USDA
United States Department of Agriculture

Undervalued Hardwoods for Engineered Materials and Components

Second Edition

Forest Service

Forest Products Laboratory

General Technical Report
FPL–GTR–276

March
2020

Abstract

This report summarizes information on the use of wood from hardwood species in engineered materials, components, and structures. It includes information on use in a wide variety of engineering products and applications.

Keywords: Wood; hardwoods; engineered products

March 2020

Ross, Robert J.; Erickson, John R., eds. 2020. Undervalued hardwoods for engineered materials and components: second edition. General Technical Report FPL-GTR-276. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 108 p.

A limited number of free copies of this publication are available to the public from the Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726-2398. This publication is also available online at www.fpl.fs.fed.us. Laboratory publications are sent to hundreds of libraries in the United States and elsewhere.

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Undervalued Hardwoods for Engineered Materials and Components

Second Edition

Edited by

Robert J. Ross, Project Leader
John R. Erickson, Former Director (deceased)
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

Contents

Preface

This edition of *Undervalued Hardwoods for Engineered Materials and Components* builds upon the first edition with important new content:

- Implications of utilizing these materials for forest managers (Chapter 1)
- Fundamental properties of wood from hardwood species (Chapter 2)
- Technologies for sorting hardwood logs (Chapter 3)
- Ultrasonic grading for hardwood veneer (Chapter 8)
- Hardwoods for specialty engineered materials and products (Chapter 12)
- Nanocellulosic products (Chapter 13)

The objective of this book is the same as that of the first edition—to serve as a primary reference on use of the undervalued resource in engineered components. It is a compilation of results obtained from research and development studies focused on using low-grade hardwood material in engineered applications.

I worked with several well-respected technical authorities in preparing this edition, and I thank the technical contributors:

Brian K. Brashaw, PhD, Program Manager, Forest Products Marketing Unit, Forest Products Laboratory, USDA Forest Service, Madison, Wisconsin, USA

John J. Janowiak, PhD, Professor Emeritus, Penn State University, University Park, Pennsylvania, USA

Ronald Sabo, Research Forest Materials Engineer, Forest Products Laboratory, USDA Forest Service, Madison, Wisconsin, USA

C. Adam Senalik, PhD, P.E., Research General Engineer, Forest Products Laboratory, USDA Forest Service, Madison, Wisconsin, USA

Edward Thomas, Research Computer Scientist, Northern Research Station, USDA Forest Service, Princeton, West Virginia, USA

James P. Wacker, P.E., Research General Engineer, Forest Products Laboratory, USDA Forest Service, Madison, Wisconsin, USA

Xiping Wang, PhD, Research Forest Products Technologist, Forest Products Laboratory, USDA Forest Service, Madison, Wisconsin, USA

Janice K. Wiedenbeck, PhD, Project Leader, Northern Research Station, USDA Forest Service, Princeton, West Virginia, USA

Michael Wiemann, PhD, Wood Technologist and Botanist, Forest Products Laboratory, USDA Forest Service, Madison, WI, USA

As in the first edition, some sections originally appeared in technical journals, research reports, and various symposium proceedings.

This book is dedicated to John R. Erickson (1934–2014), P.E., Director and Research Engineer, Forest Products Laboratory.

Undervalued Hardwoods for Engineered Materials and Components, Second Edition is available in digital format from the USDA Forest Service Forest Products Laboratory website.

Robert. J. Ross, Editor

Preface to the First Edition

The hardwood lumber industry is a key component of the forest products industry in the Lake States and Northeast regions of the United States. Sugar maple (*Acer saccharum*) and red maple (*Acer rubrum*) are two of the primary species of timber growing in these regions. High-grade lumber from these two species is very valuable, with prices exceeding $1,500 per thousand board feet. Conversely, lower grades of lumber from these species sell for only $200 to $275 per thousand board feet.

Engineered wood components represent one of the fastest growing segments of the forest products industry. Most engineered components are manufactured from softwoods such as Douglas-fir, the southern pines, or spruce-pine-fir lumber. During the past decade, significant research and development efforts have been devoted toward investigating the use of lower grade hardwood resources in engineered materials and components. Studies aimed at developing appropriate drying technologies, lumber grading procedures, and various engineered materials and components have been conducted.

This publication is a compilation of results obtained from research and development studies focused on using low-grade hardwood materials in engineered components. Part One focuses on basic information about this resource: availability, mechanical properties, log grading techniques, and appropriate drying methods. Part Two summarizes studies that examine use of this resource in trusses, laminated veneer lumber, I-joists, and other applications.

This publication was designed to serve as a primary reference on the use of the undervalued resource in engineered components. Several widely respected technical authorities were contacted and asked to prepare sections dealing with their areas of expertise. Some sections originally appeared in technical journals, research reports, and various symposium proceedings.

Robert J. Ross
John R. Erickson

Chapter 1

Undervalued Hardwood Utilization from the Forest Manager's Perspective

Jan Wiedenbeck, Research Forest Products Technologist
USDA Forest Service, Northern Research Station, Princeton, West Virginia

If new or expanded opportunities for adding value to species, sizes, and qualities of hardwood timber are to be successful, development efforts must be congruent with the needs of the front end of the supply chain—the hardwood forest resource and the owners and managers of that resource. Undervalued hardwood utilization will be feasible only where the current and future hardwood resource will support the development and where forest management objectives of forestland owners and managers will be supported.

The forest resources and decision makers that are part of this discussion are those in the Eastern United States. Western forest resources are omitted from this analysis due to the predominance of softwoods in the Rocky Mountain and Pacific Coast regions, where hardwood volume is less than 10% of total volume (Oswalt et al. 2014). The first edition of this book focused on hardwoods in the northern states (Erickson and Ross 2005). In this edition, we expand our discussion to include southern hardwoods because the South also has a higher volume of hardwoods than softwoods on timberland (Oswalt et al. 2014). In the North (20 states bounded by Minnesota, Missouri, West Virginia, and Maine), 80% of volume on timberland and 77% of roundwood harvest volume (such as sawlogs, veneer logs, pulpwood, fuelwood) is hardwood. In the South (13 states bounded by Texas, Kentucky, Virginia, and Florida), 58% of growing stock volume on forestland is hardwoods (Hartsell and Conner 2013), but hardwoods represent only 29% of roundwood harvest volume (Ince et al.2011, Oswalt et al. 2014).

When combined, the regions defined by the USDA Forest Service's Forest Inventory and Analysis program as the "North" and the "South" are referred to as the Eastern United States. The makeup of the "undervalued" hardwood component of the eastern forest can change meaningfully over time. These changes are brought about by changes in (1) the resource, (2) markets and trade, (3) the relative value of different species, (4) harvesting and processing technologies, and (5) landowner management objectives. Since the first edition of this book appeared, changes in markets and technologies have occurred that merit attention here.

Estimating the potential for and impact of expanded utilization of undervalued hardwoods in the Eastern United States is not an easy task. A reliable estimate of the potentials associated with a specific project in a defined location can be flawed—something we have seen repeatedly when a new manufacturing operation has started up only to shut down within a few years. For this reason, the goal of this chapter is simply to provide a broad overview of the range of forest management concerns that will come into play whenever and wherever undervalued hardwood utilization opportunities are deliberated.

In the context of this book, undervalued hardwoods are hardwoods that are not widely utilized in high-end consumer markets (such as cabinets, furniture, moulding). In addition, hardwood species that have a notable market share of high-end markets but for which that share is substantially lower than the species representation in the forest may be undervalued.

Eastern Forest Resource

Forests in the North are expanding. The land area of northern forests continues to increase, with 38 million acres of added forest land over the past century (Smith et al. 2009). Today, forests cover 42% of the land area in the 20 northern states. In the South, 40% of the land area is forested, whereas average forest coverage across the entire United States is only 33% (Smith et al. 2009). This trend, however, is expected to slow as the effects of urbanization in the North and South will impinge on forest land to a significant extent. By 2050, 21 of the 33 eastern states are projected to see the conversion of 9% or more of their forest land to urban areas (Nowak and Walton 2005). Six states that have large forest estates in the southeast are each likely to lose more than a million acres to urbanization by 2050. Awareness of these demographic shifts must be part of the planning process for new forest products manufacturing initiatives.

In addition, the ratio of forest growth to removals (such as harvesting, land conversion) is 1.9:1 in the North—the highest of any region in the country (Shifley et al. 2012). In the South, this ratio is 1.4:1 for all species and 1.7:1 for hardwoods (Hartsell and Conner 2013). The positive growth-to-removals ratio that we have experienced for many decades has led to a situation in which the proportion of timberland in the sawtimber size classification is large and growing while the proportional distribution of poletimber and seedling/sapling forest area has been declining. In the North, this decline in smaller size classes has been especially noteworthy (Oswalt et al. 2014). This trend means that significant volumes of sawtimber are available and that eastern forests would benefit from increased harvest levels to diversify forest landscapes. A more diverse distribution of age classes and successional types is desirable for many reasons—forest health, wildlife habitat, and sustained forest productivity are among the most frequently cited.

Growth-to-removal ratios for species groups are particularly informative in considering the utilization potential of undervalued hardwoods. Three ways of measuring the availability of hardwood species groups are presented in Table 1.1. Change in sawtimber volume between 1963 and 2011 gives a meaningful long-term view of the changing structure of eastern forests. Using this measure, yellow-poplar, soft maple, cottonwood/aspen, and ash all showed increases in sawtimber volume of more than 300% (Luppold and Miller 2014). The relative utilization coefficient provides a means of comparing relative species harvest rates and sawtimber inventory levels (Luppold and Miller 2014). Based on this measure, the “other white oak” and soft maple groups are underutilized (Table 1, Luppold ad Miller 2014). The growth-to-harvest-removal ratios again point to soft maple, “other white oaks,” and ash as having a growing presence on eastern timberland (Table 1.1). The only species group with a growth-to-removals ratio that raises concern is quaking aspen, with a ratio of 1; this ratio is expected to rise because several large plants that used aspen in the Lake States have shut down in the past decade (Luppold and Miller 2014). These ratios and results vary regionally and locally, which is why the Forest Inventory and Analysis’s EVALidator tool is heavily used for planning purposes by forest products companies, consultants, and state and federal land managers (USDA 2015).

An important forest-based factor that may affect demand (and associated value) for different species is species availability. Species that are more sparsely distributed in the forest are less likely to be developed into high-end consumer products because obtaining sufficient volumes for fulfilling orders can be difficult. Examples of species that fit this description include basswood, sycamore, and beech. In contrast, there are species that represent only a small proportion of the timber volume in eastern forests but are high-valued—black walnut and black cherry are examples. The difference between these undervalued and highly valued low-volume species is that there are regions in which you can find a heavy concentration of walnut and cherry, and thus it is feasible for manufacturers in those regions to develop products and product lines made from these species.

Table 1.1—Three measures of utilization rates compared to changes in sawtimber volume for important hardwood species in the eastern United States[a,b]

Species/species group	Sawtimber volume change between 1963 and 2011 (%)	Ratio of growth to harvest removals	Relative utilization coefficient[c]
Yellow-poplar	+554	2.6	**1.2**
Soft maple	+464	4.0	**0.7**
Cottonwood/aspen	+322	1.4	**1.5**
Ash	+302	2.9	0.8
Black walnut	+272	NC	NC
Select red oaks	+233	2.9	0.8
Other red oaks	+224	1.7	1.3
Select white oaks	+211	2.4	0.9
Hard maple	+202	2.3	1.1
Basswood	+177	NC	NC
Other white oaks	+162	3.0	**0.7**
Hickory	+152	2.8	0.8
Sweetgum	+139	1.6	**1.5**
Beech	+44	NC	NC
Tupelo/blackgum	+30	NC	NC
Yellow birch	+13	NC	NC
Black cherry	NC	2.4	1.1
Quaking aspen	NC	1.0	**2.4**

[a]Adapted from tables in Luppold and Miller (2014).
[b]NC, not calculated.
[c]The relative utilization coefficient is based on a comparison of the relative rate of harvest compared to the species’ relative sawtimber abundance, with underutilized species having a coefficient below 0.8 (in blue) and overutilized species having a coefficient above 1.2 (in red) (Luppold and Miller 2014).

Developing significant market opportunities for species that are sparsely distributed in the forest can be accomplished by incorporating them into products that can be made from a mix of species—laminated veneer lumber, I-Joists, and cross-laminated timbers, for example.

Another forest-based factor that influences utilization options is whether the species is one that tends to grow on upland or lowland sites. Harvesting of species growing on lowland sites can have additional costs and restrictions due to site accessibility challenges and environmental precautions that need to be taken to prevent degradation of the landscape and watersheds. Many hardwoods in the South that may be considered undervalued, even though they are found in high concentrations locally and regionally, fall into this category (such as swamp tupelo, green ash). Because of these harvesting constraints, using these species in products that can be made from a mix of species is the best option here as well.

Forest Ownership Considerations

Opportunities for expanded utilization of undervalued hardwoods are dependent on the forest ownership objectives and management plans of the forest landowners. In the eastern United States, this means the objectives of family and "other private" forest owners—such as timber investment management organizations (TIMOs), real estate investment trusts (REITs), forest industry—are relevant. In the northern 20 states and southern 13 states that comprise the eastern region, 55% and 58% of the forest land area, respectively, is owned by family forest landowners (Butler 2008). An additional 20% and 28% of the forest land area in the North and South are owned by "other private" entities. In sum, only 13% of forest land in the South and 25% in the North is publicly managed.

