *Adoption of unconventional approaches in construction: The case of cross-laminated timber.* Construction and Building Materials, 2016. 125: p. 690-702. https://doi.org/10.1016/j.conbuildmat.2016.08.088.
[113] Rijke, A.d. *CLT will be considered conventional in Australia by 2020*. 2015; Available from: http://www.architectureanddesign.com.au/features/comment/clt-will-be-considered-conventional-in-australia-b.
[114] Waugh, A., *Architects embrace "the beginning of the timber age"*, in *dezeen*, A. Frearson, Editor. 2015.
[115] Espinoza, O., V.R. Trujillo, M.F.L. Mallo, and U. Buehlmann, *Cross-laminated timber: Status and research needs in Europe.* BioResources, 2016. 11(1): p. 281-295.