Whole Timber Construction: A State of the Art Review

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Abstract

Forests worldwide are overstocked with small-diameter trees, putting them at increased risk of disease, insect attack, and destructive high-intensity wildfires. This overstocking is caused primarily by the low market value of these small-diameter trees, which are generally unsuitable for sawn timber production and yield low prices when sold for biomass fuel, paper, or fibre-based engineered timber products. Considerable research in recent decades has demonstrated the potential for these small-diameter trees to be used in minimally processed round segments as structural elements in buildings, bridges, towers, and other infrastructure. Recent structures have also demonstrated the use of trees with major curvature and branching, which are also of low market value, in their round form as primary structural elements. Such "whole timber" construction serves as a low-cost, low-impact building system while providing revenue to forest owners to conduct harvests of low-value trees as required for sustainable forest management. This paper reviews developments in whole timber construction, presenting new non-destructive evaluation techniques, digital survey, design and fabrication methods, new processing technologies, and a diverse range of novel connection types and structural systems. It is shown that the key materials characterisation, processing, and design challenges for whole timber construction have been largely addressed, and that whole timber has the potential to be an important complement to other timber products in construction globally in the coming decades. It is recommended that future work focus on exploit-

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ing new digital technologies and scaling whole timber structural applications through increased prefabrication.

Keywords: sustainable forestry, thinnings, round timber, whole timber, timber structures, non-destructive evaluation, sustainable construction, timber connections, structural design, digital design

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1. Introduction

1.1. Historical Applications

Minimally processed round segments of trees, or "whole timber", have been used as load-bearing elements in human structures since at least as early as the Neolithic (Coudart, 2013). Numerous examples of architecture by pre-industrial societies worldwide show the variety and ingenuity with which cultures have taken advantage of the inherent structural characteristics of timber in its whole form to create large-scale buildings, bridges, and fortifications. Particularly notable examples are the actively-bent longhouse frames of the Iroquois (Nabokov et al., 1989), the gridshell-like *Fale* of pre-colonial Samoa and Tonga (Barnes and Green, 2008), the log-type churches of pre-industrial Russia (Brumfield, 1997), and the "woven timber arch" bridges of Song-dynasty China (Figures 1a, 1b, and 16d) (Zhou et al., 2018).

Whole timber was also used on a massive scale during industrialisation in forested regions worldwide, being incorporated into bridges and various temporary structures (Figure 2) in expanding road and railway networks (Keefer, 1888). The temporary logging "trestle" bridges of the Pacific Northwest of the United States are a particularly striking example. Engineers in these areas used abundantly available timber in its whole form as combined foundation piles and above-ground load-bearing elements, rapidly erecting large bridges and viaducts at low cost. Figure 2 shows the Cedar River logging trestle bridge, built in 1925 by the Pacific States Railway Company. The bridge used 30 metre whole timbers as primary structural elements, and was among the tallest trestle bridges in the world at the time, at 62 metres in height (Slauson, 1971).

Later, whole timber was used as cost-effective utility poles for rural electrification and telecommunications (Wolfe, 1999) – a practice which continues today. Whole timber has also been used throughout history and to the present

(a)

(b)

Figure 1: 1a: The “Rainbow Bridge” in Bianjing, China, shown depicted in the Song Dynasty painting “Along the River During the Qingming Festival” by Zhang Zeduan (1085 — 1145 CE), used a “woven timber arch” of whole timber as its primary structure (Zhou et al., 2018). Public domain image (Zeduan, 1145). 1b: The Xianju Bridge is one of an estimated 100 whole timber woven timber arch bridges remaining in China (Zhou et al., 2018). Photograph by Azrael Green (CC BY-SA 3.0) (Green, 2011).

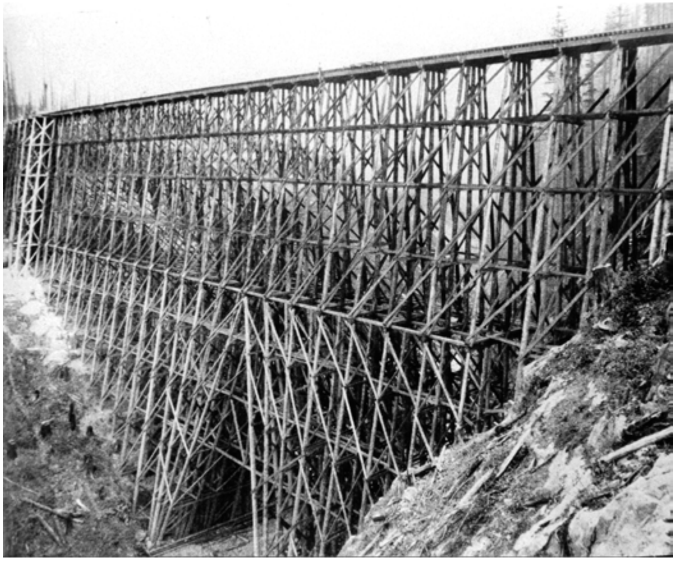


Figure 2: The Cedar River logging railroad trestle bridge, built in 1925. Photograph by Darius Kinsey (Kinsey, 1925). Courtesy of the Maple Valley Historical Society.

day as low-cost structural foundation piles. In industrialised regions, the development of inexpensive timber fasteners and the industrialisation of timber processing and distribution has led to the almost exclusive use of sawn timber and engineered timber products in above-ground structures today.

1.2. Contemporary Applications

Starting in the 1960's and continuing to the present, governments in forested regions around the world have been increasingly faced with a major forestry challenge: an overabundance of small-diameter trees (100-250 millimetres in diameter), putting forests at increased risk of destructive high-intensity wildfires, disease, and insect attack, while suppressing the growth of trees intended for commercial harvests (Wolfe and Mosely, 2000, Fernández-Golfín et al., 2007, Scott et al., 2011, Lim et al., 2013, Bayatkashkoli and Hemmati, 2015, Fuchigami et al., 2016, Erber et al., 2016, Underhill, 2017, Vega et al., 2017, Hiroshima et al., 2018).

This overstocking is caused largely by insufficient prescribed low-intensity burning in fire-prone forests, and insufficient early harvests ("thinnings") in planted forests. In plantation forestry, trees are typically planted in tight spacings to promote straightness and high growth ring density, generally with the requirement that they be thinned one or two times before final harvest. Thinning is expensive however, and the value of small-diameter trees is low in most regions, meaning that forest managers often cannot cover the costs of the thinnings necessary to ensure the health and profitability of their forests through to the final harvest.

Small-diameter trees typically have large fractions of structurally inferior juvenile wood and knots and are often too small in cross-section to yield enough structural-grade sawn timber to justify their harvest (Erikson et al., 2000, Lowell and Green, 2001, Hernandez et al., 2005). Industries which process small-diameter timber into fibre-based engineered wood products, pulp for paper production, or biomass products for energy and heating have high processing costs and suffer from global commodity market price fluctuations, resulting in low and unreliable revenues for forest owners selling to these markets (Wiedenbeck et al., 2016, Ranta et al., 2017). Structural glue-laminated beams and panels (cross-laminated timber) using boards from small-diameter trees are a promising application (Hunt and Winandy, 2003, Hernandez et al., 2005, Herawati et al., 2010, Komariah et al., 2015, Liao et al., 2017), but may also be complicated by low yields of lamination-grade boards from small-diameter trees with large fractions of juvenile wood (Hernandez et al., 2005).

A number of studies worldwide have identified the opportunity for small-diameter timbers to be used as structural elements in their whole, round form, requiring minimal processing, and offering high market value to forest owners seeking to conduct thinnings (Burton et al., 1998, Ranta-Maunus, 1999, Wolfe, 2000, LeVan-Green and Livingston, 2001, Brito, 2010). The strength-reducing effects of knots are less severe for small-diameter timber used in its whole form, because the strength of structural timber is largely governed by local fibre discontinuities around knots caused by sawing (Wolfe and Murphy, 2005). Whole timbers also have significantly higher cross-sectional area and section modulus than the largest sawn elements which can be produced from them, as determined by an inscribed rectangle at the smaller end of a tapered whole timber. The life-cycle impact of whole timber construction has also been shown to be lower than conventional sawn timber construction at a residential scale, provided whole timber is used close to its source (Cooke, 2011).

A number of whole timber structural product suppliers and fabricators have been established in recent decades (WholeTrees, n.d.d, TTT, n.d., Loggo, n.d., FEEL, n.d.), demonstrating the market potential for increased use of whole timber in high-value structural applications. These businesses, besides engaging in design and fabrication of bespoke whole timber structures, have developed and marketed standardised prefabricated whole timber construction elements such as panelised floor and wall plates (Figures 16o,16p,17a), beams (Figures 18 and 16t) and roof truss elements (Figures 16t,16i), space trusses (Figures 3a and 3b), and foundation systems at relatively high production volumes, with the potential for significant scaling in the future.

A number of researchers have also developed low-cost structural applications for whole timber in rural and developing regions (Logsdon, 1982, Jayanetti, 2000, Brito, 2010, Brito and Junior, 2012, Brose, 2018). These designs take advantage of the minimal processing, skilled labour, and expensive equipment required to build using whole timber in its most basic form. Finally, a key thread of whole timber research has explored the use of curved and forked trees, which are also of low market value, in high-value architecturally expressive structures with the help of new digital survey, design, and fabrication tools and re-imagined traditional carpentry methods (Sahu and Wang, 2015, Mollica and Self, 2016, Devadass et al., 2016, Self and Vercruysse, 2017, Von Buelow et al., 2018, WholeTrees, n.d.d, Marshall et al., 2018).

1.3. Future Applications

As timber construction, through its low life-cycle impact and carbon sequestration benefits, is increasingly seen as the most sustainable building system in many regions (Tettey et al., 2019), whole timber is likely to occupy a number of important niches in the industry depending on local resource availability, processing capability, and construction needs. Because of the potentially higher emissions associated with its transport due to low packing efficiency and often high moisture contents when used in construction (Mayhew, 2018), whole timber is likely to be most appropriate where used locally. Figure 4 shows the density of forest cover globally, and is a general indication of the regions where timber, and in particular whole timber, is likely to be an appropriate building material.

(a)

(b)

Figure 3: 3a: The roof truss of the Muroto Indoor Stadium (built in 2017 in Muroto, Japan) is the largest known whole timber spanning structure today, covering a floor area of 50 by 50 metres and doubling as an earthquake-resistant disaster relief shelter. 3b: View of structural connections in Muroto Indoor Stadium roof truss during construction. Photographs courtesy of Professor Katsuhiko Imai.

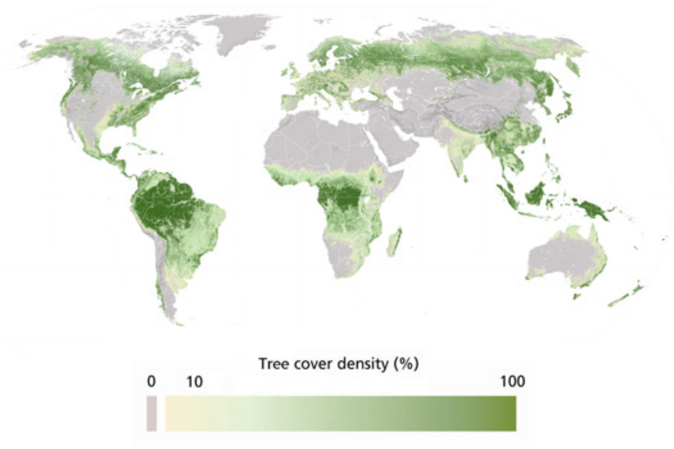


Figure 4: Global forest cover density in 2010. Adapted with permission of the United Nations Food and Agriculture Organisation (FAO, 2012).