Family forest ownerships in the North have been shrinking in size, on average. This parcelization of forest properties is a concern. In the North, the average size of family forests is about 26 acres (Shifley et al. 2012). In the South, the average acreage of these family forest holdings is slightly larger, 29 acres, but further parcelization resulting from urbanization is a concern here as well (Butler and Wear 2013). About 60% of family forest lands in the eastern United States are less than 10 acres in size; conversely, about 60% of the acreage on these family forests is contained in holdings of more than 100 acres (Butler and Wear 2013).

The size of these ownerships is important because we know that the owners of larger forest land parcels are more likely to include timber harvesting as a management objective. Smaller forest areas are more expensive to manage, and harvesting activities become inefficient on smaller acreages. Nationally, 26% of landowners who own 47% of family forestland are motivated to harvest timber from their forests, whereas a substantially larger percentage of family forest landowners (37%) owning a much smaller percentage of the family forest acreage (21%) have nontimber management objectives including, for example, aesthetics, privacy, and wildlife (Majumdar et al. 2008). It is worth noting that family forest landowners in the South, overall, are more motivated by timber growth and yield objectives than are those in other parts of the country. Larger forest holdings may explain this to some extent, but the long history of forest industry activity in the South likely contributes to forest owners in the region having a stronger timber management orientation.

The types of harvests conducted by family forest landowners and how those harvests might impact the future forest are of interest here, too. Two intensive studies of recently harvested sites in West Virginia and New York paint a picture that matches the story told throughout the eastern hardwood regions (Fajvan et al. 1998, Munsell and Germain 2007). Based on reductions in average stand diameters, 80% of these harvests would be classified as diameter-limit cuts in which larger, higher value species were removed. Only 4% of stands received silvicultural enhancement treatments—in this case crown thinnings (Fajvan et al. 1998). With this type of "forest management" on family forest land having repeated itself over time and throughout the region, species shifts to less valuable species are occurring in the understory of many forests throughout the Eastern United States. If markets for small-diameter and undervalued species were available, the hope is that these markets would compel forest landowners to conduct intermediate and clean-up harvests that would enhance or rehabilitate the forest (Munsell and Germain 2007).

Markets

Owing to changes in consumer preferences, markets, international trade, economic activity levels, and new product development, the species, sizes, and qualities of timber that fit the definition of undervalued hardwoods will change over time. Currently, cottonwood/aspen, other red oaks, yellow-poplar, other white oaks, and sweetgum are significant eastern species or species groups that may be considered lower value. Of these, only yellow-poplar and other white oaks have growth to removals ratios that are 2.0 or greater (Luppold and Miller 2014). As recently as 2000, red maple would have been included on this list of lesser value eastern hardwoods—an example of how changing markets can recalibrate this discussion.

The use of lower value species has historically been for pallets and pulpwood. The development and growth of important engineered wood products markets—oriented strandboard (OSB) and laminated veneer lumber—in the 1990s allowed for increased utilization of several low- and medium-density hardwoods of lesser value. However, in the case of OSB, overcapacity and then the collapse of the housing market during the 2007–2012 time frame led to many plant closures. This means that areas where yellow-poplar, red maple, and other species were being well-utilized for a decade or more are once again underutilized.

Demand for hardwood roundwood in pulpwood markets has diminished significantly since 1997. In the Southern Region, which today produces about three-quarters of total U.S. pulpwood, the hardwood roundwood component makes up only 19% of that production (Bentley and Cooper 2015). In fact, hardwood roundwood amounts harvested for pulpwood in the South declined 40% from 1997 when production peaked (Bentley and Cooper 2015). The Bentley and Cooper (2015) map (their fig. 6) of pulpwood mills competing for hardwood roundwood in the South shows that most areas of Kentucky and south Florida lack demand for hardwood pulpwood and demand is comparatively light in Tennessee, North Carolina, Georgia, and the northern counties of Florida. It is expected that this map has a strong correspondence with regions in the South where landowners lack meaningful markets for undervalued and small-diameter hardwoods. Lacking these markets, incentives for intermediate harvesting activities as well as stumpage prices per acre for terminal harvests will be depressed.

In the Northern Region, which produces only 15% of the Nation's pulpwood, hardwood roundwood is a larger component of pulpwood production than in the South, making up about 57% of volume (Piva et al. 2014). However, given the much lower levels of pulpwood production in this region compared with the South, only Maine, northern Wisconsin, northern Minnesota, and several counties along the spine of the Appalachians in Pennsylvania and West Virginia produced roundwood amounts comparable to those produced across the southern states (Piva et al. 2014, fig. 5). Current pulp market opportunities for undervalued hardwood roundwood are weak.

A discussion of hardwood roundwood use in pulpwood production must now be extended to include consideration of hardwood roundwood use in pellet production. Pellet production in the United States grew from almost 0 to nearly 20 million green short tons in 2013 (Abt et al. 2014). Sixty-two percent of pellet production capacity is in the South and about 28% in the North. Plans for new pellet manufacturing facilities are heavily concentrated in the South (82% of announced projects) (Abt et al. 2014), with almost all these targeting export pellet markets. The largest pellet plants are almost exclusively producing for European export markets, with smaller plants serving domestic and more local and regional markets (FutureMetrics LLC 2015).

Most pellet plants in the North utilize "clean" hardwood residues (sawdust, chips) from sawmills and other sources. This was true in the South as well until 2011, when both hardwood and softwood pulpwood showed up as part of the feedstock of several newly built, very large pellet plants targeting European pellet demand (Abt et al. 2014). In the South, the anticipated continued growth in pellet capacity indicates future price increases in both pine and hardwood non-sawtimber (poletimber/pulpwood) (Abt et al. 2014). For hardwoods, increased harvests in the South are not expected to exceed volume growth levels, but concerns about bottomland hardwood ecosystems being exploited (the export-oriented plants are located proximal to the coast and ports) are being raised (Drouin 2015). Growth of the pellet industry in the Southern Region has started to ramp up demand for undervalued hardwoods on forest land near large pellet plants, so demand for undervalued hardwoods will likely raise prices in the coastal states where these operations are locating.

On the horizon and covered in a subsequent chapter of this book is the development of cross-laminated timber (CLT) manufacturing capacity in the United States, including development of hardwood-based or mixed hardwood and softwood CLT panels. In Europe, CLT production has flourished much as wood pellet manufacturing has flourished in the United States since the turn of the century. The American standard for CLT inclusion in construction was published in 2012 (ANSI/APA 2012), but the standard allows for only certain softwoods to be used in manufacture. Research is being conducted to examine the technical feasibility of expanding the standard to include yellow-poplar, red maple, and possibly other lesser value hardwoods. An important difference to note in comparing CLT's potential with that of wood pellets is that we can expect the value-added margin in producing CLT to be greater than for wood pellets.

A final forest product market that is not now impacting the supply and utilization potential of undervalued hardwoods, but could in the future, is forest carbon offset payments. Carbon offset programs, especially ones that are tied to property tax reductions (Miller et al. 2012), could increase the participation rate of landowners in forest management planning and forest improvement projects. This, in turn, could lead to a change in stand structures and species distributions.

Ecological Impacts

Expanded use of undervalued hardwoods with the development of new and expanded engineered product markets should be positive for a wide spectrum of forest ecological outcomes. The risk of negative impacts on some measures of forest sustainability cannot be dismissed; especially if the harvests are conducted in an exploitive, unplanned fashion without regard for future ecological, economic, and social benefits.

Comparing different intensities of terminal harvests to natural disturbances such a wind and fire offers several insights (Berger et al. 2013):

- Soil nutrient retention impacts of conventional clearcutting (CC) practices are minimal, but the impacts of an energy-wood (EW) type harvest of shorter rotation stands can lead to declines in Ca, K, and Mg.
- Ground layer plant species richness impacts of CC and EW harvest can lead to a minor increase in vascular plant species richness and a potential minor decrease in nonvascular plant species richness.
- Bird and small mammal populations may decline minimally to significantly after a CC, depending on the size of the harvested area, but most species will recover. An EW harvest with shorter rotation stands can lead to significant impacts due to loss of ground cover, ground nutrients, and mast.
- Aboveground carbon losses are large with CC but recover over about 100 years. With EW harvest they are large and can recover but also could lead to decline in site productivity.

- Soil carbon losses are minimal for a CC but can potentially decline and lead to reduced site productivity with an EW harvest.
- Aquatic system nutrients, sediment, and water impacts after a CC leads to an increase in nutrients, sediment, and water yields that recover with vegetation regrowth. EW harvest impacts are larger and can lead to acidification.

Summary

The positive growth-to-removals ratio that we have experienced for many decades has led to a situation in which the proportion of timberland in the sawtimber size classification is large and growing while the proportional distribution of poletimber and seedling/sapling forest area has been declining. This trend means that significant volumes of sawtimber are available and eastern forests would benefit from increased harvest levels to diversify forest landscapes. A more diverse distribution of age classes and successional types is desirable for many reasons—forest health, wildlife habitat, and sustained forest productivity are among the most frequently cited.

In the northern 20 states and southern 13 states that comprise the eastern region, 55% and 58% of the forest land area, respectively, is owned by family forest landowners (Butler 2008). An additional 20% and 28% of the forest land area in the North and South are owned by "other private" entities. Family forest ownerships in the North have been shrinking in size, on average. This parcelization of forest properties is a concern. The size of these ownerships is important because we know that the owners of larger forestland parcels are more likely to include timber harvesting as a management objective. Smaller forest areas are more expensive to manage and harvesting activities become inefficient on smaller acreages.

The use of lower value species has historically been for pallets and pulpwood. The development and growth of important engineered wood products markets— OSB and laminated veneer lumber—in the 1990s allowed for increased utilization of several low- and medium-density hardwoods of lesser value. However, in the case of OSB, overcapacity and then the collapse of the housing market during the 2007–2012 timeframe led to many plant closures. This means there are areas where yellow-poplar, red maple, and other species that were being well utilized for a decade or more, are once again underutilized.

Demand for hardwood roundwood in pulpwood markets has diminished significantly since 1997, especially in the South. However, the advent of the pellet manufacturing industry has provided a new market option for some of the same hardwood pulpwood material.

Expanded use of undervalued hardwoods with the development of new and expanded engineered product markets should be positive for a wide spectrum of forest ecological outcomes; however, the risk of negative impacts on some measures of forest sustainability cannot be dismissed.

Undervalued hardwood utilization will be feasible only where the current and future hardwood resource will support the development and where the forest management objectives of forest landowners and managers will be supported.

Literature Cited

Abt, K.L.; Abt, R.C.; Galik, C.S.; and Skog, K.E. 2014. Effect of policies on pellet production and forests in the U.S. South: a technical document supporting the Forest Service update of the 2010 RPA Assessment. Gen. Tech. Rep. SRS-202. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 33 p.

ANSI/APA. 2012. Standard for performance-rated cross-laminated timber. ANSI/APA PRG 320-2012. Tacoma, WA: APA–The Engineered Wood Association. 23 p.

Bentley, J.W.; Cooper, J.A 2015. Southern pulpwood production, 2012. e-Resource Bulletin SRS-206. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 39 p.

Berger, A.L.; Palik, B.; D'Amato, A.W.; Fraver, S.; Bradford, J.B.; Nislow, K.; King, D.; Brooks, R.T. 2013. Ecological impacts of energy-wood harvests: lessons from whole-tree harvesting and natural disturbance. Journal of Forestry. 111(2):139-153.

Butler, B.J. 2008. Family forest owners of the United States, 2006. Gen. Tech. Rep. NRS-27. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 72 p.

Butler, B.J.; Wear, D.N. 2013. Forest ownership dynamics of southern forests. In: Wear, D.N.; Greis, J.G., eds. The Southern Forest Futures Project: technical report. General Technical Report SRS-GTR-178. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 103-121.

Drouin, R.R. 2015. Wood pellets: green energy or new source of CO_2 emissions? http://e360.yale.edu/feature/wood_pellets_green_energy_or_new_source_of_co2_emissions/2840/. (23 November 2015).

Erickson, J.R.; Ross, R.J. 2005. Undervalued hardwoods for engineered materials and components. Northern Initiatives, Forest Products Society. Madison, WI: Forest Products Society.

Fajvan, M.A.; Grushecky, S.T.; Hassler, C.C. 1998. The effects of harvesting practices on West Virginia's wood supply. Journal of Forestry. 96(5):33-39.

FutureMetrics LLC. 2015. Consolidation in the wood pellet manufacturing sector. http://futuremetrics.info/wp-content/uploads/2015/07/FutureMetrics_Consolidation_in_the_Pellet_Sector.pdf (Accessed March 1, 2016).

Hartsell, A.J.; Conner, Roger C. 2013. Forest area and conditions: a 2010 update of Chapter 16 of the Southern Forest Resource Assessment. e-Gen. Tech. Rep. SRS–174. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 32 p.

Ince, P.J.; Kramp, A.D.; Skog, K.E.; Spelter, H.N.; Wear, D.N. 2011. U.S. forest products module: a technical document supporting the Forest Service 2010 RPA assessment. Research Paper FPL-RP-662. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 61 p.

Luppold, W.G.; Miller, G.W. 2014. Changes in Eastern Hardwood Sawtimber Growth and Harvest. Forest Products Journal. 64(1):26-32.

Majumdar, I.; Teeter, L.; Butler, B. 2008. Characterizing family forest owners: a cluster analysis approach. Forest Science. 54(2):176-184.

Miller, K.A.; Snyder, S.A.; Kilgore, M.A. 2012. An assessment of forest landowner interest in selling forest carbon credits in the Lake States, USA. Forest Policy and Economics. 25:113-122.

Munsell, J.F.; Germain, R.H. 2007. Woody biomass energy: an opportunity for silviculture on nonindustrial private forestlands in New York. Journal of Forestry. 105(8):398-402.

Nowak, D.J.; Walton, J.T. 2005. Projected urban growth (2000–2050) and its estimated impact on the US forest resource. Journal of Forestry. December: 383-389.

Oswalt, S.N.; Smith, W.B.; Miles, P.D.; Pugh, S.A. 2014. Forest resources of the United States, 2012: a technical document supporting the Forest Service 2015 update of the RPA Assessment. Gen. Tech. Rep. WO-91. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office. 218 p.

Piva, R.J.; Bentley, J.W.; Hayes, S.W. 2014. National pulpwood production, 2010. Resour. Bull. NRS-89. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 74 p.

Shifley, S.R.; Aguilar, F.X.; Song, N.; Stewart, S.I.; Nowak, D.J.; Gormanson, D.D.; Moser, W.K.; Wormstead, S.; Greenfield, E.J. 2012. Forests of the Northern United States. Gen. Tech. Rep. NRS-90. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 202 p.

Smith, W.B.; Miles, P.D.; Perry, C.H.; Pugh, S.A. 2009. Forest resources of the United States, 2007. Gen. Tech. Rep. WO-78. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office. 336 p.

USDA. 2015. EVALIDator Version 1.6.0.03. Washington, DC: U.S. Department of Agriculture Forest Service. http://apps.fs.fed.us/Evalidator/evalidator.jsp. (23 November 2015).

Chapter 2

Basic Wood Properties of Hardwoods

Robert J. Ross, Supervisory Research General Engineer
Michael C. Wiemann, Research Botanist
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

This chapter summarizes basic property information for several hardwood species. After a discussion of common and scientific names, micrographs of the cross sections of several species or a representative of a species group are presented. Physical and mechanical property data, machining characteristics, and other important information are summarized. The information was taken from Davis (1962), FPL (2010), and Hardin et al. (2001). Most of this chapter was originally published as Ross and Wiemann (2012).

Common and Scientific Names

The use of scientific (botanical) names is key to obtaining accurate information about the properties of the wood. Most trees and their woods have a number of common names, and unrelated species can often share the same common name. Common names can be given in reference to the form, use, or a characteristic of the tree, and they vary from region to region.

The scientific name is a two-part identifier that provides a unique name. The first part of the name is the genus and the second part is the species. When written, the genus is capitalized and both the genus and species are placed in italics type (or underlined, if necessary). This naming system dates back to 1753, when Carl von Linne (Linnaeus) wrote *Species Plantarum*. The use of scientific names prevents confusion and the incorrect identifications that can result when using common names. Because anatomical and other characteristics of a wood influence its utilization potential, correctly identifying the wood is crucial. Table 2.1 lists the common and scientific names of several hardwood species.

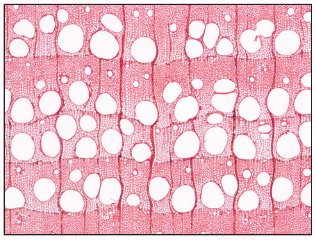
Species Descriptions

Each species or group of species is described in terms of its principal location, characteristics, and uses. Information on historical and traditional uses is provided to illustrate their utility. Accompanying each description is a low-magnification micrograph of a representative cross section of each species or species group. The slides for these micrographs are from the Forest Products Laboratory collection. The micrographs are reproduced at magnifications of approximately 15×. Their color is a consequence of the stains used to accentuate anatomical features and is not indicative of the actual wood color.

Table 2.1—Common and scientific names of several hardwood species

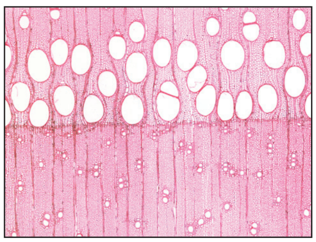
Common name	Scientific name
Ash	*Fraxinus*
Black ash	*Fraxinus nigra*
Blue ash	*Fraxinus quadrangulata*
Green ash	*Fraxinus pennsylvanica*
Oregon ash	*Fraxinus latifolia*
White ash	*Fraxinus americana*
Birch	*Betula*
Gray birch	*Betula populifolia*
Paper birch	*Betula papyrifera*
River birch	*Betula nigra*
Sweet birch	*Betula lenta*
Yellow birch	*Betula alleghaniensis*
Elm	*Ulmus*
American elm; white elm	*Ulmus americana*
Rock elm; cork elm	*Ulmus thomasii*
Slippery elm; red elm	*Ulmus rubra*
Horse-chestnut	*Aesculus*
Ohio buckeye; fetid buckeye	*Aesculus glabra*
Yellow buckeye	*Aesculus flava*
Maple	*Acer*
Bigleaf maple	*Acer macrophyllum*
Black maple	*Acer nigrum*
Boxelder	*Acer negundo*
Red maple	*Acer rubrum*
Silver maple	*Acer saccharinum*
Sugar maple	*Acer saccharum*
Oak	*Quercus*
Black oak	*Quercus velutina*
Bur oak	*Quercus macrocarpa*
Cherrybark oak	*Quercus pagoda*
Chestnut oak	*Quercus montana*
Laurel oak	*Quercus laurifolia*
Live oak	*Quercus virginiana*
Northern red oak	*Quercus rubra*
Overcup oak	*Quercus lyrata*
Pin oak	*Quercus palustris*
Post oak	*Quercus stellata*
Scarlet oak	*Quercus coccinea*
Southern red oak	*Quercus falcata*
Swamp chestnut oak	*Quercus michauxii*
Swamp white oak	*Quercus bicolor*
Water oak	*Quercus nigra*
White oak	*Quercus alba*
Willow oak	*Quercus phellos*
Willow	*Salix*
Black willow	*Salix nigra*

Ash (Black Ash)



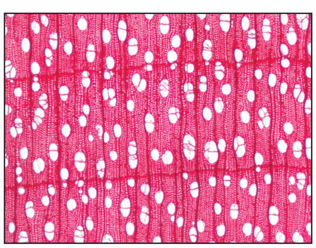
Black ash (*Fraxinus nigra*) grows in the Northeast and Midwest. Its heartwood is a darker brown than that of American white ash; its sapwood is light-colored or nearly white. The wood of the black ash group is lighter in weight (basic specific gravity of 0.45 to 0.48) than that of the white ash group (basic specific gravity greater than 0.50). Principal uses for black ash are decorative veneer, cabinets, millwork, furniture, cooperage, and crates.

Ash (White Ash Group)



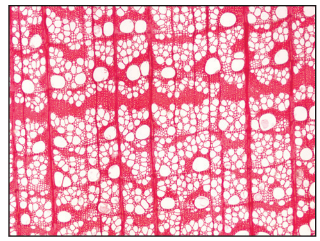
Important species of the white ash group are American white ash (*Fraxinus americana*) and green ash (*F. pennsylvanica*). These species grow in the eastern half of the United States. The heartwood of the white ash group is brown, and the sapwood is light-colored or nearly white. Second-growth trees are particularly sought after because of the inherent qualities of the wood from these trees: it is heavy, strong, hard, and stiff, and it has high resistance to shock. American white ash is used principally for nonstriking tool handles, oars, baseball bats, and other sporting and athletic goods. For handles of the best grade, some handle specifications call for not less than 2 nor more than 7 growth rings per centimeter (not less than 5 nor more than 17 growth rings per inch). The additional weight requirement of at least 690 kg/m^3 (43 lb/ft^3) at 12% moisture content ensures high-quality material. Principal uses for the white ash group are decorative veneer, cabinets, furniture, flooring, millwork, and crates.

Birch



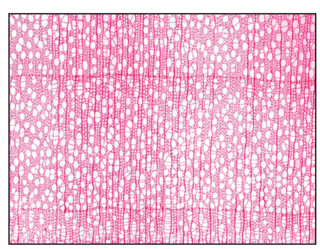
The three most important species are yellow birch (*Betula alleghaniensis*), sweet birch (*B. lenta*), and paper birch (*B. papyrifera*). These three species are the source of most birch lumber and veneer. Other birch species of some commercial importance are gray birch (*B. populifolia*) and river birch (*B. nigra*). Paper birch is transcontinental, whereas the other species grow principally in the northeast and the Lake States; yellow and sweet birch also grow along the Appalachian Mountains to northern Georgia. Yellow birch has white sapwood and light reddish-brown heartwood. Sweet birch has light-colored sapwood and dark brown heartwood tinged with red. For both yellow and sweet birch, the wood is heavy, hard, and strong, and it has good shock-resisting ability. The wood is fine and uniform in texture. Paper birch is lower in weight, softer, and lower in strength than yellow and sweet birch. Birch shrinks considerably during drying. Yellow and sweet birch lumber is used primarily for the manufacture of furniture, boxes, baskets, crates, wooden ware, cooperage, interior woodwork, and doors; veneer plywood is used for doors, furniture, paneling, cabinets, aircraft, and other specialty uses. Paper birch is used for toothpicks, tongue depressors, ice cream sticks, and turned products, including spools, bobbins, small handles, and toys.

Elm



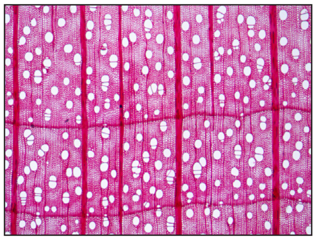
Elm grows in the eastern United States and includes American elm (*Ulmus americana*), slippery elm (*U. rubra*), and rock elm (*U. thomasii*). American elm is also known as white elm, slippery elm as red elm, and rock elm as cork elm. American elm is threatened by two diseases, Dutch Elm disease and phloem necrosis, which have killed hundreds of thousands of trees. Elm sapwood is nearly white and its heartwood is light brown, often tinged with red. Elm may be divided into two general classes, soft and hard, based on the density and strength of the wood. Soft elm includes American elm and slippery elm. It is moderately heavy, has high shock resistance, and is moderately hard and stiff. Hard elm is somewhat heavier than soft elm. Elm has excellent bending qualities. Historically, elm lumber was used for boxes, baskets, crates, slack cooperage, furniture, agricultural supplies and implements, caskets and burial boxes, and wood components in vehicles. Today, elm lumber and veneer are used mostly for furniture and decorative panels. Hard elm is preferred for uses that require strength.

Horse Chestnut (Buckeye)



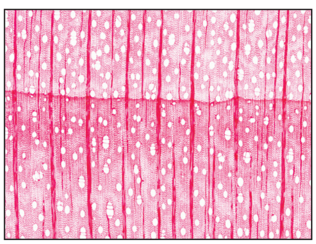
Buckeye consists of two species, yellow buckeye (*Aesculus flava*) and Ohio buckeye (*A. glabra*). These species range from the Appalachians of Pennsylvania, Virginia, and North Carolina westward to Kansas, Oklahoma, and Texas. The white sapwood of buckeye merges gradually into the creamy or yellowish white heartwood. The wood is uniform in texture, generally straight grained, light in weight, soft, and low in shock resistance. It is rated low on machinability such as shaping, mortising, boring, and turning. Buckeye is suitable for pulping for paper. In lumber form, it has been used principally for furniture, boxes and crates, food containers, wooden ware, novelties, and planing mill products.

Maple (Hard Maple Group)



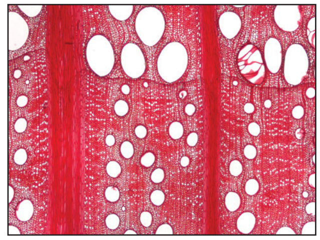
Hard maple includes sugar maple (*Acer saccharum*) and black maple (*A. nigrum*). Sugar maple is also known as rock maple, and black maple as black sugar maple. Maple lumber is manufactured principally in the Middle Atlantic and Great Lake States, which together account for about two-thirds of production. The heartwood is usually light reddish-brown but sometimes considerably darker. The sapwood is commonly white with a slight reddish-brown tinge. It is usually 8 to 12 cm (3 to 5 in.) wide. Hard maple has a fine, uniform texture. It is heavy, strong, stiff, hard, resistant to shock, and has high shrinkage. The grain of sugar maple is generally straight, but birdseye, curly, or fiddleback grain is often present and selected for furniture or novelty items. Hard maple is used principally for lumber and veneer. A large proportion is manufactured into flooring, furniture, cabinets, cutting boards, pianos, billiard cues, handles, novelties, bowling alleys, dance and gymnasium floors, spools, bobbins, and bowling pins.

Maple (Soft Maple Group)



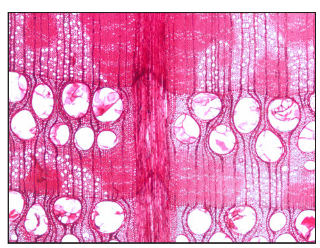
Soft maple includes red maple (*Acer rubrum*), silver maple (*A. saccharinum*), boxelder (*A. negundo*) in the eastern United States, and bigleaf maple (*Acer macrophyllum*) in the western United States. Silver maple is also known as white, river, water, and swamp maple; red maple as water, scarlet, white, and swamp maple; and boxelder as ash-leaved, three-leaved, and cut-leaved maple. Heartwood and sapwood are similar in appearance to hard maple. Heartwood of soft maple is somewhat lighter in color than the sapwood. The wood of soft maple, primarily silver and red maple, resembles that of hard maple but is not as heavy, hard, or strong. Soft maple is used for railroad crossties, boxes, pallets, crates, furniture, veneer, wooden ware, and novelties, and is also used as a less expensive alternative to hard maple in architectural millwork.