As climate change further intensifies the frequency and severity of major wildfires (Jolly et al., 2015, Seidl et al., 2017), a key application of whole timber construction in future may be in and near communities at risk of forest fire. Whole timber construction businesses in these areas could provide high-value markets for small-diameter timber from fuel reduction thinnings near such communities, where such fuel treatments are most effective at reducing risk to life and property from wildfires (Schoennagel et al., 2017). The building systems sold by these businesses could provide low-cost, low-impact construction solutions needed for disaster relief shelter, relocation, and reconstruction efforts as part of a regional adaptive wildfire resilience strategy.

Many regions, particularly in the Global South, face significant affordable housing and infrastructure shortages (Bredenoord et al., 2014), which must be addressed using construction technologies with low associated greenhouse gas emissions if global emissions are to be kept within safe levels. Subject to appropriate mechanical characterisation, the use of low-value timber from abundant industrial tree plantations in these areas as structural elements in minimally processed whole form could serve as part of a low-cost, low-impact building solution for affordable housing and infrastructure in these developing regions.

Finally, new digital technologies for survey, design, and fabrication of structures using trees with significant curvature and branching may create potential

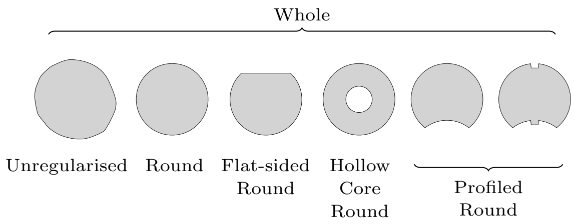


Figure 5: Classification of whole timber by degree and type of processing.

for new high-value construction markets for such low-value trees in developed regions, contributing to a more balanced consumption of forest resources in these areas.

1.4. Review Aims and Scope

In the past several decades, a significant body of research on whole timber construction has developed worldwide, and numerous innovative and celebrated structures have been built using whole timber (Figures 3a,7a,7b,17b,19a,19b,20,21, Table 5). Major efforts by the United States Forest Products Lab and a European project around the turn of the millennium produced reviews of the literature of whole timber materials testing, design, and construction at the time (Ranta-Maunus, 1999, Jayanetti, 2000, Wolfe, 2000, Barnard, 2001, Stern, 2001, LeVan-Green and Livingston, 2001). There has, however, been no globally comprehensive review of whole timber construction since these publications. This has resulted in unrealised potential as innovations in material survey and characterisation, processing technologies, connection design, and structural systems since this time have not been applied in other locations where they could have positive social and environmental impact. This paper reviews the literature and built examples of whole timber construction over the past two decades, with the aim of facilitating better cross-fertilisation of ideas globally in the field and accelerating future research and design.

In the past, literature in the field has typically referred to unsawn timber as “round timber”, regardless of whether timbers had been used in its original irregular and tapered form, mechanically rounded to a circular section, or undergone further mechanical processing. In this paper, for clarity, the term “whole timber” is introduced as an overarching definition to describe timbers which are left substantially whole, but may undergo various degrees of additional processing. This processing may include mechanical rounding, flat-siding, hollow coring, profiling, or no mechanical processing other than debarking, in which case timbers are considered to be "unregularised" (Figure 5). Where relevant, the degree of processing, as defined in Figure 5, is mentioned explicitly in the text.

2. Properties of Whole Timber

Whole timber (in particular, small-diameter, forked, and curved timber) has a number of physical characteristics which distinguish it from sawn timber products, and which must be considered for construction purposes. The following sections discuss these properties.

2.1. Bending Strength of Whole Timber

Various studies have demonstrated that unsawn timbers have higher and less variable bending strengths than sawn timbers (Sandoz, 1991, Wolfe, 2000). This increased strength can be attributed to two factors: unbroken fibre continuity around knots in unsawn timbers, and a favourable shape factor for circular timber sections in bending compared to rectangular ones.

Local fibre discontinuities around knots in sawn sections are the main factor contributing to bending failure in sawn timber. In unsawn timber, fibres travel around knots, resulting in a semi-ductile failure phase and higher ultimate strength in bending (Sandoz, 1991).

In an investigation of the bending strength of non-standard timber cross-sections, Newlin and Trayer (1924) found that small clear timber samples with circular cross-sections exhibited average bending strengths approximately 1.15 times that of square sections of equivalent area. This increased strength can be attributed to the effect of section geometry on the elastic-plastic failure behaviour of timber cross-sections in bending (Brunner, 2000).

In practice, whole timbers are often partially sawn to have one or more flat faces (flat-sided), notched, or mechanically rounded to constant diameters in order to simplify connection details and fabrication procedures, or due to aesthetic preference. Flat-siding breaks fibre continuity in the most highly stressed regions of the timber cross-section, resulting in reduced bending strengths, but apparently without significant effect on compression strengths or longitudinal modulus of elasticity (Villasante et al., 2016). ASTM D3957, a standard intended for grading of whole timber for log home construction, provides guidance on the maximum depth of such flat-siding, limiting the removals to 30% of the radius of the whole timber), and recommends that the favourable form effect ascribed to unsawn whole timbers not be applied to flat-sided whole timbers (ASTM, 2015). Notching timbers (flat-siding timbers for a portion of their length) also has certain strength reducing effects, which may not be accurately accounted for in conventional design standards for rectangular sections. Dewey et al. (2018) describes approaches for accounting for strength reductions due to notches in whole timber sections. See Section 5.3 for a discussion of the effects of mechanical rounding.

The improved bending strength of whole timber is often cited as a reason for using it in structures (Wolfe and Mosely, 2000). While whole timbers likely have higher bending strengths than similarly-sized sawn timber elements, it is important to point out that member stiffness and connection strengths (not member bending strengths) more typically govern the design of timber structures.

It should also be noted that the presence of juvenile wood in whole timber (Figure 6) affects the failure mode in bending. Green et al. (2008) found that timbers of small diameters (3 - 7 inches (75-175 millimetres)) and large proportions of juvenile wood failed in bending in a "brash" (brittle) manner, raising some concerns about their appropriateness for use in bending applications with minimal load-sharing.

2.2. Juvenile Wood in Whole-Timber

Juvenile wood, also known as "corewood" or "crownwood", is the wood produced during the first 5-20 years of growth of a tree in its active crown (see Figure 6) (Moore and Cown, 2017, Kretschmann, 2010). Juvenile wood is known to have undesirable mechanical properties for use as structural timber, with roughly 10% to 50% lower bending strength, tensile strength, and modulus of elasticity than mature wood (Kretschmann, 2010). Juvenile wood also exhibits much higher longitudinal shrinkage when dried than mature wood (as much as 10 times higher) (Kretschmann, 2010), which may lead to increased dimensional instability, such as twisting, during drying (Boren and Barnard, 2000). Juvenile

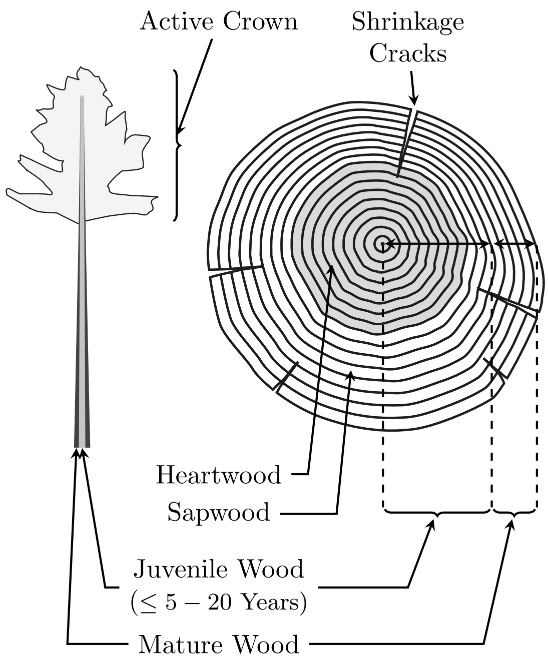


Figure 6: Occurence of heartwood, sapwood, juvenile wood and mature wood in trees. Longitudinal shrinkage cracks related to drying are also shown. Adapted in part from Kretschmann and Cramer (2007). Courtesy of the United States Department of Agriculture Forest Service, Forest Products Laboratory.

wood is also likely to be less naturally resistant to decay than mature wood (Latorraca et al., 2011, Schimleck et al., 2018), and to contain more knots (Wolfe and Murphy, 2005), which further reduce its strength.

The emphasis on the use of young, small-diameter trees in whole-timber construction means that whole timber used in construction is likely to have high proportions of juvenile wood. Selection and grading standards for structural whole timber often exclude timbers of small diameters, or specify minimum growth ring densities to limit the amount of juvenile wood in structural timbers (ASTM, 2017d,b, AS, 2010). This means that the design values provided by these standards are not safely applicable to many small-diameter timbers, and designers must conduct their own destructive testing to characterise the properties of the whole timber considered for construction (See Section 4.1 for a discussion of destructive testing of whole timber).

It is also important to point out that, although standard timber design guidance typically includes a favourable size effect strength adjustment for timbers of smaller cross-sections based on the Weibull "weakest link" theory of brittle material failure, this adjustment cannot safely be applied to timbers with large fractions of juvenile wood. Larson et al. (2004) confirmed the existence of a size effect for whole timbers, but noted that this effect was counteracted by the presence of juvenile wood in timbers with large proportions of it.

2.3. Mechanical Properties of Curved Timber

Trees may develop significant curvature as a reaction to available light, obstacles, competitors, or due to the effects of wind or snow loads (Groover, 2016). Trees with major curvature have poor market value, and may have unfavourable mechanical properties due to their growing conditions. When any limb of a tree grows at an angle of greater than one or two degrees beyond vertical, it is likely to develop what is known as "reaction wood" (Wiedenhoeft, 2010, Groover, 2016). Reaction wood helps trees respond to asymmetrical gravity loads experienced during growth (Groover, 2016). Reaction wood may also be formed in vertically-growing trees subjected to increased lateral wind loads experienced, for example, after a thinning (Cown, 1974). In hardwoods, reaction wood manifests itself as "tension wood" and is largely found in the portion of the cross-section experiencing tension. In softwoods, reaction wood takes the form of "compression wood" and is found in the portion of a limb experiencing compression (Wiedenhoeft, 2010). Reaction wood is usually denser than normal wood, and may be stronger. It however, exhibits much higher longitudinal shrinkage when dried to below fibre saturation point than normal wood (up to 5 times greater in tension wood and up to 10 times greater in compression wood) (Glass and Zelinka, 2010). This can result in significant warping and checking (longitudinal cracking) upon drying (Wiedenhoeft, 2010).

There is little literature concerning the mechanical properties of whole timbers with significant curvature (and therefore, containing large fractions of reaction wood). Designers seeking to use curved timbers in construction should be aware of the properties of reaction wood, and exercise good engineering judgement as to the appropriateness of the selected timbers for the chosen structural application. It should be pointed out that due to fibre continuity, the structural performance and dimensional stability of curved timbers used whole is likely better than if those timbers were sawn.