Oak (Red Oak Group)



Most red oak comes from the Eastern States. The principal species are northern red oak (*Quercus rubra*), black oak (*Q. velutina*), southern red oak (*Q. falcata*), and pin oak (*Q. palustris*). The sapwood is nearly white and roughly 2 to 5 cm (1 to 2 in.) wide. The heartwood is brown with a tinge of red. Sawn lumber of the red oak group cannot be separated by species on the basis of wood characteristics alone; however, northern red oak lumber from the Lake States has a higher value because of tighter growth rings and uniformity of color than Appalachian or Southern red oak. This is true with other hardwood species and is due to slower growth caused by a shorter growing season. Red oak lumber can be separated from white oak by the size and arrangement of pores in latewood and because it generally lacks tyloses in the pores. The open pores of red oak make this species group unsuitable for tight cooperage, unless the barrels are lined with sealer or plastic. Quartersawn lumber of the oaks is distinguished by its broad and conspicuous rays. Wood of the red oaks is heavy. Rapidly grown, second-growth wood is generally harder and tougher than finer textured, old-growth wood. The red oaks have rather high shrinkage upon drying. The red oaks are primarily cut into lumber, railroad crossties, mine timbers, fence posts, veneer, pulpwood, and fuelwood. Ties, mine timbers, and fence posts require preservative treatment for satisfactory service. Red oak lumber is remanufactured into flooring, furniture, general millwork, boxes, pallets and crates, agricultural implements, caskets, wooden ware, and handles. It is also used in railroad cars and boats.

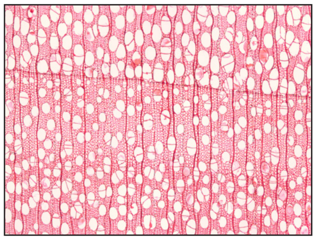
Oak (White Oak)



White oak lumber comes chiefly from the South, South Atlantic, and Central States, including the southern Appalachian area. The principal species is *Quercus alba*. The sapwood of white oak is nearly white and roughly 2 to 5 cm (1 to 2 in.) wide. The heartwood is generally grayish brown. Heartwood pores are usually plugged with tyloses, which tend to make the wood impenetrable to liquids. Consequently, white oak is suitable for barrels that are used to contain liquids. The wood of white oak is somewhat heavier than the wood of red oak. Its heartwood has good decay resistance. White oak is usually cut into lumber, railroad crossties, mine timbers, fence posts, veneer, fuelwood, and many other products. Because of its impermeability to liquids, high-quality white oak heartwood is especially sought for tight cooperage.

An important use of white oak is planking and bent parts of ships and boats; heartwood is often specified because of its decay resistance. White oak is also used for furniture, flooring, pallets, agricultural implements, railroad cars, truck floors, furniture, doors, and millwork.

Willow (Black)



Black willow (*Salix nigra*) is the most important of the many willows that grow in the United States. It is the only willow marketed under its own name. Most black willow comes from the Mississippi Valley, from Louisiana to southern Missouri and Illinois. The heartwood of black willow is grayish brown or light reddish brown and frequently contains darker streaks. The sapwood is whitish to creamy yellow. The wood is uniform in texture, with somewhat interlocked grain, and is light in weight. It has exceedingly low strength as a beam or post, is moderately soft, is moderately high in shock resistance, and has moderately high shrinkage. Black willow is principally cut into lumber, which is then remanufactured into boxes, pallets, crates, caskets, and furniture. Small amounts are used for slack (non-watertight) cooperage, veneer, excelsior, charcoal, pulpwood, and fence posts.

Characteristics

All wood is composed of cellulose, lignin, hemicelluloses, and minor amounts (usually less than 10%) of extraneous materials contained in a cellular structure. Variation in the characteristics and proportions of these components and differences in cellular structure make woods heavy or light, stiff or flexible, and hard or soft. The properties of a single species are relatively constant within limits; therefore, selection of wood by species alone may sometimes be adequate. To use wood to its best advantage and most effectively in engineering applications, however, specific characteristics or physical properties must be considered.

Grain and Texture

The terms grain and texture are used rather loosely. Grain is often used to describe the relative sizes and distribution of cells, as in fine grain and coarse grain. Grain is also used to indicate the direction of fibers, as in straight grain, spiral grain, and curly grain. Wood finishers refer to wood as open grained and close grained, which are terms reflecting the relative size of the pores, which determines whether the surface needs a filler. Earlywood and latewood within a growth increment usually consist of different kinds and sizes of wood cells, this difference results in differences in appearance of the growth rings;the resulting appearance is the texture of the wood. Coarse texture can result from wide bands of large vessels, such as in oak. Fine-textured

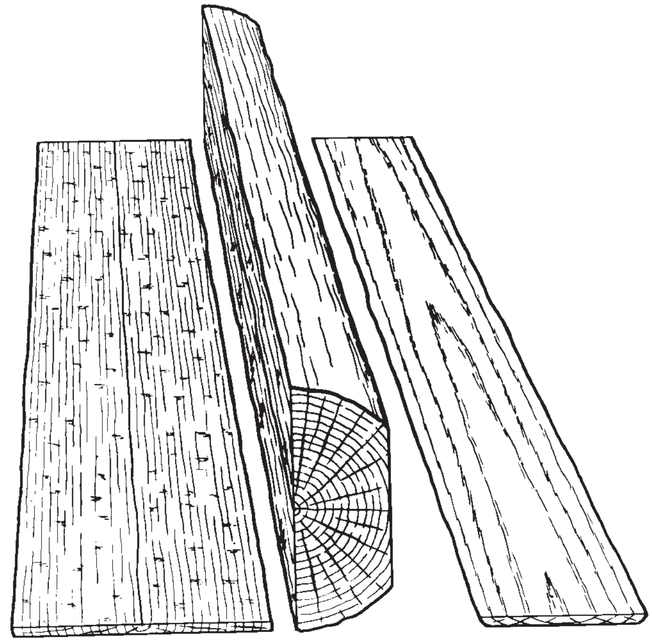


Figure 2.1—(a) Quartersawn and (b) plainsawn boards cut from a log.

woods have small cell diameters. Woods that have larger but uniform-sized cells are considered medium-textured woods. “Even” texture generally means uniformity in cell dimensions. When the words grain or texture are used in connection with wood, the meaning intended should be made clear.

Plainsawn and Quartersawn

Lumber can be cut from a log in two distinct ways:

1. tangential to the annual rings, producing flatsawn or plainsawn lumber in hardwoods and flatsawn or slash-grained lumber in softwoods, and
2. perpendicular to the growth rings (parallel to the rays), producing quartersawn lumber in hardwoods and edge-grained or vertical-grained lumber in softwoods (Fig. 2.1).

Quartersawn lumber is not usually cut strictly parallel with the rays, and in plainsawn boards, the surfaces next to the edges are often far from tangential to the rings. In commercial practice, lumber with rings at angles of 60° to 90° to the wide surface is called quartersawn, and lumber with rings at angles of 0° to 30° to the wide surface is called plainsawn. Hardwood lumber in which annual rings form angles of 30° to 60° to the wide faces is sometimes called bastard sawn. For many purposes, either plainsawn or quartersawn lumber is satisfactory. The distinction is important because many wood properties vary with grain direction, with each type having certain advantages that can be important for a particular use. Some advantages of plainsawn and quartersawn lumber are given in Table 2.2.

Table 2.2—Some advantages of plainsawn and quartersawn lumber

Plainsawn	Quartersawn
Shrinks and swells less in thickness	Shrinks and swells less in width
Round or oval knots affect surface appearance less than spike knots in quartersawn boards; boards with round or oval knots are not as weak as boards with spike knots	Cups, surface checks, and splits less in seasoning and use
Shakes and pitch pockets, when present, extend through fewer boards	Does not allow liquids to pass through readily in some species
Figure patterns resulting from annual rings and some other types of figure are brought out more conspicuously	Figure patterns resulting from pronounced rays, interlocked grain, and wavy grain are brought out more conspicuously
Is less susceptible to collapse in drying	Raised grain caused by separation in annual rings does not become as pronounced
Easier to obtain, and therefore less expensive	Holds paint better in some species
	Sapwood appears in boards at edges and its width is limited by its width in the log

Table 2.3—Color and figure of several common hardwood species

		Type of figure	
Common name	Color of dry heartwood[a]	Plainsawn lumber or rotary-cut veneer	Quartersawn lumber or quarter-sliced veneer
Ash, black	Moderately dark grayish brown	Conspicuous growth rings; occasional burl	Distinct but inconspicuous growth ring stripes; occasional burl
Ash, white	Grayish brown, sometimes with reddish tinge	Conspicuous growth rings; occasional burl	Distinct but inconspicuous growth ring stripes; occasional burl
Birch, paper	Light brown	Faint growth rings	No figure
Birch, sweet	Dark reddish brown	Distinct but inconspicuous growth rings; occasionally wavy grain	Occasionally wavy grain
Birch, yellow	Reddish brown	Distinct but inconspicuous growth rings; occasionally wavy grain	Occasionally wavy grain
Elm, American and rock	Light grayish brown, usually with reddish tinge	Distinct, inconspicuous growth rings with fine wavy pattern	Faint growth ring stripes
Elm, slippery	Dark brown with shades of red	Conspicuous growth rings with fine patterns	Distinct but inconspicuous growth ring stripes
Maple: black, red, silver, and sugar	Light reddish brown	Faint growth rings, occasionally birds-eye, curly, and wavy	Occasionally curly and wavy
Oaks, all red oaks	Light brown, usually with pink or red tinge	Conspicuous growth rings	Pronounced flake; distinct, inconspicuous growth ring stripes
Oaks, all white oaks	Light to dark brown, rarely with reddish tinge	Conspicuous growth rings	Pronounced flake; distinct, inconspicuous growth ring stripes

[a]Sapwood of all species is light in color or virtually white unless discolored by fungus or chemical stains.

Decorative Features

The decorative value of wood depends upon its color, figure, and luster, as well as the way in which it takes fillers, stains, and transparent finishes. Because of the combinations of color and the multiplicity of shades found in wood, only general color descriptions of the various kinds of wood can be given. Sapwood of most species is light in color; in some species, sapwood is practically white.

For some uses, white sapwood of certain species, such as maple, may be preferred to the heartwood. In most species, heartwood is darker and fairly uniform in color, but in some such as basswood, cottonwood, and beech, there is little or no difference in color between sapwood and heartwood. Table 2.3 describes the color and figure of several common hardwoods.

On the surface of plainsawn boards and rotary-cut veneer, the annual growth rings frequently form elliptic and parabolic patterns that make striking figures, especially when the rings are irregular in width and outline on the cut surface.

On quartersawn surfaces, these growth rings form stripes, which are not especially ornamental unless they are

Table 2.4—Average moisture content of green wood, by species

Common species name	Moisture content (%)	
	Heartwood	Sapwood
Ash, black	95	—
green	—	58
white	46	44
Birch, paper	89	72
sweet	75	70
yellow	74	72
Elm, American	95	92
rock	44	57
Maple, silver	58	97
sugar	65	72
Oak, northern red	80	69
southern red	83	75
white	64	78

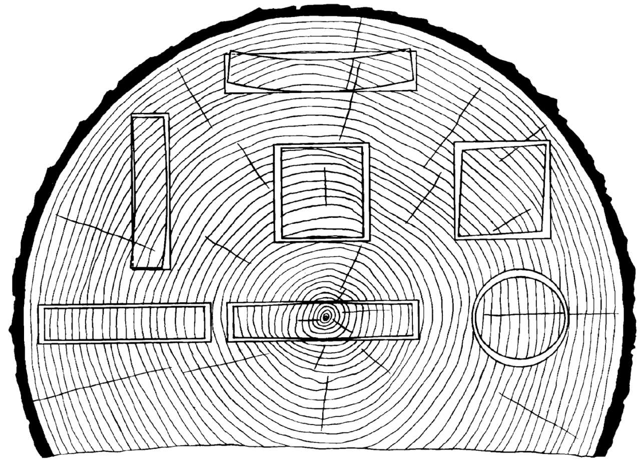


Figure 2.2—Characteristic shrinkage and distortion of flat, square, and round pieces as affected by direction of growth rings. Tangential shrinkage is about twice as great as radial.

irregular in width and direction. Relatively large rays sometimes appear as flecks that can form a conspicuous figure in quartersawn oak and sycamore. When oak is used for furniture, the wood is cut to minimize the appearance of the broad rays. With interlocked grain, which slopes in alternate directions in successive layers from the center of the tree outward, quartersawn surfaces show a ribbon effect, either because of the difference in reflection of light from successive layers when the wood has a natural luster or because cross grain of varying degree absorbs stains unevenly. Much of this type of figure is lost in plainsawn lumber. In open-grained hardwoods, the appearance of both plainsawn and quartersawn lumber can be modified greatly by the use of fillers of different colors. Knots, pin wormholes, bird pecks, decay in isolated pockets, birds-eye, mineral streaks, swirls in grain, and ingrown bark are decorative in some species when the wood is carefully selected for a particular architectural treatment.

Moisture Content

Moisture content of a piece of wood is defined as the weight of water in wood expressed as a fraction, usually a percentage, of the weight of the ovendry wood. Density, shrinkage, strength, and other properties depend upon the moisture content of wood.

In trees, moisture content can range from about 30% to more than 200% of the weight of dry wood substance. In hardwoods, the difference in moisture content between heartwood and sapwood depends on the species. The average moisture content of green heartwood and sapwood of several species is given in Table 2.4. These values are considered typical, but there is considerable variation within and between trees. Variability of moisture content exists even within individual boards cut from the same tree.

Moisture can exist in wood as free water (liquid water or water vapor in cell cavities) or as bound water within cell walls. Green wood is often defined as freshly sawn wood in which the cell walls are completely saturated with water; and, green wood usually contains additional water in the cavities. The moisture content at which the cell walls are completely saturated but the cell cavities are empty is the fiber saturation point. The moisture content at which both the cell cavities and cell walls are completely saturated with water is the maximum possible moisture content. Wood specific gravity is the major determinant of maximum moisture content. Cell cavity volume decreases as specific gravity increases, so maximum moisture content also decreases as specific gravity increases because there is less room available for free water.

Shrinkage

Wood is dimensionally stable when its moisture content is greater than the fiber saturation point. Wood changes dimension as it gains or losses moisture below that point. It shrinks when losing moisture from the cell walls and swells when gaining moisture in the cell walls. This shrinking and swelling can result in warping, checking, splitting, and loosening of tool handles, gaps in strip flooring, or performance problems that detract from the usefulness of the wood product. Therefore, it is important that these phenomena be understood and considered when they can affect a product in which wood is used.

With respect to shrinkage characteristics, wood is an orthotropic material. It shrinks most in the direction of the annual growth rings (tangentially), about half as much across the rings (radially), and only slightly along the grain (longitudinally). The combined effects of radial and tangential shrinkage can distort the shape of wood pieces because of the difference in shrinkage and the curvature of annual rings. The major types of distortion as a result of these effects are illustrated in Figure 2.2.

Transverse and Volumetric

Data have been collected to represent the average radial, tangential, and volumetric shrinkage of numerous species by methods described in American Society for Testing and Materials (ASTM) D143—Standard Method of Testing Small Clear Specimens of Timber (ASTM 2018). Shrinkage values, expressed as a percentage of the green dimension, are listed in Table 2.5. The shrinkage of wood is affected by a number of variables. In general, greater shrinkage is associated with greater density. The size and shape of a piece of wood can affect shrinkage, and the rate of drying for some species can affect shrinkage. Transverse and volumetric shrinkage variability can be expressed by a coefficient of variation of approximately 15%.

Table 2.5—Shrinkage values of several hardwood species

	Shrinkage[a] (%) from green to ovendry moisture content		
Common species name	Radial	Tangential	Volumetric
Ash, black	5.0	7.8	15.2
blue	3.9	6.5	11.7
green	4.6	7.1	12.5
Oregon	4.1	8.1	13.2
pumpkin	3.7	6.3	12.0
white	4.9	7.8	13.3
Birch, Alaska paper	6.5	9.9	16.7
gray	5.2	—	14.7
paper	6.3	8.6	16.2
river	4.7	9.2	13.5
sweet	6.5	9.0	15.6
yellow	7.3	9.5	16.8
Buckeye, yellow	3.6	8.1	12.5
Elm, American	4.2	8.5	14.6
cedar	4.7	10.2	15.4
rock	4.8	8.1	14.9
slippery	4.9	8.9	13.8
winged	5.3	11.6	17.7
Maple, bigleaf	3.7	7.1	11.6
black	4.8	9.3	14.0
red	4.0	8.2	12.6
silver	3.0	7.2	12.0
striped	3.2	8.6	12.3
sugar	4.8	9.9	14.7
Oak (red group)			
black	4.4	11.1	15.1
laurel	4.0	9.9	19.0
northern red	4.0	8.6	13.7
pine	4.3	9.5	14.5
scarlet	4.4	10.8	14.7
southern red	4.7	11.3	16.1
water	4.4	9.8	16.1
willow	5.0	9.6	18.9
Oak (white group)			
bur	4.4	8.8	12.7
chestnut	5.3	10.8	16.4
live	6.6	9.5	14.7
overcup	5.3	12.7	16.0
post	5.4	9.8	16.2
swamp, chestnut	5.2	10.8	16.4
white	5.6	10.5	16.3
Willow, black	3.3	8.7	13.9

[a]Expressed as a percentage of the green dimension.

Longitudinal

Longitudinal shrinkage of wood (shrinkage parallel to the grain) is generally quite small. Average values for shrinkage from green to ovendry are between 0.1% and 0.2% for most species of wood. Certain types of wood, however, exhibit excessive longitudinal shrinkage, and these should be avoided in uses where longitudinal stability is important. Reaction wood and wood from near the center of trees (juvenile wood) of some species shrink excessively parallel to the grain. Reaction wood and juvenile wood can shrink 2% lengthwise from green to ovendry. Wood with cross grain exhibits increased shrinkage along the longitudinal axis of a piece.

Reaction wood exhibiting excessive longitudinal shrinkage can occur in the same board with normal wood. The presence of this type of wood, as well as cross grain, can cause serious warping, such as bow, crook, or twist, and cross breaks can develop in the zones of high shrinkage.

Density and Specific Gravity

Two primary factors affect the density of wood products: the amount of dry wood substance and moisture content. A third factor, minerals and extractable substances, has a marked effect only on a limited number of species. The density of wood, exclusive of water, varies greatly both within and among species. Although the density of most species falls between about 320 and 720 kg/m^3 (20 and 45 lb/ft^3), the range of density actually extends from about 160 kg/m^3 (10 lb/ft^3) for balsa to more than 1,040 kg/m^3 (65 lb/ft^3) for some other imported woods. A coefficient of variation of about 10% is considered suitable for describing the variability of density for common U.S. hardwood species.

Wood is used in a wide range of conditions and has a wide range of moisture content values in use. Moisture makes up part of the weight of each product in use; therefore, the density must reflect this fact. This has resulted in the density of wood often being determined and reported on the basis of moisture content in use.

The calculated density of wood, which includes the water contained in the wood, is usually based on average species characteristics. This value should always be considered an approximation because of the natural variation in anatomy, moisture content, and ratio of heartwood to sapwood that occurs. Nevertheless, this determination of density usually is sufficiently accurate to permit proper utilization of wood products where weight is important. Such applications range

Table 2.6—Some machining and related properties of several hardwood species

Common species name	Planing: perfect pieces (%)	Shaping: good to excellent pieces (%)	Turning: fair to excellent pieces (%)	Boring: good to excellent pieces (%)	Mortising: fair to excellent pieces (%)	Sanding: good to excellent pieces (%)	Steam bending: unbroken pieces (%)	Nail splitting: pieces free from complete splits (%)	Screw splitting: pieces free from complete splits (%)
Ash	75	55	79	94	58	75	67	65	71
Birch	63	57	80	97	97	34	72	32	48
Birch, paper	47	22	—	—	—	—	—	—	—
Elm, soft	33	13	65	94	75	66	74	80	74
Maple, bigleaf	52	56	80	100	80	—	—	—	—
Maple, hard	54	72	82	99	95	38	57	27	52
Maple, soft	41	25	76	80	34	37	59	58	61
Oak, red	91	28	84	99	95	81	86	66	78
Oak, white	87	35	85	95	99	83	91	69	74
Willow	52	5	58	71	24	24	73	89	62

from the estimation of structural loads to the calculation of approximate shipping weights.

To standardize comparisons of species or products and estimations of product weight, specific gravity is used as a standard reference basis, rather than density. The traditional definition of specific gravity is the ratio of the density of the wood to the density of water at a specified reference temperature (often 4.4 °C (40 °F)) where the density of water is 1.0000 g/cm^3. To reduce confusion introduced by the variable of moisture content, the specific gravity of wood usually is based on the ovendry weight and the volume at some specified moisture content.

Commonly used bases for determining specific gravity are ovendry weight and volume at

a. green,
b. ovendry, and
c. 12% moisture content.

Ovendry weight and green volume are often used in databases to characterize specific gravity of species and is referred to as basic specific gravity.

Working Qualities

The ease of working wood with hand tools generally varies directly with the specific gravity of the wood. The lower the specific gravity, the easier it is to cut the wood with a sharp tool. Specific gravity values can be used as a general guide to the ease of working with hand tools.

A wood species that is easy to cut does not necessarily develop a smooth surface when it is machined. Consequently, tests have been made with many U.S. hardwoods to evaluate them for machining properties. Results of these evaluations are given in Table 2.6.

Decay Resistance

Wood kept constantly dry does not decay. In addition, if wood is kept continuously submerged in water, even for long periods of time, it does not decay significantly by the common decay fungi regardless of the wood species or the presence of sapwood. Bacteria and certain soft-rot fungi can attack submerged wood, but the resulting deterioration is very slow. A large proportion of wood in use is kept so dry at all times that it lasts indefinitely.

Moisture and temperature, which vary greatly with local conditions, are the principal factors that affect rate of decay. Wood deteriorates more rapidly in warm, humid areas than in cool or dry areas. High altitudes, as a rule, are less favorable to decay than are low altitudes because the average temperatures at higher altitudes are lower and the growing season for fungi, which cause decay, is shorter. The heartwood of common native species of wood has varying degrees of natural decay resistance. Untreated sapwood of substantially all species has low resistance to decay and usually has a short service life under decay-producing conditions. The decay resistance of heartwood is greatly affected by differences in the preservative qualities of the wood extractives, the attacking fungus, and the conditions of exposure.

Considerable difference in service life can be obtained from pieces of wood cut from the same species, even from the same tree, when used under apparently similar conditions. Precise ratings of decay resistance of heartwood of different species are not possible because of differences within species and the variety of service conditions to which wood is exposed. However, broad groupings of many native species, based on service records, laboratory tests,

Table 2.7—Grouping of several hardwood species according to average heartwood decay resistance

Resistant	Slightly or nonresistant
Oaks, white[a]	Ashes
	Birches
	Buckeye
	Elms
	Hickories
	Maples
	Willows

[a]More than one species included, some of which may vary in resistance from that indicated.

and general experience, are helpful in choosing heartwood for use under conditions favorable to decay. Table 2.7 lists such groupings for several hardwood species, according to their average heartwood decay resistance. The extent of variations in decay resistance of individual trees or wood samples of a species is much greater for most of the more resistant species than for the slightly or nonresistant species.

Where decay hazards exist, heartwood of species in the resistant or very resistant category generally gives satisfactory service, but heartwood of species in the slightly or nonresistant category will usually require some form of preservative treatment. For mild decay conditions, a simple preservative treatment—such as a short soak in preservative after all cutting and boring operations are complete—will be adequate for wood low in decay resistance.

Mechanical Properties

The mechanical properties presented in this section were obtained from tests of small pieces of wood termed "clear" and "straight grained" because they did not contain characteristics such as knots, cross grain, checks, and splits. These test pieces did have anatomical characteristics such as growth rings that occurred in consistent patterns within each piece.

Many of the tabulated mechanical properties of hardwoods were derived from extensive sampling and analysis procedures. These properties are represented as the average for that species. Variability, or variation in properties, is common to all materials. Because wood is a natural material and the tree is subject to many constantly changing influences (such as moisture, soil conditions, and growing space), wood properties vary considerably, even in clear material.

Although it is beyond the scope of this chapter to list all the mechanical properties for the hardwood species discussed, a brief description of four important mechanical properties widely used in evaluating the potential performance of a wood species in many applications is presented. Table 2.8 provides values for modulus of rupture, modulus of elasticity, compression stress perpendicular to grain, and hardness values for various hardwood species. These clear wood properties should not be used for calculation of structural properties without consideration of growth characteristics such as location of knots and slope of grain.

Modulus of Rupture

The modulus of rupture (MOR) reflects the maximum load-carrying capacity of a member in bending. MOR is an accepted criterion of strength, although it is not a true stress because the formula by which it is computed is valid only to the elastic limit.

Modulus of Elasticity

The modulus of elasticity (MOE) obtained from a simple bending test is frequently reported for wood. Elasticity implies that deformations produced by low stress are completely recoverable after loads are reduced or removed. A high MOE value indicates that species of wood will deform less under a given load than a species that has a low MOE value.

Compressive Stress Perpendicular to Grain

Compressive stress perpendicular to grain is reported as stress at proportional limit. There is no clearly defined ultimate stress for this property.

Hardness

Hardness is generally defined as resistance to indentation using a modified Janka hardness test, measured by the load required to embed a 11.28-mm (0.444-in. ball to one-half its diameter. Values presented are the average of radial and tangential penetrations.

Literature Cited

ASTM. 2018. D143-14—Standard test methods for small clear specimens of timber. West Conshohocken, PA: ASTM International.

Davis, E.M. 1962. Machining and related characteristics of United States hardwoods. Technical Bulletin No. 1267. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

FPL. 2010. Wood handbook—wood as an engineering material. General Technical Report FPL–GTR–113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 508 p.

Hardin, J.W.; Leopold, D.J.; White, F.M. 2001. Textbook of dendrology. New York, NY: McGraw-Hill. 534 p.

Ross, R.J.; Wiemann, M.C. 2012. Part Two—Basic wood properties of hardwoods affected by invasive species. In: B.K. Brashaw, R.J. Ross, X. Wang, M.C. Wiemann, eds. Wood utilization options for urban trees infested by invasive species. Duluth, MN: University of Minnesota. pp. 13–27.