2.4. Mechanical Properties of Forked Timber

The mechanical properties of timbers with forks are not well understood. A number of researchers have studied the anatomical features of branch junctions (Shigo, 1985, Slater and Ennos, 2013, Slater et al., 2014, Slater and Ennos, 2015, Özden et al., 2017), and the mechanical behaviour of junctions (Mattheck and Vorberg, 1991, Smiley, 2003, Gilman, 2003, Dahle et al., 2006, Kane, 2007, Kane et al., 2008, Ciftci et al., 2014, Slater and Ennos, 2015, Buckley et al., 2015, Liang, 2015). At the time of writing, little actionable guidance for determination of design capacities of junctions has resulted from these studies. Several studies have suggested that the best predictor of the strength of junctions subjected to spreading was the ratio of the diameters between branches (Gilman, 2003, Farrell, 2003, Kane et al., 2008). However, even this was a relatively poor predictor ($r \approx 0.55$) and not necessarily applicable to species outside of the studies conducted. Some authors have suggested that the strength of junctions with codominant branches (branches of similar diameter and no clearly subordinate branch) is lower than equivalent junctions with clearly subordinate branches (Smiley, 2003, Gilman, 2003, Kane et al., 2008). Kane et al. (2008) cautions that codominant junctions should be considered to have capacities of approximately 70% of non-codominant ones (at least for the species and diameter ranges considered). Designers should proceed with caution when specifying forked timbers in their structures and exercise good engineering judgement based on the available literature concerning the species and junction typologies under consideration. Figures 7a and 7b show an example of forked timbers successfully used as primary structural elements in a roof truss (Mollica and Self, 2016, Devadass et al., 2016).

3. Geometric Survey

An accurate geometric survey of whole timber, whether of standing trees before harvest, or of felled timber, is a critical step in whole timber construction, particularly if the timbers used will not be processed to uniform diameters (see Section 5.3 for a discussion of mechanical rounding). Accurate geometric measurements are required for back-calculation of mechanical properties during

(a)

(b)

Figure 7: 7a: The Wood Chip Barn uses whole beech and larch timbers from the surrounding forest as primary structural elements. (Mollica and Self, 2016, Devadass et al., 2016). 7b: Forked beech timbers are used as part of a Vierendeel frame in the Wood Chip Barn (Mollica and Self, 2016, Devadass et al., 2016). Courtesy of the Architectural Association School of Architecture.

destructive and non-destructive testing, for structural design, and for fabrication purposes.

3.1. Survey Methods

Traditionally, geometric information about whole timber for construction has been collected using conventional manual measurement tools (tape measure, tree callipers). In these cases basic measures are recorded: usually length, butt and tip diameter, sweep and crook (Jayanetti, 2000, ASTM, 2017b,d). Taper is typically assumed to be linear between end-diameter measurements (Wolfe and Mosely, 2000). In the past two decades, new 3D scanning tools such as photogrammetry and LIDAR, combined with new CAD approaches and digital fabrication tools have made it increasingly possible for designers to consider timber with highly irregular geometries (forks, major curvature) for construction (see Figures 7a and 7b) (Stanton, 2010, Monier et al., 2013, Sahu and Wang, 2015, Mollica and Self, 2016, Devadass et al., 2016, WholeTrees, n.d.a, Self and Vercruysse, 2017, Von Buelow et al., 2018, Marshall et al., 2018, Allner and Kroehnert, 2018).

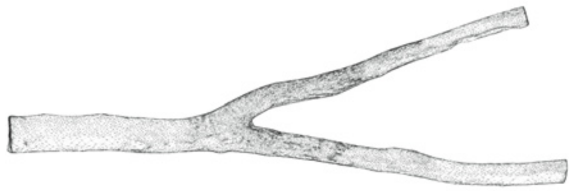
3.2. Scan Data Post-Processing and Registration

A key challenge with using 3D scanning technologies for whole timber construction is the rationalisation of surface representations (Figure 8a) into forms which are more convenient for structural design, analysis, and fabrication. Miller (2013), Devadass et al. (2016), and Allner and Kroehnert (2018) used a "skeleton" representation (Figure 8b) whereby a skeleton representing the area centroid of circles fitted to a timber surface representation was used for alignment of structural members during design, and for a finite element analysis.

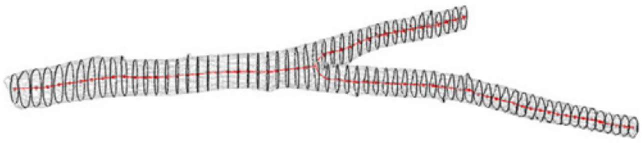
Another challenge in 3D scanning applications for whole timber is the accurate registration of scan data to physical timbers for fabrication and assembly purposes. Devadass et al. (2016) described a method whereby physical marker holes on timbers were captured in photogrammetry scans and used as physical positioning points on a fabrication jig.

3.3. Forest Inventory Data

Increasingly, airborne and terrestrial laser scanning (Figure 9) and photogrammetry are being used for forest inventory by forest managers (Hyyppä



(a)



(b)

Figure 8: 8a: Surface mesh representation of timber produced using photogrammetry. 8b: “Skeleton” representation of a whole timber generated from post-processing of surface mesh representation (Mollica and Self, 2016). Adapted with permission of the Architectural Association School of Architecture.

et al., 2018). Some of these tools are capable of producing three-dimensional surface representations of individual trees for entire forest plots with millimetre-level precision (Liang et al., 2016). Such digital survey data of forests is expected to become increasingly commonplace as technology matures and costs are reduced (Liang et al., 2016). In future, this inventory data, subject to appropriate mechanical characterisation and identification of strength-reducing defects in the trees in question, could be used to explore feasible whole timber designs which take into account the regional availability of trees with particular geometric characteristics (diameter, taper, curvature, forks).

4. Material Characterisation

In order to design safe, serviceable, and efficient structures, designers must be able to accurately characterise the mechanical properties of the structural materials to be used. The determination of characteristic materials properties values for whole timber for construction is challenging for a number of reasons.

Firstly, whole timber is typically not sold by conventional timber products suppliers as a graded structural product. This means that designers must often purchase whole timber directly from foresters or landowners and conduct their

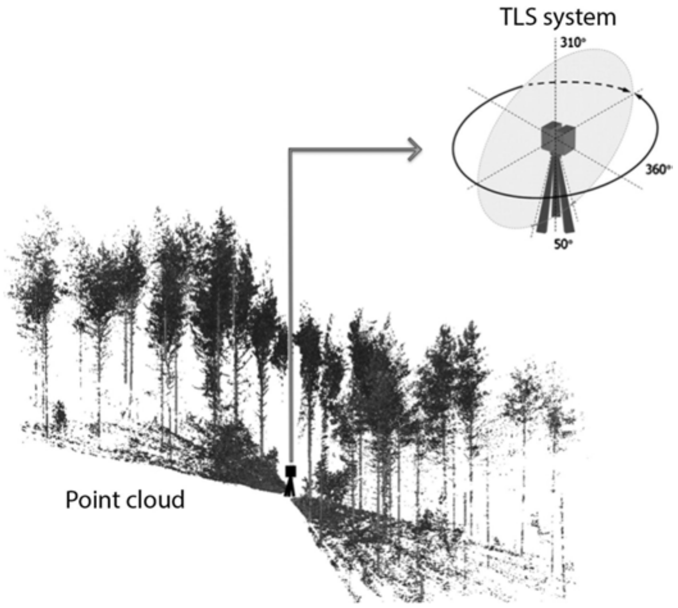


Figure 9: Terrestrial laser scanning (TLS) of a forest plot. With permission from Liang et al. (2016).

Table 1: Selected material grading, testing, and design standards relevant to whole timber construction (ASTM, 2017d, 2015, ANSI, 2017, ASTM, 2014, 2017b, 2015, 2017a,c, NDS, 2018, BSI, 2010, 2005, NZS, 1993, 2001, ICC, 2017).

Organisation	Number	Relevance to Whole Timber Construction
Selection & Grading		
ASTM	D3200	Adapts ASTM D25 whole timber pile visual grading criteria and ASTM D2899 design adjustments to structural whole timbers.
ASTM	D3957	Visual grading rules and design value adjustments for flat-sided and profiled round timber elements.
ANSI	O5.1	Visual grading criteria for utility poles.
EN	14229	Visual grading criteria and destructive testing methods for utility poles.
NZS	3605	Visual grading criteria and proof testing methods for "house piles" and construction poles and piles.
Destructive Testing		
ASTM	D198	Test methods for full-scale timber elements of any cross-section (applicable to whole timber).
ASTM	D1036	Cantilever bending tests for utility poles and methods for extracting small clear samples from whole timber.
EN	14251	Test methods for full-scale whole timber for use in structures.
Design		
ASTM	D2899	Design value adjustments for whole timber piles.
ICC	400	Log home design standard.
ANSI/AWC	NDS	United States timber design standard. Includes section dedicated to whole timber design, referencing ASTM D2899.
NZS	3603	New Zealand timber design standard. Provides strength adjustments for mechanical peeling (debarking).
AS/NZS	7000	Provides strength adjustments for mechanical rounding of whole timbers.

own material characterisation, which may be an unfamiliar and daunting process. Furthermore, designers seeking to building with whole timber often aim to use trees with small diameter, high proportions of juvenile wood, and curvature and branching. Trees with these characteristics often fall outside of scope of the limited standards available for whole timber material grading, testing, and design. Table 1 summarises a selected list of standards globally which are often used as guidance for whole timber research, design, and construction. This summary is intended to facilitate finding relevant guidance for specific whole timber research and construction scenarios more easily.

The rest of this section describes methods designers can take to determine characteristic mechanical properties of whole timber for construction. Generally, designers have three approaches by which to determine the characteristic mechanical properties values of whole timber. These approaches may be used independently, or in combination with one another:

1. Determine characteristic values from *standard guidance for visual grading / selection* themselves or through a certified grading company. Timber must be of a species and provenance included in the guidance and meet minimal grade criteria.
2. Conduct *destructive tests of a representative sample* of the whole timber material to infer characteristic values for the remaining material to be used in construction.
3. Develop a *non-destructive evaluation model* for a similar or representative sample of the material, then use this non-destructive evaluation method to grade all of the material to be used in construction.

Designers have also used non-destructive evaluation methods as preliminary timber selection aids and as an additional safety measure to identify defects and unexpectedly poor unfavourable mechanical properties in individual members.

4.1. Destructive Testing

A number of built projects have used destructive testing to determine the mechanical properties of whole-timber to be used in construction (Huybers, 2002, Woodward and Zoli, 2013). Destructive testing is also used to develop statistical relationships between non-destructive evaluation results and the true strength properties of a batch of whole timber members.