Table 2.8—Strength properties of some commercially important hardwoods grown in the United States (inch-pound)[a]

Common species name	Moisture content	Specific gravity[b]	Static bending: Modulus of rupture (lbf in^{-2})	Static bending: Modulus of elasticity[c] ($\times 10^6$ lbf in^{-2})	Compression perpendicular to grain (lbf in^{-2})	Side hardness[d] (lbf)
Ash, black	Green	0.45	6,000	1.04	350	520
	12%	0.49	12,600	1.60	760	850
blue	Green	0.53	9,600	1.24	810	—
	12%	0.58	13,800	1.40	1,420	—
green	Green	0.53	9,500	1.40	730	870
	12%	0.56	14,100	1.66	1,310	1,200
Oregon	Green	0.50	7,600	1.13	530	790
	12%	0.55	12,700	1.36	1,250	1,160
white	Green	0.55	9,500	1.44	670	960
	12%	0.60	15,000	1.74	1,160	1,320
Birch, paper	Green	0.48	6,400	1.17	270	560
	12%	0.55	12,300	1.59	600	910
sweet	Green	0.60	9,400	1.65	470	970
	12%	0.65	16,900	2.17	1,080	1,470
yellow	Green	0.55	8,300	1.50	430	780
	12%	0.62	16,600	2.01	970	1,260
Elm, American	Green	0.46	7,200	1.11	360	620
	12%	0.50	11,800	1.34	690	830
rock	Green	0.57	9,500	1.19	610	940
	12%	0.63	14,800	1.54	1,230	1,320
slippery	Green	0.48	8,000	1.23	420	660
	12%	0.53	13,000	1.49	820	860
Maple, bigleaf	Green	0.44	7,400	1.10	450	620
	12%	0.48	10,700	1.45	750	850
black	Green	0.52	7,900	1.33	600	840
	12%	0.57	13,300	1.62	1,020	1,180
red	Green	0.49	7,700	1.39	400	700
	12%	0.54	13,400	1.64	1,000	950
silver	Green	0.44	5,800	0.94	370	590
	12%	0.47	8,900	1.14	740	700
sugar	Green	0.56	9,400	1.55	640	970
	12%	0.63	15,800	1.83	1,470	1,450
Oak (red group)						
black	Green	0.56	8,200	1.18	710	1,060
	12%	0.61	13,900	1.64	930	1,210
cherrybark	Green	0.61	10,800	1.79	760	1,240
	12%	0.68	18,100	2.28	1,250	1,480
laurel	Green	0.56	7,900	1.39	570	1,000
	12%	0.63	12,600	1.69	1,060	1,210
northern red	Green	0.56	8,300	1.35	610	1,000
	12%	0.63	14,300	1.82	1,010	1,290
pin	Green	0.58	8,300	1.32	720	1,070
	12%	0.63	14,000	1.73	1,020	1,510
scarlet	Green	0.60	10,400	1.48	830	1,200
	12%	0.67	17,400	1.91	1,120	1,400
southern red	Green	0.52	6,900	1.14	550	860
	12%	0.59	10,900	1.49	870	1,060

Table 2.8—Strength properties of some commercially important hardwoods grown in the United States (inch-pound)[a] (con.)

Common species name	Moisture content	Specific gravity[b]	Static bending: Modulus of rupture (lbf in^{-2})	Static bending: Modulus of elasticity[c] ($\times 10^6$ lbf in^{-2})	Compression perpendicular to grain (lbf in^{-2})	Side hardness[d] (lbf)
Oak (red group) (con.)						
water	Green	0.56	8,900	1.55	620	1,010
	12%	0.63	15,400	2.02	1,020	1,190
willow	Green	0.56	7,400	1.29	610	980
	12%	0.69	14,500	1.90	1,130	1,460
Oak (white group)						
bur	Green	0.58	7,200	0.88	680	1,110
	12%	0.64	10,300	1.03	1,200	1,370
chestnut	Green	0.57	8,000	1.37	530	890
	12%	0.66	13,300	1.59	840	1,130
live	Green	0.80	11,900	1.58	2,040	—
	12%	0.88	18,400	1.98	2,840	—
overcup	Green	0.57	8,000	1.15	540	960
	12%	0.63	12,600	1.42	810	1,190
post	Green	0.60	8,100	1.09	860	1,130
	12%	0.67	13,200	1.51	1,430	1,360
swamp chestnut	Green	0.60	8,500	1.35	570	1,110
	12%	0.67	13,900	1.77	1,110	1,240
swamp white	Green	0.64	9,900	1.59	760	1,160
	12%	0.72	17,700	2.05	1,190	1,620
white	Green	0.60	8,300	1.25	670	1,060
	12%	0.68	15,200	1.78	1,070	1,360
Willow, black	Green	0.36	4,800	0.79	180	—
	12%	0.39	7,800	1.01	430	—

[a]Results of tests on clear specimens in the green and air-dried situations.
[b]Specific gravity is based on weight when ovendry and volume when green or at 12% moisture content.
[c]Modulus of elasticity measured from a simply supported, center-loaded beam, on a span depth ratio of 14/1. To correct for shear deflection, the modulus can be increased by 10%.
[d]Side hardness is measured when load is perpendicular to grain.

Chapter 3

Sorting Hardwood Logs

R. Edward Thomas, Research Computer Scientist
USDA Forest Service, Northern Research Station, Princeton, West Virginia

Xiping Wang, Research Forest Products Technologist
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

Hardwood logs vary widely in quality within species, harvest site, and even the same tree. Key to efficient utilization of the hardwood resource is an efficient and accurate determination of the quality of each log. Holes, knots, wounds, and other growth defects (Fig. 3.1) on logs reduce strength and appearance of any resulting products and thus reduce the value of the log and its products (Carpenter et al. 1989). Log end defects, such as rot, decay, shake, and split (Fig. 3.2), give hints to the interior quality of the log (Carpenter et al. 1989). Although log end defect information is very important, it can be difficult if not impossible to know a defect's full extent with only visual inspection.

Depending on their severity, log shape defects such as crook (an abrupt bend in the log) and sweep (a gentle uniform arc from end to end) deformities (Fig. 3.3) can significantly reduce the amount of dimension lumber that can be sawn from a log. Further, because of the presence of sloped grain, the strength of lumber sawn from such a log is normally lower than that from a straight log. Surface, end, and shape defects like these can be found during visual inspection. However, if the log is to be converted into pulp or fuel wood, then these defects are of no consequence.

The USDA Forest Service hardwood log grading rules (hereinafter "Forest Service log grades") were developed to provide a way of classifying logs by quality (Rast et al. 1973). The log grading rules are composed of six grades: Veneer, Factory 1, Factory 2, Factory 3, Construction, and Local-Use, in order of highest quality and value to lowest. The smallest log covered by these grades has a length of 8 ft (2.44 m) and small-end diameter of 8 in. (203 mm).

Veneer grade includes very high-valued logs for appearance veneer production and some relatively clear low-valued ones for peeler or core-stock veneer. The attributes that make a good hardwood veneer log were explored in depth by Wiedenbeck et al. (2003). Factory grade logs are those typically sawn to make dimensional lumber, with grade and value of the lumber sawn determined by National Hardwood Lumber Association (NHLA) grading rules (NHLA 2014). Using factory grades, one can estimate volume and value of the sawn lumber (Hanks et al. 1980). Construction grade logs are suitable for railway ties, timbers, and other one-piece structural products. Grade and value of construction grade products can be determined by the construction grade section of the NHLA grading rules or by tie specifications of the Railway Tie Association (2003). Products sawn from local-use grade logs are suitable for products that do not require high strength, durability, or fine appearance. Typical products from local-use logs include pallet parts, mine timbers, and blocking. Figure 3.4 illustrates the relative proportion of logs and products for the different Forest Service log grades, where each segment shows the approximate proportion of total log production for that quality and product combination. For example, in Figure 3.4 we can see that only 10% of all hardwood logs will meet the requirements of veneer grade. However, within veneer

Figure 3.1—Typical hardwood log surface defects. Defect types (left to right): overgrown knot, heavy distortion, wound, hole, and unsound knot.

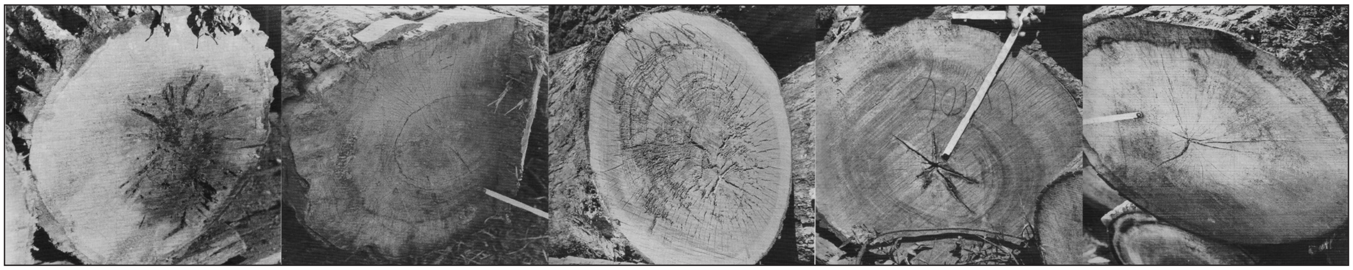


Figure 3.2—Typical hardwood log end defects. Defect types (from left to right): oak timber worm holes and associated rot, ring shake, advanced stage decay, spider heart, and early stage decay (Carpenter et al. 1989).

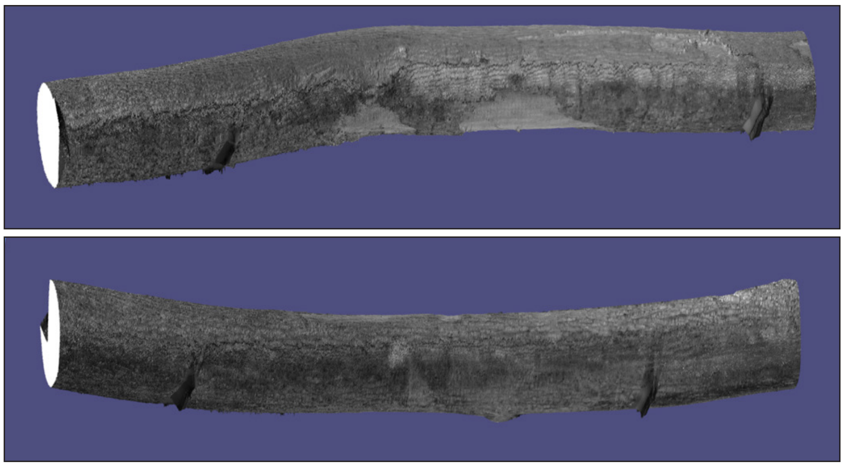


Figure 3.3—Crook (top image) and sweep (bottom image) shape deformities of hardwood logs.

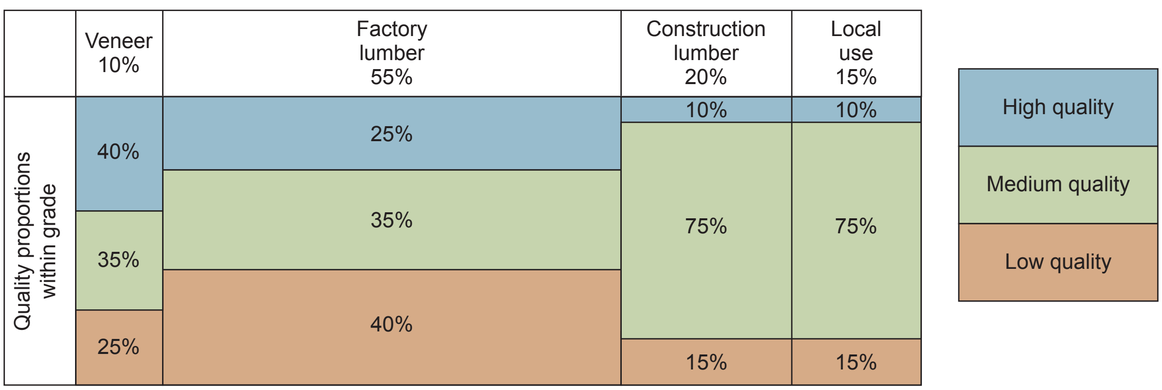


Figure 3.4—Estimated Forest Service log grade, product, and quality percentages of total hardwood log production (Rast et al. 1973).

grade, only 40% (4% of the entire log population) are of a high enough quality to make appearance grade veneer.

Although the Forest Service log grades provide a means of determining quality and value of a large proportion of hardwood logs, they do not cover logs smaller than 8 ft (2.44 m) long and small-end diameters less than 8 in. (203 mm). The Forest Service log grades also require a visual inspection, which some believe can be burdensome. As a result, some companies have developed abbreviated log grading rules loosely based on the Forest Service log grades. These inspections are faster but generally regarded as less accurate.

More modern technology provides two distinctly different methods of determining hardwood log quality in addition to visual inspection. Acoustic wave methods utilize a mechanical impact to generate low-frequency stress waves propagating longitudinally through the log and record the reverberation of the waves within the log. At the microscopic level, energy storage and dissipation properties of the log are controlled by orientation of wood cells and structural composition, factors that contribute to static elasticity and strength of wood. Such properties are observable as frequency of wave reverberation and rate of wave attenuation. Research has showed that propagation velocity of acoustic waves is a good predicting parameter for wood deterioration caused by any wood decay mechanism (Pellerin et al. 1985, Pellerin and Ross 2002, Wang et al. 2004a). Another method, laser scanning, uses two or more laser line scanners to profile the log. These systems can provide high-resolution scans that capture surface defect information or low-resolution scans that record only log shape. Although laser scanning systems were originally developed and installed in softwood sawmills, they are becoming more common in hardwood mills. Acoustic wave and laser scanning methods are explained in detail in the following sections.