Destructive testing of “small clear samples” cut from whole timbers are a relatively convenient and cost-effective way of characterising the mechanical properties of timber in question disregarding the strength-reducing effects of knots and slope of grain (Woodward and Zoli, 2013). Results from small clear sample tests can only be adjusted to design values for full-scale members when the timbers tested conform to the grading rules established in the grading and selection standard corresponding to the given design value adjustment standard. These grading rules prescribe limits on strength-reducing characteristics such as knots, slope of grain, and other defects. ASTM D25, for example, provides grading rules for whole timbers to be used as structural piles, for which ASTM D2899 is the relevant design value adjustment standard (ASTM, 2017b,c). Destructive testing of full-scale members must be conducted in order to establish the strength properties of whole timbers when the timbers in question do not conform to grade criteria. The EN 14251 standard provides full-scale destructive test methods specifically for structural whole timbers, and ASTM D198 and D4761 provide destructive test methods primarily intended for timbers with rectangular cross-sections, but are also applicable to whole timbers (BSI, 2005, ASTM, 2015, 2013).

4.2. Non-Destructive Evaluation Techniques

Non-destructive evaluation (NDE) of structural timber is often used to estimate the mechanical properties, and, in particular the strength, of timber without actually having to test that material to destruction. Visual grading, the oldest NDE approach for timber, allows for prediction of strength by correlating externally visible growth characteristics and strength-reducing traits with destructive tests. A key research challenge for whole timber construction has been the application of more sophisticated timber NDE methods, such as machine stress grading, acoustic and vibration methods, and x-ray scanning to whole timber to improve the accuracy and speed of mechanical properties characterisation of whole timber for construction. Table 2 provides a selected list of research into NDE methods for whole timber, and is intended to allow researchers to quickly determine which studies over the past two decades are

Table 2: Selected research into non-destructive evaluation techniques for whole timber. The symbol • indicates that the study in question used the given NDE method. For each study, it is indicated whether the timbers used were mechanically rounded or left unregularised.

Author	Mechanically Rounded?	Visual Grading	Static Bending	Transverse Vibration	Longitudinal Stress Wave	X-Ray
Chui et al. (1999)	No	•	•	•		
Ranta-Maunus (1999)	No	•	•		•	•
Wolfe and Mosely (2000)	No		•		•	
Wang et al. (2001b)	No		•	•	•	
Wang et al. (2004)	No				•	
Green et al. (2004)	Yes	•	•	•	•	
Green et al. (2006)	Yes	•	•	•	•	
Prieto et al. (2007)	Yes	•	•		•	
Fernández-Golfín et al. (2007)	Yes	•	•		•	
Morgado et al. (2009)	No	•	•			
Vestøl and Høibø (2010)	No	•	•			
Giudiceandrea et al. (2011)	No					•
Moore et al. (2013)	No		•		•	
Elsener et al. (2013)	No		•			
Roussel et al. (2014)	No					•
Giudiceandrea et al. (2016)	No					•
Carreira et al. (2017)	No		•	•		
Vega et al. (2017)	Yes	•	•		•	
Morgado Telmo F. M. et al. (2017)	No	•	•		•	
Ruy et al. (2018)	No	•			•	

relevant background literature for the NDE method which is to be studied or applied, taking into account whether timbers were tested in unregularised or mechanically rounded form.

While many of these studies demonstrate the feasibility of NDE techniques for whole timber strength grading, it is important to point out that before such methods can be used to grade whole timber with confidence in the field, extensive testing for large numbers of timbers of the species and provenance in question must first be carried out to develop the statistical relationships between NDE tests and actual strength values determined by destructive testing. Some whole timber supply and construction businesses have invested in extensive testing programs to develop NDE models for their whole timber resource, with the aim of improving the accuracy of design values and reducing over-design of whole timber elements in their built structures (SBIR, n.d.).

4.2.1. Visual Grading

A number of visual grading standards have been developed for whole timber. ASTM D3200 was developed in order to adapt existing grading rules for whole timber piles to the use of whole timber as structural poles on a single grade pass/fail basis, and was included into the United States National Design Specification for Wood Construction in 2001 (Line et al., 2004). ASTM D3200 replaces the diameter and taper requirements of ASTM D25 visual grading standard for piles, but otherwise uses all the rules specified in D25, and recommends that ASTM D2899, the design standard for whole timber piles, be used to determine design values for structural poles.

The log home industry has developed a standard (ASTM D3957) intended as guidance for log suppliers to develop their own commercial visual grading rules and design values for whole timbers intended for use in log buildings (Burke, 2004, ASTM, 2015). In particular ASTM D3957 provides guidance on developing visual grading methods for whole timbers which have been flat sawn on one face, and therefore are more vulnerable to fibre continuity-related failures than unsawn whole timbers. D3957 categorises unsawn and flat-sided whole or round timbers intended for use as bending elements as “sawn round timber beams”.

To date, two timber products inspection companies (Timber Products Inspection (TPI, n.d.) and the Log Home Council (Log and Timber Homes Concil

(LHC), n.d.)) have been accredited to provide commercial grading services for sawn round timber beams according to grading rules which they have developed based on ASTM D3957 for a number of species of timber commercially available in the United States (Burke, 2004, TPI, 2008). Sawn round timbers are intended for use in structures as bending or compression elements. Their grades are typically listed as "Unsawn" along with two to three grades ("No 1", "No 2" etc.) for timbers which are sawn on one face. Occasionally, "Unsawn" timbers are graded into two separate strength classes.

Based on a study of small diameter whole timber conducted as part of a major European research project, Ranta-Maunus (1999) proposed a voluntary product standard (VPS-SRT-2) for the development of new visual grading standards for whole timber intended for use as structural poles. Ranta-Maunus (1999) developed and proposed one such visual grading standard for Scandinavian-grown Scots Pine and Norway spruce smaller than 200 mm in diameter based on testing conducted during the study, but no other visual grading standards have been developed based on VPS-SRT-2.

Qualitative grading standards (such as EN 1927, EN 1316) also exist in some countries for preliminary sorting of logs during purchasing, but the grading criteria in these standards, have, by definition, not been correlated with destructive tests, and so cannot be used to estimate strength properties (BSI, 2008, 2012).

Visual grading criteria also exist for utility poles (ANSI O5.1, EN 14229), but these may be of limited applicability to structural whole timber because the governing failure mode of utility poles is bending failure due to transverse loads as cantilever columns rigidly fixed at their base, a scenario not common for whole timber used in construction.

Visual grading is convenient because it requires minimal equipment and can be carried out easily in remote sites. However the mechanical properties values predicted by visual grading may be quite conservative because of the relatively poor correlation between visually observable characteristics and mechanical behaviour. Green et al. (2006) found that ASTM 3957 visual grading procedures for mechanically rounded 9 inch (23 cm) logs resulted in very conservative predictions of bending and compression strength. For a group of softwood species, allowable bending strengths predicted by visual grading were 40%-60% of those determined by destructive testing, and predicted compression strengths were around 40% of testing-derived values.

4.2.2. Static Bending

Non-destructive static transverse bending tests, typically referred to as "mechanical grading" or "machine stress grading", are a common non-destructive evaluation technique in sawn timber grading. These tests, conducted in the elastic range, are used to estimate the longitudinal modulus of elasticity (MOE) of the timber element. In timber, longitudinal MOE is strongly correlated with strength properties, and this relationship is the basis for a number of NDE techniques which, by measuring the MOE of timbers, provide a means for predicting their strength (Galligan and McDonald, 2000, Ross, 2015). The MOE-strength correlation has also been shown to be strong ($r \approx 0.75$) for small-diameter whole timber (De Vries and Gard, 1998, Morgado et al., 2009). Although a number of authors have successfully demonstrated the use of mechanical grading for whole timber (see Table 2), imperfections in the roundness and straightness of unregularised whole timbers made accurate determination of their geometric properties difficult, affecting the accuracy of MOE calculations (Wang et al., 2001b). The geometric survey methods described in Section 3 could be applied here to obtain more accurate measurements of geometry for such bending tests. The tapered form of unregularised whole timbers also makes the back-calculation of MOE from load-displacement results somewhat more challenging than for timbers which have been processed to a uniform diameter. Wolfe and Mosely (2000) describe a "moment-area" method for performing these calculations for tapered members based on a hybrid of methods described in ASTM D143 and ASTM D1036 (ASTM, 2014, 2017a). Alternatively, finite element methods using a "skeletonisation" approach could be conveniently applied here using log geometries determined by 3D scanning.

4.2.3. Acoustic Methods

Acoustic NDE methods for timber use impacts or transducers to induce internal stress waves in timber samples. Various characteristics of these waves are then recorded to infer properties of the timber in question (Wang and Carter, 2015). The most mature acoustic NDE technology applicable to whole timber

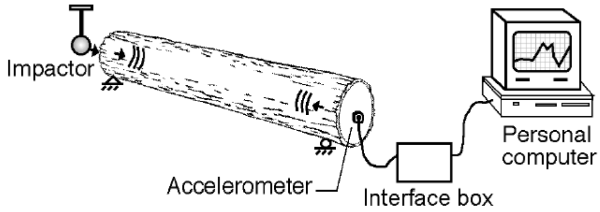


Figure 10: Longitudinal stress-wave testing of whole timbers (Wang et al., 2001a). Courtesy of the United States Department of Agriculture Forest Service, Forest Products Laboratory.

characterisation is longitudinal stress wave testing (Figure 10). Longitudinal stress wave testing works by inducing a stress wave at the end of a timber with a hammer or a transducer and recording the time taken for the wave to travel along the length of the timber, either through a single time-of-flight measurement, or through a resonance measurement which captures the repeated reflection of the stress wave from end-to-end in the timber (Ross, 2015). The longitudinal MOE of the timber is inferred by assuming one-dimensional wave behaviour, and calculated using the equation $MOE = C^2\rho$, where C is the velocity of the stress wave, as calculated by its time of flight and the length of the timber, and ρ is the mean overall density of the timber. As with static bending, this MOE is then used to predict strength. A number of studies have demonstrated the effectiveness of longitudinal stress wave testing for strength grading of whole timber (see Table 2). However, Wang et al. (2004) found that log diameter had a significant effect on longitudinal stress wave velocity for small diameter timbers. Wang et al. (2004) proposed a multi-variable regression model which included log diameter as a predictor of stiffness. This model resulted in relatively good prediction of modulus of elasticity (as measured by static bending tests of the same material) with coefficients of determination of $R^2 \approx 0.7$ to $R^2 \approx 0.9$. The effect of log diameter on stress wave velocity was also confirmed by Ruy et al. (2018).

A number of commercial products are available for longitudinal stress wave testing, as handheld devices or as devices integrated into the heads of harvesters or sawmill production lines. The relatively strong predictive power and ease of use of longitudinal stress wave testing in the field and throughout the supply chain of whole timber products make it a powerful tool for selection and grading

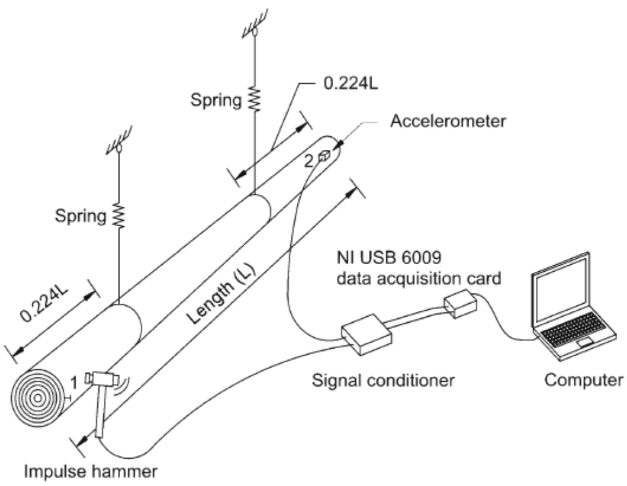


Figure 11: Transverse vibration testing setup for non-destructive evaluation of whole timbers used by Carreira et al. (2017). With permission from Carreira et al. (2017).

of whole timber for structural applications. A growing body of research has also explored more sophisticated measures of wave behaviour in whole timber elements with respect to orthotropic material properties, and more accurate models of stress wave propagation (Elsener et al., 2013, Subhani et al., 2016, Xu et al., 2018, Wang et al., 2018).

A number of studies have also demonstrated the effectiveness of acoustic methods for NDE of standing trees (Senalik et al., 2014, Rudnicki et al., 2017), which could be useful for improving the efficiency and usable yield of harvests of whole timber for construction purposes.

4.2.4. Transverse Vibration Testing

Transverse vibration testing (Figure 11) works by measuring the displacement time history of a slender timber element subjected to a transverse impact. The timber is assumed to behaving as a single degree of freedom damped oscillator as it vibrates transversely in its fundamental bending mode. A natural frequency is inferred from the displacement time history, which is then used to back-calculate the MOE of the timber (Ross, 2015). As with static bending and longitudinal stress wave testing, this MOE is then used to predict strength based on the strong correlation between MOE and strength. A number of studies have demonstrated that transverse vibration is an effective means of predicting the stiffness of whole timber (see Table 2) (Green et al., 2006, Carreira et al., 2017). Wang et al. (2001b) found that transverse vibration testing appeared to be less sensitive to geometric imperfections than longitudinal stress wave testing. However, the tapered cross-section of unregularised whole timbers may still complicate accurate back-calculation of MOE from vibration results. Chui et al. (1999) and Murphy (2000) proposed methods for performing this calculation for tapered round timbers. Here again, 3D scanning and a finite element analysis could help to address issues related to geometric variability.

4.2.5. X-Ray Methods

X-ray scanning of timber works by recording the attenuation of radiation which has passed through a timber element (in the same way as used in medical imaging or other common X-ray applications). The degree of attenuation of radiation is related to density (Wei et al., 2011), and, because timber strength and stiffness is strongly correlated with its density, can be used to infer mechanical properties (Oja et al., 2001). X-ray scanning can also be used to detect defects or foreign objects in timber (Longuetaud et al., 2012, Johansson et al., 2013, Krähenbühl et al., 2014, Roussel et al., 2014). X-ray scanners commonly used in timber imaging are single-directional, multi-directional, or involve a rotating emitter and sensory arrays. Fixed-position X-ray scanners with emitters in perpendicular arrangements are used fairly widely in sawmills for log segregation by the predicted value of sawn products yielded from them and to optimise sawing patterns based on observed knot locations and log cross-section (Grundberg and Grönlund, 1997, Skog and Oja, 2010, Wei et al., 2011). In rotating systems, computed tomography (CT) methods are used to process recorded signals to construct a volumetric representation of the density of a region of timber (Wei et al., 2011). Recently, a CT-type X-ray scanning system using rotating cone-type emitters has been developed which can accurately characterise the internal properties of entire logs volumetrically at a line speed of 3 meters per second (Giudiceandrea et al., 2011, 2016, Microtec, 2018). Such fully volumetric representations, which are currently used for sawing optimisation, could also be used for developing non-destructive evaluation models for timbers intended for use as structural elements in their whole form (Grundberg and Grönlund, 1997). Because knots are the primary strength-reducing characteristics in timber, three-dimensional internal knot geometries and locations could likely be used to develop accurate predictions of strength in whole timbers.

5. Materials Preparation and Processing

The harvesting and preparation of whole timber for service in structures involves a number of specialised processing operations - some of which have strength-reducing effects. The following sections discuss developments in whole timber processing for construction.

5.1. Harvesting

Ranta-Maunus (1999) and Jayanetti (2000) provide guidance on harvesting of small-diameter whole timber for construction. It is important to note that mechanised harvester head-rollers may damage the exterior surface of small-diameter timbers, resulting in aesthetic defects, and potentially strength-reducing damage (Ranta-Maunus, 1999). Sahu and Wang (2015), Mollica and Self (2016), and WholeTrees (n.d.a) used manual (hand-held chainsaw) harvesting.

5.2. Debarking

Whole timbers must be debarked if they are to be used in structures. Debarking improves drying speed and is required for most preservative treatments (Jayanetti, 2000, Lebow, 2010). Debarking can be done manually using a debarking spud (Jayanetti, 2000), or using a range of mechanised mobile, stationary, or harvester-mounted debarking machinery. Mechanical debarking is much faster than manual debarking, but typically results in damage to external fibres, a less attractive surface finish, and may fail to fully remove all bark. The NZS 3603 design standard for timber structures provides strength reduction factors for poles which been mechanically debarked (see Table 3). The efficiency of debarking greatly depends on the species and time of harvest. Debarking efficiency for some softwood species is as much as 50% lower in winter as compared to summer (Heppelman et al., 2016). Law (2010), Sahu and Wang (2015), Mollica and Self (2016), and WholeTrees (n.d.a) all used manual debarking for at least some of the whole timber in their structures.

5.3. Mechanical Rounding

Whole timbers are often mechanically rounded into cylinders of uniform cross-section, or even into "cigar"-like forms (Darcy, 2017), for convenience in fabrication, connection detailing (Reelick, 2004, Walford and Reelick, 2006), and aesthetic preference. Ranta-Maunus (1999) and Larson et al. (2004) found that mechanical rounding reduced bending strengths of whole timber by about 5-20%, likely depending largely on the fraction of juvenile wood in the remaining section. Larson et al. (2004) also observed that mechanically rounded timbers failed in a more brittle way than unregularised timbers, due to broken fibre continuity around knots. The Australian and New Zealand standard AS/NZS 7000 provides mechanical properties reduction factors (Table 3) for mechanically rounded poles of some softwood species.

Table 3: Mechanical properties adjustments for softwoods due to mechanical peeling (debarking) according to New Zealand timber design standard NZS 3603 (NZS, 1993) and mechanical rounding according to Australia and New Zealand standard AS/NZS 7000 (AS/NZS, 2016). *f_b: bending strength, $f_{c\|}$: compression strength parallel to the grain, $f_{c\perp}$: compression strength perpendicular to the grain, f_t: tensile strength parallel to the grain, MOE: longitudinal modulus of elasticity.*

Operation	f_b	$f_{c\|}$	$f_{c\perp}$	f_t	MOE
Mechanical Peeling	0.9	1.0	–	0.85	1.0
Mechanical Rounding	0.75	0.9	1.0	0.75	0.95

5.4. Drying

The drying of whole timbers to their anticipated in-service moisture content is challenging for a number of reasons. Firstly, whole timbers dry much slower than sawn timber at conventional structural dimensions because of their relatively low surface area to volume ratio and comparatively large section depth, resulting in more energy-intensive and costly drying and potentially higher inventory costs. Secondly, whole timbers tend to develop significant longitudinal cracks ("checks") on their exterior as they dry (See Figures 6 and 12a). These longitudinal cracks are caused by internal stresses which are the result of two factors: the difference between the drying shrinkage rate of wood in the tangential and radial directions and the moisture content gradients created by the exterior of whole timbers drying faster than their interior (Park et al., 2014). The rate of tangential shrinkage in timber is typically about twice that of radial shrinkage (Glass and Zelinka, 2010). Smaller-diameter timbers may exhibit less longitudinal cracking than larger-diameter timbers, likely due to the reduced severity of the moisture gradients induced during drying due to their smaller cross-section (Evans et al., 2000).

Longitudinal cracks do not have a significant impact on member structural behaviour, but can significantly reduce the strength of connections when they occur near fasteners (Huybers, 1987, Ranta-Maunus, 1999, Jayanetti, 2000, Wolfe, 2000, Eckelman, 2004). Such cracks may also reduce durability by providing access to the interior of timbers for moisture, fungi, and insects if they extend deeper than the penetration depth of the preservative treatment, or into the heartwood, which is typically more difficult to treat than the sapwood closer to the exterior (Figure 6) (Batchelar, 2012). Longitudinal cracks may also be undesirable for aesthetic reasons.

Many designers have opted to fabricate and install whole timbers in the green condition with the knowledge that timbers will dry in service and continue to develop checks and exhibit some dimensional changes (Burton et al., 1998, Make, 2018). Designers should be careful to note the generally reduced strength and stiffness properties of green timber in these cases.

Others have opted to air- or kiln-dry their whole timber before installation (Batchelar, 2012, Batchelar and Newcombe, 2014b,a), which has the additional benefit of killing any insects which may later contribute to degradation (Mayhew, 2018). Air drying generally appears to produce more checking than kiln-drying. High-temperature kiln-drying has been found to be more effective than conventional kiln-drying for reducing longitudinal cracking, but also somewhat reduces the strength of whole timbers (Ranta-Maunus, 1999). ASTM D2899 provides reduction factors for strength properties based on the type of conditioning performed to whole timbers, based on compression tests of conditioned whole-section piles (see Table 4) (ASTM, 2017c).

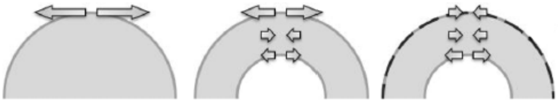
Table 4: ASTM D2899 Reduction factors for strength due to conditioning of whole timbers (ASTM, 2017c).

Air-Drying	Kiln-Drying	Boulton Drying	Normal Steaming	Marine Steaming
1.0	0.9	0.95	0.8	0.74

(a)

(b)

Figure 12: 12a) Whole timbers exhibit longitudinal cracking when dried. 12b) Cored timbers show less longitudinal cracking due to reduced internal drying stresses. Photographs courtesy of TTT Products Ltd. and Mark L. Batchelar.



(a) (b) (c)

Figure 13: Visualisation of drying stresses in a) uncored round timber b) cored round timber c) cored round timber sealed with polyethylene wrap around its exterior. Adapted with permission from Park et al. (2014).

Longitudinal cuts ("kerfs") made in timbers prior to drying have been used to relieve internal drying stresses and control the location of cracks (Chabloz and Dupraz, 2000, Evans et al., 2000, Yeo et al., 2007). This technique may be useful for ensuring that cracks do not occur near fasteners and reduce the strength of connections.

Another approach for improving drying in whole timber is the mechanical removal of the inner core of whole timbers prior to drying (Figure 12b) (Batchelar, 2012). Coring significantly reduces drying times by increasing the exposed surface area of whole timbers. Coring also significantly reduces longitudinal checking by reducing the internal stresses induced by differences in tangential vs. radial shrinkage rates, and by reducing the severity of internal moisture gradients (Park et al., 2014). Yeo et al. (2007) found that coring could reduce kiln-drying time by one half when drying 150 mm and 210 mm diameter round timbers to a target moisture content of 15%. Applying a vapour barrier such as a polyethylene wrap to the exterior of cored whole timbers during drying can further reduce longitudinal checking to apparently almost none, by establishing an inverted moisture gradient during drying which counteracts the stresses induced by the difference in tangential vs. radial shrinkage rates (Figure 13) (Park et al., 2014).