Acoustic Assessment of Hardwood Logs

Acoustic technologies have been well established as material evaluation tools in the past several decades, and their use has become widely accepted in the forest products industry for on-line quality control and products grading (Schad et al. 1995, Pellerin and Ross 2002, Ross et al. 2004). Recent research developments on acoustic sensing technology offer further opportunities for wood manufacturers and forest owners to evaluate raw wood materials (standing trees, stems, and logs) for general wood quality and intrinsic wood properties. The use of longitudinal acoustic wave techniques for wood quality assessment is based on the accurate measurement of propagation velocity of a stress wave generated by a mechanical impact. Acoustic velocities in logs and long stems of known length are typically measured using a resonance-based approach. In log acoustic measurement, an acoustic sensor is mounted or held on one end of a log. A stress wave is initiated by a mechanical impact on the same end and the stress waveforms are subsequently recorded by an electronic unit. This acoustic approach is based on the observation of hundreds of acoustic pulses resonating longitudinally in a log and provides a weighted average acoustic velocity. Most resonance-based acoustic tools have a built-in fast Fourier transformation (FFT) program that can analyze and output the natural frequencies of acoustic signals. Log acoustic velocity is then determined from

$$C_L = 2f_0L$$

where C_L is acoustic velocity of logs (m/s), f_0 is fundamental natural frequency of an acoustic wave signal (Hz), and L is log length (end-to-end) (m).

Figure 3.5 shows an industrial log sorting tool (Hitman HM200) manufactured by Fibre-gen (Christchurch, New Zealand) that can be used for sorting or grading tree stems, logs, and poles for stiffness performance. This hand-held tool is equipped with a Monitran P100 accelerometer mounted in a rubber bossing, which allows it to vibrate freely and thus monitor the oscillation of the cross section of a log tapped with a hammer. The HM200 tool can make

Figure 3.5—A resonance-based acoustic tool (Hitman HM200) used to measure acoustic velocity in hardwood logs (Brashaw et al. 2013).

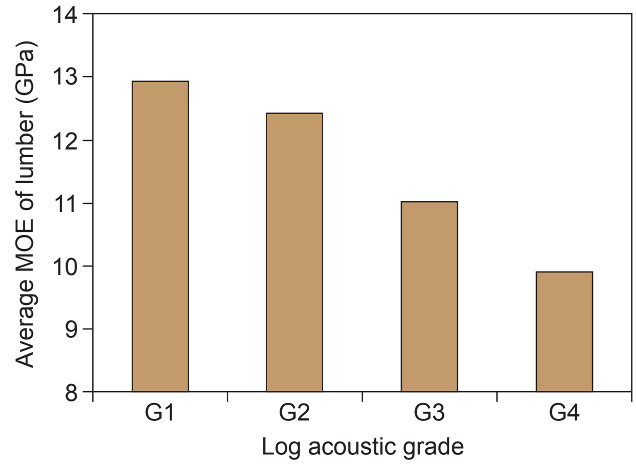


Figure 3.6—Red maple log acoustic grade versus average MOE of lumber (Wang et al. 2004c).

reliable measurements at a wide range of frequencies (1 to 30 Hz) and temperatures (–55 to 250 °C) (Achim et al. 2011).

The ability to improve log sorting with resonance-based acoustic methods has been well recognized in the softwood industry (Walker and Nakada 1999; Harris et al. 2003; Huang et al. 2003; Carter and Lausberg 2003; Wang et al. 2002, 2004b). Research has shown that log acoustic measures can be used to predict strength and stiffness of structural lumber that would be produced from a log (Aratake et al. 1992, Aratake and Arima 1994, Ross et al. 1997, Iijima et al. 1997, Wang 1999, Wang et al. 2002). This opened the way for acoustic technology to be applied in mills for sorting softwood logs and stems for structural quality.

To validate the usefulness of the resonance acoustic method for sorting hardwood logs, Wang et al. (2004c) conducted a mill study to examine the effect of log acoustic sorting on lumber stiffness and lumber E-grades (modulus of elasticity classes). After acoustically testing 107 red maple logs, they sorted the logs into four classes according to acoustic velocity. Figure 3.6 illustrates the average lumber MOE for each log class, with a significant differentiation and clear trend between the log acoustic classes. They further compared log acoustic classes to lumber E-grades and found a good relationship between them. Logs that have a high acoustic velocity contain higher proportions of high-stiffness lumber.

Research has also shown that physical and chemical changes in hardwoods, at both macro- and micro-structure level, could affect the acoustic characteristics of trees and logs. A previous study investigated the use of a resonance acoustic technique to nondestructively assess the extent of borer infestation in red oak logs affected by oak decline (Wang et al. 2007). Large numbers of black oak (*Quercus velutina* Lam.) and scarlet oak (*Q. coccinea* Muenchh.) trees are declining and dying in the Missouri Ozark forest as a result of the outbreak of red oak borer (*Enaphalodes rufulus* (Haldeman)) attacks. Borer-infested trees produce low-grade logs that become extremely problematic to merchandize as the level of infestation increases in the forest stand. Signs of physical damage such as worm holes, grub holes, and decay are the typical symptoms associated with borer attacks. In this study, 360 logs were acoustically tested and segregated into six classes based on acoustic velocity ranges of the logs:

G1: less than 2.6 km/s

G2: 2.6–2.8 km/s

G3: 2.8–3.0 km/s

G4: 3.0–3.2 km/s

G5: 3.2–3.4 km/s

G6: greater than 3.4 km/s

All boards were graded according to local mill (Canoak, Inc., Salem, Missouri) grades: Select—clear face on both sides with no knots or defects; No. 1—clear face on one side with less than 20% knots or defects on the second face; No. 2—clear face on one side with greater than 20% but less than 40% knots or defects on the second face; No. 3—no clear faces with less than 40% knots or defects on either side; and Pallet stock—no clear faces with greater than 40% knots or defects on both sides.

Figure 3.7 shows how the yield of appearance grade boards changes as log acoustic velocity changes. Board yield and log acoustic velocity had a direct relationship in the first three grades (Select, No. 1, No. 2). As log velocity increased, yields of these higher grade boards increased. On the other hand, board yield of the low grades (No. 3 or "pallet stock") decreased significantly as log velocity increased. These two opposite velocity grade trends reflected distinct differences between good-quality boards with less or no borer infestation and poor-quality boards with severe borer attacks. According to the hardwood grading rules (Wang et al. 2007), the higher grade boards must have one or two clear faces with no or few defects, suggesting that they were not affected by borer infestation or had only localized infestation. Pallet stock boards, on the other hand, are typically of poor quality with more widespread or severe defects. About 45% of the Missouri boards were in this grade. This reflects the quality problem associated with oak tree decline in the region. The velocity-grade trends suggest that log acoustic velocity could be effectively used to segregate severely infested stems and logs from good stems and logs.

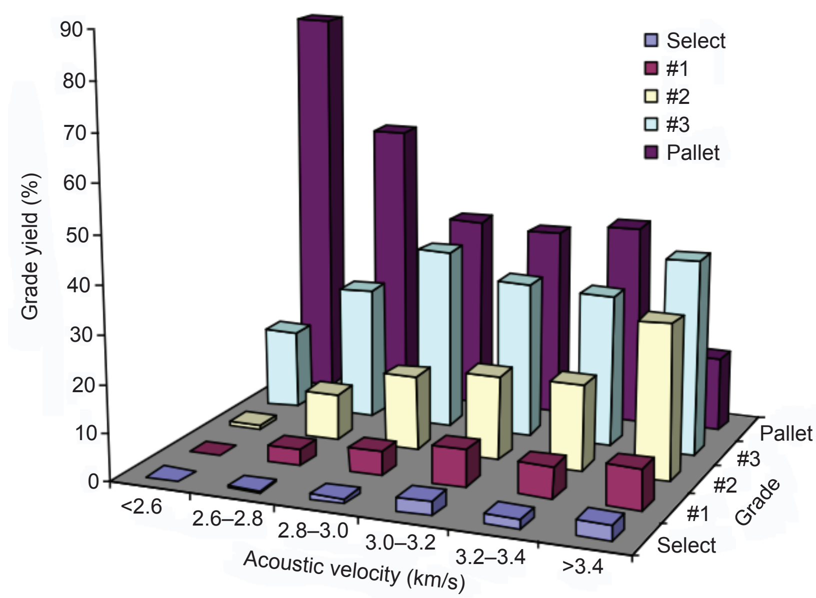


Figure 3.7—Relationship between log acoustic velocity and board grade yield for borer-infested red oak logs (Wang et al. 2007).

In a practical log-sorting process, the industry can achieve benefits by developing a sorting strategy based on log sources and desired end products. Currently, companies implementing acoustic sorting strategies measure only the velocity of acoustic waves and segregate logs into velocity groups using predetermined cut-off velocity values. Appropriate cut-off acoustic velocity values can be determined for either selecting the highest quality logs for superior structural applications or isolating the low grade logs for nonstructural uses in those cases where the principle log quality concern relates to log soundness (presence or absence of decay).

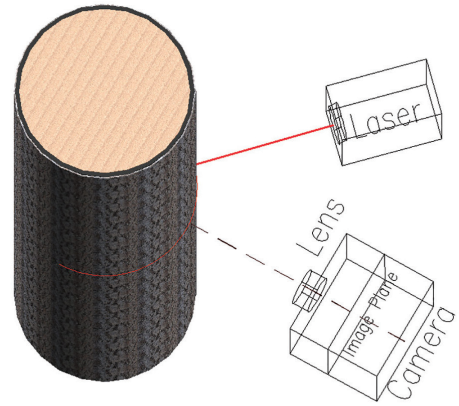


Figure 3.10—Diagram of scanning head showing laser, camera, and image plane.

Laser Scanning Assessment of Hardwood Logs

The use of laser scanning technology has become an accepted and economical means of determining the size, shape, and features of logs and lumber. The key components of a laser-scanning system are a laser line generator and a camera. Figure 3.8 shows an industrial laser scanner unit manufactured by JoeScan (Vancouver, Washington) that can be used with either logs or lumber. On this particular scanner, the laser aperture is on the left and the camera is on the right. Laser scanner designs have several variations, with some having multiple laser beams and a single camera and others having two cameras and a single laser. Using two cameras avoids areas of missing data that occur when a protrusion on the surface prevents a camera from “seeing” the laser. Rather than project a single point, the scanners project a line onto the surface of the object being scanned. Figure 3.9 shows the laser line projected onto the surface of a log. The camera and laser are separated by a measured distance, and the camera is aimed toward the laser line at a specific angle. Using the camera angle, distance between camera and laser, and triangulation, distance of points along the laser line projected on an object can be determined. In many instances, scanning systems are calibrated using an object with a known shape and size. Figure 3.10 shows the mechanics of projecting a point from the laser line onto the camera’s image plane. Processing the location of points on the laser line onto the camera’s image plane allows the shape and size of an object to be calculated.

Figure 3.8—Typical industrial laser scan head used in log and lumber applications.

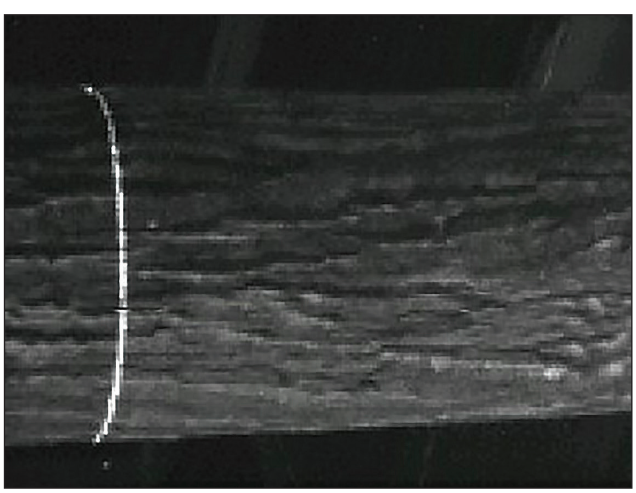


Figure 3.9—Laser scan line as projected onto a log during 3D scanning.

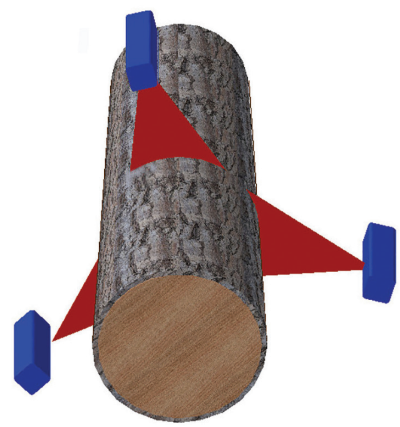


Figure 3.11—Typical configuration for laser scanning logs.

Laser scanning systems must be able to discriminate between the laser line and the surface being scanned. Most scanners use lasers in the visible spectrum; others scan in the invisible (near infrared and ultraviolet) spectrum. Visible spectrum scanners must operate out of direct sunlight, exposure to which can prevent the scanner from finding the laser on the surface being scanned.