It should be noted that while coring does not appear to have a significant effect on compressive strengths (Yeo et al., 2007) and likely not on tensile strengths either, it has been shown to reduce bending strengths by 10-30% depending on the inner diameter of the cored timber (Lim et al., 2013) when timbers with large fractions of juvenile wood are used, and after adjusting for the reduced section modulus of the cored timber. Lim et al. (2013) attributed this reduced bending strength to a tensile failure perpendicular to the grain caused by a “flattening” failure mode. This strength reduction was not observed, however, in Radiata Pine timbers with low proportions of juvenile wood when core diameter was limited to 1/3 of the total timber diameter (Batchelar, 2019).

5.5. Fabrication

Figure 14: Subtractive fabrication of connections in irregular forked timbers using a router mounted on a 6-axis industrial manufacturing arm (Mollica and Self, 2016, Devadass et al., 2016). Photograph by Swetha Vegesana. Courtesy of the Architectural Association School of Architecture.

One of the most significant advancements in fabrication methods for whole timber construction in recent years has been the use of new digitally-enabled fabrication tools (Mollica and Self, 2016, Devadass et al., 2016, Self and Vercruysse, 2017, Von Buelow et al., 2018, Vercruysse et al., 2018). Mollica and Self (2016), Devadass et al. (2016) and Von Buelow et al. (2018) describe techniques for fabrication of bespoke connections in irregular forked timbers using timber routers mounted on 6-axis fabrication arms (Figure 14). Vercruysse et al. (2018) explored the use of bandsaws and chainsaws mounted to multi-axis positioning arms for bespoke digitally navigated fabrication of whole timbers.

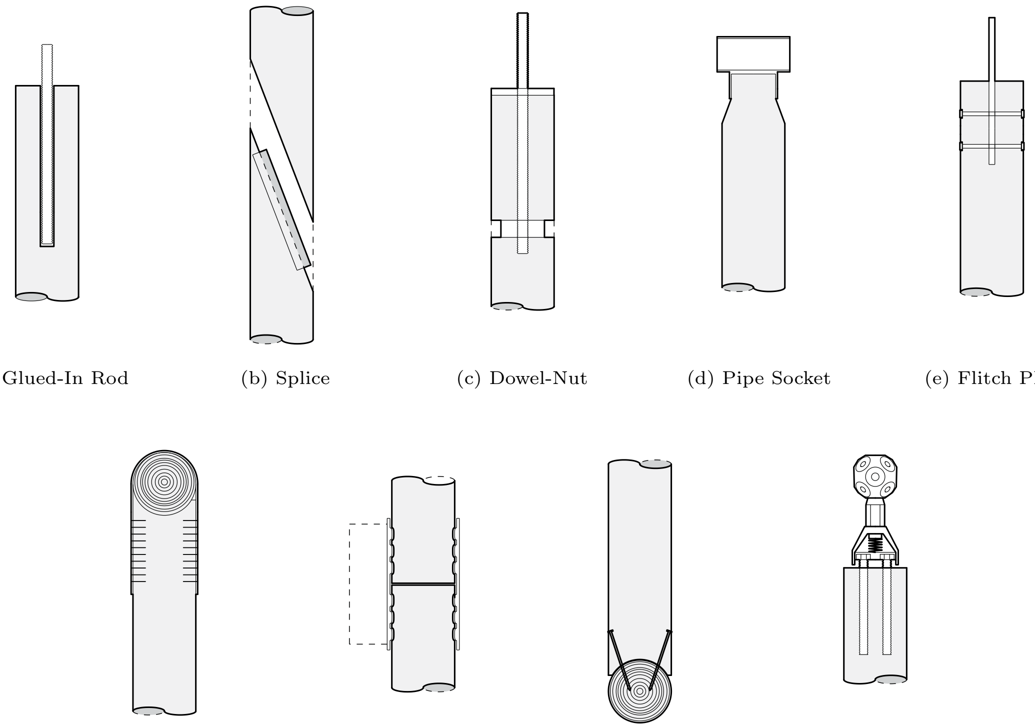
Another significant advance has been the development of fabrication techniques for standardised truss, composite-member, and panelised structural systems in whole timber, discussed in greater detail in Sections 6 and 7. Among these, new techniques discussed by Batchelar (2012) and Batchelar and Newcombe (2014b,a) for coring round timbers up to 18 meters in length are particularly promising, because they offer reduced drying time, reduced shipping weight, improved dimensional stability, reduced longitudinal cracking, and allow for new internally post-tensioned connection types. It should be pointed out that no coring techniques for curved and forked timber have yet been developed, despite the increasing sophistication in subtractive digital fabrication methods for whole timber in recent years.

5.6. Protection

All timber is vulnerable to attack by fungi and insects, resulting in a loss of strength and stiffness, and undesirable aesthetic effects. One strategy to maximise the durability of whole timber structures is to use naturally durable species. Woodward and Zoli (2013) and Baxter et al. (2018) used Black Locust, a naturally durable hardwood in whole timber construction to achieve good durability without preservative treatment. In many cases, however, additional preservative treatment is required to improve durability. Jayanetti (2000) discusses a number of detailing and preservative treatment strategies for maximising the durability of whole timber construction, and strategies for addressing termite attack.

Batchelar and Newcombe (2014b,a) describe how coring of whole timbers can be used to achieve reported 100% pressure-based preservative penetration by increasing surface area and by removing the heartwood of the timber, which is more difficult to treat effectively than sapwood (See Figure 6) (Lebow, 2010). It should be noted that Radiata Pine, the species used by Batchelar and Newcombe (2014b), has a particularly low ratio of heartwood to sapwood. Preservative penetration in cored timbers of species with larger proportions of heartwood may be less successful.

6. Connections



(a) Glued-In Rod (b) Splice (c) Dowel-Nut (d) Pipe Socket (e) Flitch Plate

(f) Nail Plate (g) Annular Groove (h) Toe-nailed Screw (i) Lag Screw in End-Grain

Figure 15: Selected whole timber structural connections. References: (a): (Burton et al., 1998, Morgado et al., 2013, Schober et al., 2018) (b): (Burton et al., 1998) (c): (Wolfe et al., 2000, Eckelman, 2004, Mollica and Self, 2016, Brose, 2018) (d): (Al-Khattat, 2008, Woodward and Zoli, 2013) (e): (Huybers, 1987, Lowenstein, 2002, Huybers, 2002, Lusambo and Wills, 2002, Barnard, 2001, Make, 2018, Gorman et al., 2012, Morgado et al., 2013, WholeTrees, n.d.a, Darcy, 2017) (f): (Jayanetti, 2000, Brito, 2010, Brito and Junior, 2012, Gorman et al., 2012) (g): (Morris et al., 2009) (h): (Make, 2018) (i): (Imai et al., 2002, 2016)

The design and fabrication of safe, cost-effective, and high-capacity structural connections are among the greatest challenges in whole timber construction. Longitudinal shrinkage cracking, when it occurs near fasteners, can reduce connection capacities by precipitating tensile failures perpendicular to the grain. Juvenile wood can reduce embedment strengths of fasteners, particularly closer to the centre of timbers (Barnard, 2001). A further challenge is the development of connections which can accommodate multiple unregularised whole timbers at a node.

6.1. Dowel-type connections

The most commonly used engineered connections for whole timber are dowel-type connections (Figures 15c and 15e), which are well accommodated for by existing design standards for timber construction. A common approach to conservatively adapt dowel-type connection design rules to whole timbers is to size the connections assuming that only a rectangle inscribed into the cross-section of the timber is engaged structurally (Miller-Johnson and Ernst, 2018). When large proportions of juvenile wood (which typically has lower density than mature wood) are likely to be present, however, conventional connection design methods based on Johansen's equations are likely to be unsafe (Barnard, 2001). In these instances, destructive testing of connections should be conducted.

6.1.1. Flitch plates

The most commonly used and studied dowel-type connections for whole timber are "flitch plate" connections (Figure 15e), which combine a central steel plate with bolts or pipes as dowels (Lowenstein, 2002, Make, 2018, Gorman et al., 2012, Morgado et al., 2013, Darcy, 2017, Baxter et al., 2018). This connection type accommodates irregular whole timber cross-sections fairly easily, is relatively straightforward to fabricate, and, when sized correctly, fails in a ductile manner through plastic hinge formation in the dowels. A number of early studies in engineered whole timber construction explored the use of external wire lacing in pipe-type flitch plate connections to reduce the effects of shrinkage cracks on connection capacity (Huybers, 1987, 2002, Lusambo and Wills, 2002).

6.1.2. Dowel-nuts

Another connection type which has seen considerable research is the "dowel-nut" connection (Figure 15c), favoured for its simple fabrication and low cost (Wolfe et al., 2000, Eckelman, 2004, Mollica and Self, 2016, Brose, 2018). Mollica and Self (2016) demonstrated a "cross-bolt" configuration combined with mass-customised CNC-fabricated 3D mated timber surfaces to achieve a dowel-nut-like pipe and bearing washer connection which could accommodate irregular whole timber geometries meeting at a node. Split rings were used to provide shear transfer at these connections.

6.1.3. Screws

Another important trend in whole timber connection design has been the increasing use of screws (Malo and Ellingsbø, 2010, Make, 2018, Frese and Blaß, 2014). Imai et al. (2002, 2016) and Miyahara et al. (2016) demonstrated the use of specially-designed lag screws glued into the end-grain of small-diameter timbers as part of a high-capacity spatial truss nodal connection (Figure 15i). Self-tapping mass timber screws have also been explored as a means of reducing the effects of splitting in dowel-type connections in whole timber (Klajmonová and Lokaj, 2014).

6.2. Glued connections

Glued-in rods (Figure 15a) have also been explored as a high-capacity connection for whole timber, and when sized correctly, also exhibit ductile failure (Burton et al., 1998, Morgado et al., 2013). Schober et al. (2018) demonstrated the use of concrete-type adhesives for glued-in rods to address quality control and cracking issues associated with thin glue lines. These connections were combined with bespoke cast polymer-concrete nodes which accommodate diverse member geometries and angles at nodes well. 3D-printing of nodes may also provide a means of accommodating multiple whole timbers at connections, an approach which has been demonstrated for whole-culm bamboo (Amtsberg and Raspall, 2018).

Glue has also been used to achieve splice connections (Figure 15b) (Burton et al., 1998) and even finger joints in round and flat-sided round timber (Flach and Hernandez, 2003, Piao et al., 2013). Pipe-seated glued connections (Figure 15d) have also been used for round timber (Woodward and Zoli, 2013).

6.3. External plates and sheaths

A number of connection types have also been explored using external steel plates or sheaths. Jayanetti (2000), Brito (2010), Brito and Junior (2012), and Gorman et al. (2012) discuss nail plate connections (Figure 15f). Morris et al. (2009) demonstrated an annular-groove sheath connection (Figure 15g) for round timbers designed to achieve moment resistance, typically a major challenge in any timber connection, and whole timber connections especially.

7. Structural Systems

7.1. Trusses

One of the most common applications of whole timber in construction has been in trusses - in particular exposed roof trusses (Figures 7a,7b and 19a,19b) (Huybers, 1987, 2002, Wolfe et al., 2000, Lowenstein, 2002, Zhang et al., 2013, Miyahara et al., 2016, WholeTrees, n.d.a, Brose, 2018). Exposed roof trusses are a particularly appropriate application of whole timber because they showcase the structural potential of whole timber prominently, maximising visual impact, while generally having lower design loads, simpler envelope attachment details, and less stringent deflection and vibration limits compared to other building components. Whole timber has also been successfully used in roofs in single-layer grid-shells (Imai et al., 2002, Fujimoto et al., 2002, 2009, 2016), and in double layer grid-shells (Burton et al., 1998).

Whole timber trusses have also been used for pedestrian bridges (Figure 20) (Yeh and Lin, 2007, Al-Khattat, 2008, Woodward and Zoli, 2013). Post-tensioning was used by Al-Khattat (2008) to achieve glue-free seated pipe connections. Spatial truss systems for whole timber have also been applied in tower structures (Huybers, 2002, Batchelar, 2012, Klajmonová and Lokaj, 2015). Batchelar (2012) demonstrated the use of hollow-core round timbers as structural elements in spatial trusses for telecommunications towers.

A number of designers have addressed the challenge of fabricating large numbers of whole timber truss elements efficiently, typically through the design of easily-fabricated connections and simplified assembly sequences. Gundersen (2015) demonstrated a system for hybrid steel and whole timber parallel chord roof truss elements (Figures 21 and 16i), which eliminated the need for time-consuming fabrication of angled timber-timber connections of whole timbers in the chord and web. Imai et al. (2002, 2016), Zhang et al. (2013), and Miyahara et al. (2016) discuss the use of a standardised node connection for large scale round timber space trusses which allows for efficient fabrication by minimally trained workers. Gonçalves et al. (2014) and Bukauskas (2015) proposed trussed structural column modules for use in prefabricated kit-type whole timber construction. Such kits of parts could simplify the design and fabrication of whole timber structures through the marketing and sale of a range of prefabricated structural-scale modules similar to those found in the steel and pre-cast concrete industries.

7.2. Frames

Whole timber has also been shown to be effective in frame-type structures, despite challenges in developing moment connections for whole timber. Morris et al. (2009) demonstrates how moment-resisting annular-groove connections (Figure 15g) can be used in multi-storey portal frame structures. Kroeker (2007), in an approach similar to that described in Burton et al. (1998) for spliced actively bent arch members, demonstrates the use of a two-layer moment-resisting composite member using actively-bent small-diameter whole timbers as chords, and short whole timber elements as web members.

A number of structures have also demonstrated the potential for curved and forked irregular whole timbers to be used in frame structures. A number of residential-scale structures have been built using forked and curved timbers in a post and beam type arrangement, successfully mating the irregular geometries of the irregular structural whole timbers with regularised envelope elements (Baxter et al., 2018). Mollica and Self (2016) and Von Buelow et al. (2018) demonstrated the use of forked timbers in Vierendeel frame arrangements (Figures 7a,7b,16j), relying on the moment capacity of fork junctions to reduce the number of connections and triangulating members. A patent by Thornton and Blair (2017) presents a novel solution for small-scale portal frame construction using round timbers combined with panelised timber boards to achieve moment capacity through composite action.

7.3. Wall Elements

The use of whole timber in wall assemblies is particularly promising because of its potential to provide a high-volume low- and mid-rise construction market for whole timber products. Batchelar and Newcombe (2014b) and Batchelar and Newcombe (2014a) demonstrated how hollow-core round timbers could be joined with shear-keys into panel elements with shear resistance (Figures 17a,16o), and combined with internal post-tensioning cables to achieve good seismic performance in a 5-story residential structure. Wu et al. (2015, 2018) proposed and tested a system for light-frame stud walls made with whole timbers cut in half and arranged with their flat sides facing outwards, with steel shear connectors to achieve composite action (Figure 16s). Sahu and Wang (2015) demonstrated a contemporary innovation on traditional log wall construction techniques through the use of irregular curved whole timbers for a non weather-tight single story free-form log wall (Figure 16e), which was enabled by digital scanning, design, and fabrication.

7.4. Floor and Bridge Deck Systems

Chabloz and Dupraz (2000), Chapman and Dodd (2007, 2008) and Batchelar (2012) demonstrated floor systems using round timber (Figure 16p). Chapman and Dodd (2007, 2008) found that such floor systems had good acoustical performance. Several studies have explored the use of unregularised and round timber floor systems with shear-connected concrete toppings (Figure 16q) (Batchelar, 2012, Skinner et al., 2014). Skinner et al. (2014) found that the concrete topping, by increasing the modal mass of the whole timber-concrete composite floor elements, brought them to within occupant comfort vibration serviceability limits. Whole timber-concrete composite spanning systems have also been effectively applied in low-cost, high-capacity road bridges in rural and developing regions (Logsdon, 1982, Pigozzo et al., 2004, Brito and Junior, 2012, Rodrigues et al., 2013).

Thornton and Blair (2011) and Thornton and Thornton (2019) demonstrated a system for constructing I-beams using round timbers as flanges, and plywood or another engineered timber product as web material (Figure 16r). Similarly, Gorman et al. (2016) proposed and tested a system for I-beams built up using two halves of a small-diameter round timber as the chords, and a piece of sawn timber as the web (Figure 16r).

Thornton and Blair (2014, 2016), Thornton (2018a,b) demonstrate a system for creating spanning elements using small-diameter round timbers by mating them at profiled surfaces and connecting them with angled glued-in through-bolts to achieve shear resistance (Figures 18 and 16t). Thornton and Blair (2014) also discussed methods for connecting such elements longitudinally to achieve longer spans. Loggo (n.d.) presents ways in which these elements can be used in rapidly-erected residential construction. This application is particularly promising because it allows for the use of very small-diameter timbers and waste "peeler cores" from veneer production in a potentially high-volume structural application.

7.5. Foundations

Hollow coring has also allowed significant innovations in whole timber foundation structures, including allowing for water jetting and cement grout injection through the core of round timber piles for more effective pile driving and soil stabilisation (Batchelar, 2012, Batchelar and Newcombe, 2014a). Raft-type foundation systems have also been developed using crossing arrangements of hollow-core round timbers (TTT, 2015).

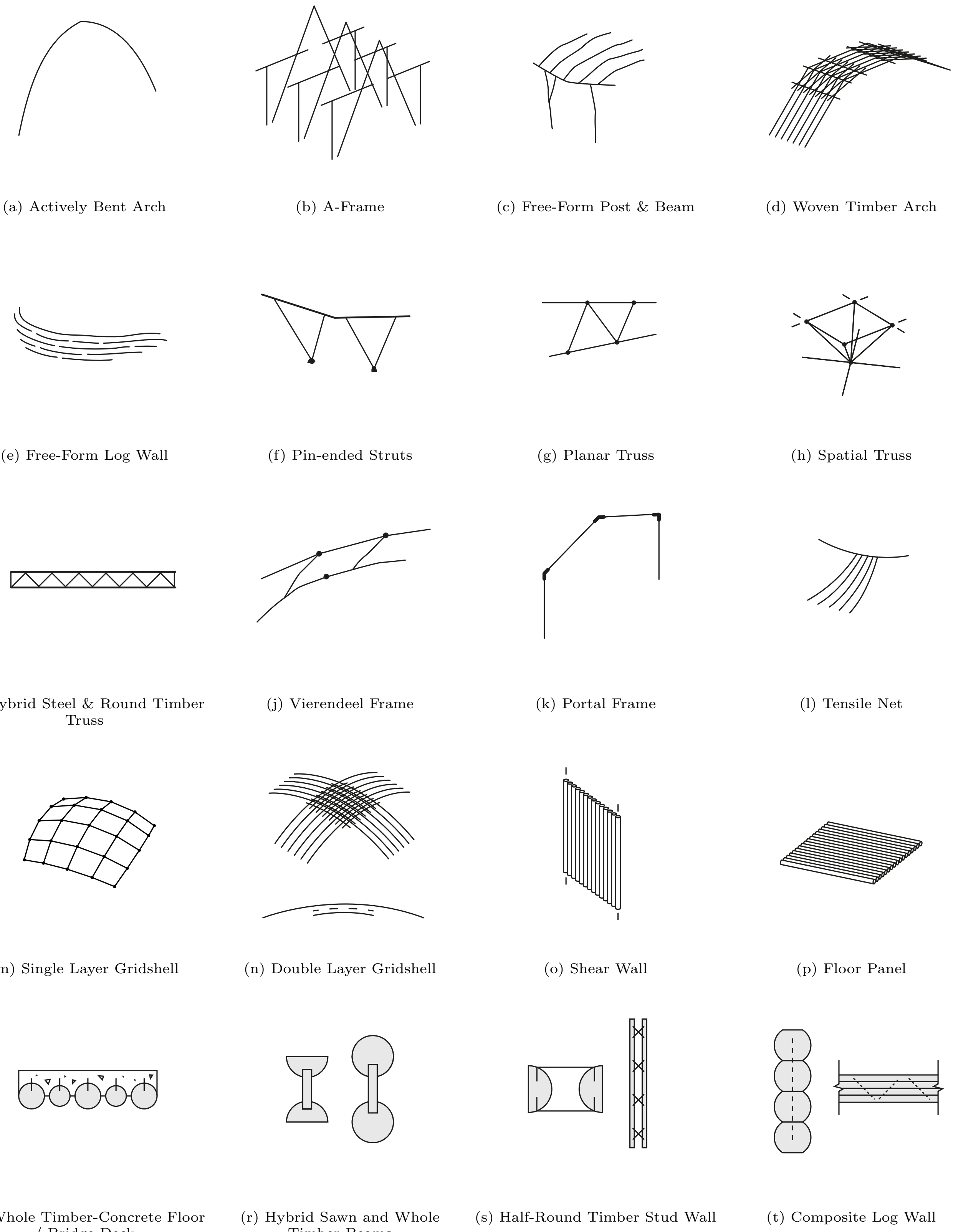
7.6. Structural "Form-Fitting"

A key challenge in the design of whole timber structural systems is the matching of available whole timbers to desired structural forms. Unlike standardised construction products, whole timber elements must be used "as-is", rather than specified based on a predetermined structural design. This constraint presents an interesting design problem for architects and engineers working with whole timber. A number of researchers and designers have explored the challenge of developing computational "assignment" or "form-fitting" approaches to discover and optimise structural forms which are both buildable and satisfy structural requirements given predetermined finite inventories of whole timber elements (Monier et al., 2013, Stanton, 2010, Mollica and Self, 2016, Bukauskas et al., 2017a,b, 2018, Von Buelow et al., 2018, Allner and Kroehnert, 2018, Marshall et al., 2018). This research has demonstrated the feasibility of assignment algorithms for determining viable structural geometries given finite inventories of diverse elements, and has identified the need for generaliseable computational approaches which designers could use for the design of a wide range of whole timber structural typologies.

Table 5: Selected list of structures using whole timber built since around the year 2000. For structures built before this time, see (Burton et al., 1998, Ranta-Maunus, 1999, Stern, 2001, Huybers, 2002). A more extensive list of structures, including historic examples, can be found online at the Whole Timber Structures Database (Bukauskas, 2018).

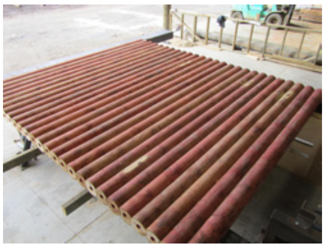
Structure	Structural System(s)	Connections	References	Year
Muroto Indoor Stadium	Spatial truss	Lag screws in end-grain	Miyahara et al. (2016)	2017
Scott Visitor Center	Pin-ended struts	Lag screws in end-grain	LFA (2015)	2016
Festival Foods Grocery Store	Planar trusses	Bolted flitch plates, internal bearing bar	WholeTrees (n.d.a)	2016
Treetop Walkway at Westonbirt Arboretum	Pin-ended struts	Bolted flitch plates	Darcy (2017), BuroHappold (2018)	2016
Wood Chip Barn	Vierendeel trusses / trussed arches	Pipe/washer-seated crossing bolts with digitally fabricated mortise and tenon, split rings	Mollica and Self (2016), Devadass et al. (2016), Self and Vercruysse (2017)	2016
Huia Road Residence	Hollow core round timber shear walls	Shear keys, post-tensioning rods	Batchelar and Newcombe (2014a)	2016
Boiler House	Freeform log walls	Packers with screws	Sahu and Wang (2015)	2015
Hanifl Garage	Hybrid whole timber-steel truss	Integrated single-bolt flitch plates	WholeTrees (n.d.b), Gundersen (2015)	2014
Te Wharehou O Tuhoe	Various hollow core round timber structural systems	Various	Batchelar and Newcombe (2014b,a)	2014
Lake Bunyoni School Dining Hall	Reciprocal frame roundhouse	Bolted lap joint	Dickson and Parker (2014)	2014
Hollow Core Round Timber Telecommunications Towers	Trussed tower	External sheath with annular grooves	Batchelar (2012)	2013
Salvia Dome	Spatial truss	Lag screws in end-grain	Miyahara et al. (2016)	2013
Underhill Residence	Post and beam, freeform	Bolted lap joint	WholeTrees (n.d.c)	2013
Squibb Park Bridge	Underslung cable bridge	Glued pipe socket	Woodward and Zoli (2013)	2013
Big Shed	Planar trusses	Bolted flitch plates, mass-timber screws	Make (2018)	2012
Bohdanka Observation Tower	Trussed tower, shear-bolted compound whole timber columns	Bolted flitch plate	Kala et al. (2012), Klajmonová and Lokaj (2015)	2011
Sustainability Centre at Prickly Nut Wood	A-frame	Bolted lap joint	Law (2010)	2010
Pictou Landing Health Centre	Actively-bent arch	Various	Kroeker (2007)	2007
Round Timber Concrete Composite Bridge	Whole timber-concrete composite bridge deck	Epoxy-bonded shear rods	Brito (2010)	2006
Japan Railway Yashiro-Cho Station Hall	Single-layer gridshell	Lag-screws in end grain	FEEL (2011)	2005
Lowndes Residence	Portal frame	External sheath with annular grooves	Morris et al. (2009)	2004
Ivy Dome	Spatial truss	Lag screws in end-grain	Miyahara et al. (2016)	2003
Doncaster Earth Centre Photovoltaic Roof	Spatial truss	Bolted flitch plates	Lowenstein (2002)	2001
Balbeg House	Actively-bent arch	Various	Chrisp et al. (2003)	2001
Gifu Academy of Forest Science and Culture	Spatial truss and struts	Various	Gifu (2018)	2000
Academy Mont-Cenis Herne	Pin-ended struts	Bolted flitch plates	Hegger, Hegger and Schleiff Architekten (1999)	1999
Le Sentier Road Bridge	Whole timber-concrete composite bridge deck	Shear connectors to concrete	Natterer (2004)	1997
Lyss School of Forestry	Whole timber columns, single-layer whole timber floor system	Various	Chabloz and Dupraz (2000)	1997

[Interactive geospatial visualisation of the locations of structures in Table 5 should be included here. KML file included with submission: WholeTimberStructuresLocations_InteractiveGeospatialData.kml]

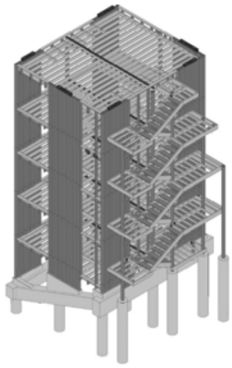


(a) Actively Bent Arch
(b) A-Frame
(c) Free-Form Post & Beam
(d) Woven Timber Arch
(e) Free-Form Log Wall
(f) Pin-ended Struts
(g) Planar Truss
(h) Spatial Truss
(i) Hybrid Steel & Round Timber Truss
(j) Vierendeel Frame
(k) Portal Frame
(l) Tensile Net
(m) Single Layer Gridshell
(n) Double Layer Gridshell
(o) Shear Wall
(p) Floor Panel
(q) Whole Timber-Concrete Floor / Bridge Deck
(r) Hybrid Sawn and Whole Timber Beams
(s) Half-Round Timber Stud Wall
(t) Composite Log Wall

Figure 16: Selected structural systems in whole-timber. References: (a): (Burton et al., 1998, Chrisp et al., 2003, Kroeker, 2007) (b): (Law, 2010, 2018) (c): (WholeTrees, n.d.d,n) (d): (Zhou et al., 2018) (e): (Sahu and Wang, 2015) (f): (Hegger, Hegger and Schleiff Architekten, 1999, LFA, 2015) (g): (Make, 2018, WholeTrees, n.d.a) (h): (Huybers, 1987, 2002, Wolfe et al., 2000, Lowenstein, 2002, Woodward and Zoli, 2013, Zhang et al., 2013, Miyahara et al., 2016, Brose, 2018) (i): (WholeTrees, n.d.b, Gundersen, 2015) (j): (Mollica and Self, 2016) (k): (Morris et al., 2009) (l): (Burton et al., 1998) (m): (Fujimoto et al., 2002, 2009, 2016, Von Buelow et al., 2018) (n): (Burton et al., 1998) (o): (Batchelar, 2012, Batchelar and Newcombe, 2014a) (p): (Batchelar, 2012, Batchelar and Newcombe, 2014b,a) (q): (Logsdon, 1982, Chabloz and Dupraz, 2000, Pigozzo et al., 2004, Chapman and Dodd, 2007, Batchelar, 2012, Brito and Junior, 2012, Rodrigues et al., 2013, Skinner et al., 2014) (r): (Gorman et al., 2016, Thornton and Blair, 2017, Thornton and Thornton, 2019) (s): (Wu et al., 2015, 2018) (t): (Thornton and Blair, 2014, 2016, Thornton, 2018a,b)



(a)



(b)

Figure 17: 17a: Panelised wall element using hollow-core round timbers shear-keyed together to achieve shear resistance (Batchelar and Newcombe, 2014a). 17b: Earthquake-resistant post-tensioned hollow-core round timber shear wall system in a 5-storey residential structure built in 2016 in Wellington, New Zealand, a highly seismic zone (Batchelar and Newcombe, 2014a). Images courtesy of TTT Products Ltd. and Mark L. Batchelar.

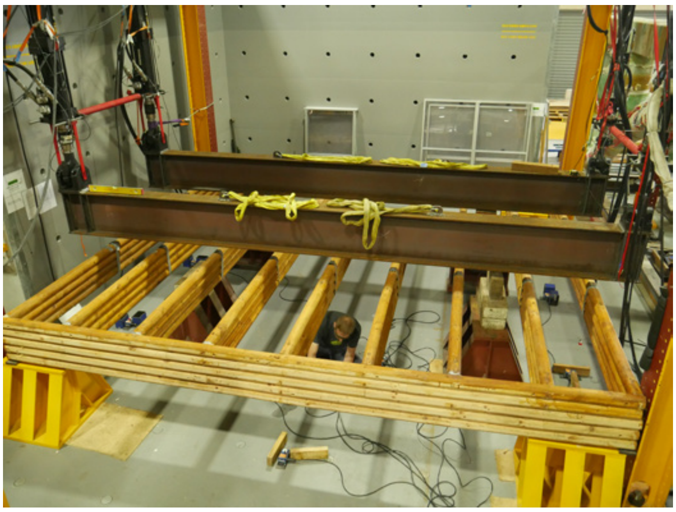


Figure 18: Prefabricated floor system using composite log wall elements consisting of profiled round small-diameter timbers and angled through-bolts for shear resistance (Thornton and Blair, 2014, 2016, Loggo, n.d.). Photograph courtesy of Loggo Pty Ltd.

(a)

(b)

Figure 19: 19a: Unregularised Ash trees culled from local urban parks are used as columns in the Festival Foods grocery store roof. (WholeTrees, n.d.a). 19b: Red Pine trees from overstocked forests are used in 16-metre span whole timber trusses which were prefabricated off-site. (WholeTrees, n.d.a). Photographs courtesy of WholeTrees Structures.

Figure 20: Naturally durable round Black Locust timbers are used in an underslung cable arrangement in the Squibb Park pedestrian bridge (Woodward and Zoli, 2013).

Figure 21: Trusses with whole timber chords and steel web members are used as spanning elements in the Hanifl garage project. (Gundersen, 2015, WholeTrees, n.d.b). Photograph courtesy of WholeTrees Structures.

8. Conclusions

8.1. Summary of Developments

The diversity and sophistication of whole timber construction practices have increased significantly in the past two decades. Research methods and commercially available technology for geometric survey and non-destructive evaluation of timber have advanced, creating opportunities for increasingly accurate and convenient whole timber material characterisation. The design challenges identified by Wolfe (2000), Ranta-Maunus (1999), and others have largely been addressed through innovations in materials processing, connections, and structural systems which have demonstrated the feasibility of whole timber construction for a wide range of contexts. These advancements include highly mechanised value-added processes, bespoke digital fabrication approaches, and technologies appropriate in developing regions. A number of whole timber suppliers and fabrication companies have also demonstrated the effectiveness of prefabrication, vertical supply chain integration, and investment in process optimisation for scaling whole timber production (TTT, n.d., WholeTrees, n.d.d, FEEL, n.d., Loggo, n.d.). New solutions have also been developed to address longitudinal cracking, a significant technical and aesthetic impediment to greater whole timber adoption. These include new coring and drying methods, as well as reinforcement techniques for whole timber connections using self-tapping screws.

Although innovative technologies and methods have been developed, whole timber construction has not achieved the widespread adoption and scale that would be required to adequately address the issues of overstocking experienced in forests worldwide, or to help address housing and infrastructure shortages in developing regions through the use of low-value timber.

8.2. Future Work

In order to scale whole timber construction faster and more effectively, future research should focus on the development of cost-effective and marketable structural solutions for whole timber. In particular, research into structural systems should focus on prefabricated floor, wall, and roof systems which can allow for whole timber to be used in high-volume residential and commercial construction. Future research should also continue to investigate opportunities for digital technologies to scale and improve whole timber construction.

There has been little to no research into the fire performance of whole timber in structures. Given uncertainties which have recently been identified regarding the structural behaviour of timber elements in fire conditions (Schmid et al., 2015), future research should investigate the fire performance of whole timber structural elements and connections.

As timber construction in general sees more widespread adoption worldwide in coming years, a key objective of researchers in this field should be to investigate whole timber structural systems as an alternative and complement to more established engineered timber construction technologies. As timber construction technologies at all building scales continue to mature and diversify, it is likely that whole timber structural systems and components will occupy an increasingly important role in applications where they are an environmentally, socially, and economically appropriate building solution.

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