A typical method of laser scanning logs is to pass the log through an array of three to four laser scanning heads arranged around the log (Fig. 3.11). Typically, the logs are on a chain and are passed through the scanner. During laser scanning, a series of scan lines are projected around the circumference of the log along its length. The resolution of the scanning system is the distance between the scan lines. The shorter the distance between the scan lines, the higher the resolution. The resolution of a log laser scanning system is normally between 6 and 24 pixels/in., although much higher resolutions are possible. The higher the resolution, the greater the detail captured about the log and the greater the amount of data that must be processed. The log images shown in Figure 3.3 are high-resolution scans of yellow-poplar (*Liriodendron tulipifera*) logs at a resolution of 0.0625 in. This scan is from an experimental scanner developed by the Forest Service (Thomas et al. 2008). In the scan imagery, it is easy to discern defects in the image as well as log shape.

More importantly, grade yield and value of lumber can be estimated and optimized before sawing. High-resolution laser scanning provides additional processing metrics that can be beneficial. Given a high-resolution scan, as those shown in Figure 3.3, log volumes can be determined that are comparable in accuracy to those obtained using immersion tanks (Thomas and Bennett 2014). Using diameter and species information, the thickness of the bark can be estimated along the length of the log, permitting logs to be sorted by estimated diameter inside bark measurements and volume of bark residue that may be produced to be estimated.

Methods have been developed for automated detection of severe defects on hardwood log surfaces (Thomas and Thomas 2011, Thomas et al. 2008). These methods use parallel processing and contour analysis approaches to detect bumps and depressions associated with severe surface defects. In addition, these methods can grade the log to Forest Service log grades, and the potential grade recovery of the log can be determined using the yield tables developed by Hanks et al. (1980). In addition, models have been developed that estimate internal defect locations and sizes using surface defect measurements for hardwood logs (Thomas 2016). Combining the external and internal defect information allows one to get a more complete understanding of log quality. More importantly, such data permit optimization of the sawing process to produce maximum value (Lin et al. 2011).

Summary

Acoustic wave methods utilize a mechanical impact to generate low-frequency stress waves propagating longitudinally through a log and record the reverberation of the waves within the log. Intrinsic wood properties of logs are observable as frequency of wave reverberation and the rate of wave attenuation. Commercial acoustic tools have been widely accepted by those segments of the forest products industry manufacturing structural products in on-line quality control and log segregation. Propagation velocity of acoustic waves in a log is also a good prediction parameter for wood deterioration caused by any wood decay mechanism, thus allowing logs to be sorted for internal soundness.

Laser scanning is an inexpensive, fast, and accurate method of measuring log diameter, length, and volume. Scanning systems also measure crook, sweep, and eccentricity of the log to a fraction of a millimeter. In addition, most surface defects regarded as degrade defects by the Forest Service grading rules are detected during laser data image processing. This permits logs that have been laser-scanned to be sorted not only by diameter and length, but also by quality.

One important reason for sorting logs is to remove logs from the processing stream that have little or no profit potential. This concept is commonly known as the “break-even log”—processing a log of lower quality than the break-even log results in a net loss for the processor. Ideally, avoiding the break-even log (and those only slightly better) helps the processor to realize their target profit margin. Logs that give little or no real financial return from processing should be sold to other processors that can economically process these logs into products with less stringent or different quality standards, such as rail ties, pallet lumber, pulp, fuel, or other similar products. Laser and acoustic scanning methods provide a means of automating the sort to improve mill profitability.

Acoustic and laser scanning methods are complementary approaches to log scanning. Each addresses the weaknesses or inabilities of the other. We are currently exploring the feasibility of combining the two approaches, which should provide a more complete data picture of the log—size, shape, surface defects, and degree of soundness.

Literature Cited

Achim, A.; Paradis, N.; Carter, P.; Hernandez, R.E. 2011. Using acoustic sensors to improve the efficiency of the forest value chain in Canada: a case study with laminated veneer lumber. Sensors. 11: 5716–5728.

Aratake, S.; Arima, T. 1994. Estimation of modulus of rupture (MOR) and modulus of elasticity (MOE) of lumber using higher natural frequency of log in pile of logs

II—possibility of application for Sugi square lumber with pith. Mokuzai Gakkaishi. 40(9): 1003–1007.

Aratake, S.; Arima, T.; Sakoda, T.; Nakamura, Y. 1992. Estimation of modulus of rupture (MOR) and modulus of elasticity (MOE) of lumber using higher natural frequency of log in pile of logs—possibility of application for Sugi scaffolding board. Mokuzai Gakkaishi. 38(11): 995–1001.

Brashaw, B.K.; Wang, X.; Fellman, D.; Ross, R.J.; Xu, H. 2013. Acoustic assessment technologies for optimal wood products and biomass utilization. In: Ross, R.J.; Wang, X., eds. Proceedings: 18th International Nondestructive Testing and Evaluation of Wood Symposium. General Technical Report FPL–GTR–226. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. pp. 150-160.

Carpenter, R.D.; Sonderman, D.L.; Rast, E.D. 1989. Defects in hardwood timber. Agricultural Handbook No. 678. Washington, DC. U.S. Department of Agriculture, Forest Service. 88 p.

Carter, P.; Lausberg, M. 2003. Application of Hitmam® acoustic technology—the Carter Holt Harvey experience. FIEA paper. 6 p.

Hanks, L.F.; Gammon, G.L.; Brisbin, R.L. Rast, E.D. 1980. Hardwood log grades and lumber grade yields for factory grade lumber logs. Forest Service Res. Pap. NE–468. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 92 p.

Harris, P.; Petherick, R.; Andrews. M. 2003. Acoustic resonance tools. In: Proceedings, 13th International Symposium on Nondestructive Testing of Wood. August 19–21, 2002, University of California Berkeley, California. pp. 195–201.

Huang, C.L.; Lindstrom, H.; Nakada, R.; Ralston, J. 2003. Cell wall structure and wood properties determined by acoustics—a selective review. Holz als Roh- und Werkstoff. 61(2003): 321–335.

Iijima, Y.; Koizumi, A.; Okazaki, Y.; Sasaki, T.; Nakatani, H. 1997. Strength properties of sugi grown in Akita Prefecture III: some relationships between logs and sawn lumber. Mokuzai Gakkaishi. 43(2): 159–164.

Lin, W.; Wang, J.; Thomas, R.E. 2011. A three-dimensional optimal sawing system for small sawmills in central Appalachia. In: Proceedings of the 17th Central Hardwoods Forest Conference, April 5–7, 2010, Lexington, KY. Gen. Tech. Rep. P-78. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. pp. 67–75.

NHLA. 2014. Rules for the measurement and inspection of hardwood and cypress. Memphis, TN: National Hardwood Lumber Association. 104 p.

Pellerin, R.; Ross, R.J. 2002. Nondestructive evaluation of wood. Madison, Wisconsin: Forest Products Society. 210 p.

Pellerin, R.F.; DeGroot, R.C.; Esenther, G.R. 1985. Nondestructive stress wave measurements of decay and termite attack in experimental wood units. In: Proceedings, 5th International Symposium on Nondestructive Testing of Wood, September 9–11, 1985, Pullman, WA. Pullman, WA: Washington State University. pp. 319–353.

Railway Tie Association. 2003. Specifications for timber crossties. http://www.rta.org/assets/docs/rtaspecificationsbooklet.pdf, Railway Tie Association, Fayetteville, Georgia. 9 p. (Accessed January 13, 2016)

Rast, E.D.; Sonderman, D.L.; Gammon, G.L. 1973. A guide to hardwood log grading. Gen. Tech. Rep. NE–1. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 31 p.

Ross, R.J.; McDonald, K.A.; Green, D.W.; Schad, K.C. 1997. Relationship between log and lumber modulus of elasticity. Forest Products Journal. 47(2): 89–92.

Ross, R.J.; Erickson, J.R.; Brashaw, B.K.; Wang, X.; Verhey, S.R.; Forsman, J.W.; Pilon, C.L. 2004. Yield and ultrasonic modulus of elasticity of red maple veneer. Forest Products Journal. 54(12): 220–225.

Schad, K.C.; Kretschmann, D.E.; McDonald, K.A.; Ross, R.J.; Green, D.W. 1995. Stress wave techniques for determining quality of dimensional lumber from switch ties. Res. Note FPL–RN–0265. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 12 p.

Thomas, R.E. 2016. Equations for predicting internal defect measurements of common Appalachian hardwoods. Res. Pap. FPL–RP–686. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 16 p.

Thomas, R.E.; Bennett, N. 2014. Accurately determining log and bark volumes of saw logs using high-resolution laser scan data. In: Groninger, John W.; Holzmueller, Eric J.; Nielsen, Clayton K.; Dey, Daniel C., eds. Proceedings, 19th Central Hardwood Forest Conference, March 10–12, 2014, Carbondale, IL. Gen. Tech. Rep. NRS–P–142. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. pp. 299–310.

Thomas, L.; Thomas, R.E. 2011. A graphical automated detection system to locate hardwood log surface defects using high-resolution three-dimensional laser scan data. In: Fei, S.; Lhotka, J.M.; Stringer, J.W.; Gottschalk, K.W.; Miller, G.W., eds. Proceedings, 17th central hardwood forest conference; 2010 April 5–7; Lexington, KY. Gen. Tech. Rep. NRS–P–78. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 92–101.

Thomas, R.E.; Thomas, L.; Shaffer, C. 2008. Defect detection on hardwood logs using high-resolution laser scan data. In: Proceedings of the 15th International Symposium on Nondestructive Testing of Wood, September 10–12, 2007, Duluth, MN. Natural Resources Research Institute, University of Minnesota, Duluth: 163–167.

Walker, J.C.F.; Nakada, R. 1999. Understanding corewood in some softwoods: a selective review on stiffness and acoustics. International Forestry Review. 1(4): 251–259.

Wang, X. 1999. Stress wave-based nondestructive evaluation (NDE) methods for wood quality of standing trees. Ph.D. dissertation. Houghton, Michigan: Michigan Technological University. 187 p.

Wang, X.; Ross, R.J.; Mattson, J.A.; Erickson, J.R.; Forsman, J.W.; Geske, E.A.; Wehr, M.A. 2002. Nondestructive evaluation techniques for assessing modulus of elasticity and stiffness of small-diameter logs. Forest Products Journal. 52(2): 79–85.

Wang, X.; Divos, F.; Pilon, C.; Brashaw, B.K.; Ross, R.J.; Pellerin, R.F. 2004a. Assessment of decay in standing timber using stress wave timing nondestructive evaluation tools—a guide for use and interpretation. Gen. Tech. Rep. FPL–GTR–147. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 12 p.

Wang, X.; Ross, R.J.; Brashaw, B.K.; Punches, J.; Erickson, J.R.; Forsman, J.W.; Pellerin, R.F. 2004b. Diameter effect on stress-wave evaluation of modulus of elasticity of small-diameter logs. Wood and Fiber Science. 36(3): 368–377.

Wang, X.; Ross, R.J.; Green, D.W.; Brashaw, B.K.; Englund, K.; Wolcott, M. 2004c. Stress wave sorting of red maple logs for structural quality. Wood Science and Technology. 37: 531–537.

Wang, X.; Stelzer, H.E.; Wiedenbeck, J.; Lebow, P.K.; Ross, R.J. 2007. Assessing wood quality of borer-infested red oak logs with a resonance acoustic technique. Wood and Fiber Science. 41(2): 180–193.

Wiedenbeck, J.; Wiemann, M.; Alderman, D.; Baumgrass, J.; Luppold, W. 2003. Defining hardwood veneer log quality attributes. Gen. Tech. Rep. NE–313. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 36 p.

Chapter 4

Grading and Properties of Hardwood Structural Lumber

C. Adam Senalik, Research General Engineer
David W. Green, Supervisory Research General Engineer (deceased)
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

Structural lumber markets have traditionally been dominated by softwood species. Historically, however, hardwood species have been extensively used for certain structural products, such as timbers for railway and highway bridges, railway ties, and mine timbers, and for pallets and containers. In the 1920s, when uniform procedures were first developed for structural grading, allowable properties were assigned to both hardwood and softwood species (appendix D of Green and Evans 2001). In 1922, the National Lumber Manufacturers' Association (currently the American Forest & Paper Association) produced span tables for joists and rafters for both hardwood and softwood species. Allowable properties for hardwoods were included in the first edition of the *National Design Specification* in 1944 but did not appear in the 1960 edition. In the 1970s and 1980s, studies were published on the technical and economic feasibility of producing 2-in.-thick dimension lumber from several hardwood species, including aspen, paper birch, basswood, and yellow-poplar (for example, Maeglin and Boone 1983, 1985; Gerhards 1983; Erickson et al. 1986). A number of hardwood species were once again included in the 1988 revision of the 1986 *National Design Specification* (DeBonis and Bendtsen 1988). Despite this interest, the only hardwood species occasionally available on a commercial basis was yellow-poplar, which was available in dimension lumber and manufactured into trusses. The historic lack of interest in 2-in.-thick structural dimension lumber from hardwood species can largely be attributed to low market acceptance and low profit margins for commodity lumber. In the early 1990s, the National Timber Bridge Initiative and decreased availability of western softwoods resulted in renewed interest in using hardwoods for structural applications. Recently, there has been some interest in producing 2-in.-thick commercial lumber from hardwoods for use in trusses and I-joists. This chapter summarizes information on properties and grading of 2-in.-thick dimension lumber resulting from research studies conducted since about 1990.

Visually Graded Dimension Lumber

The American Softwood Lumber Standard, Voluntary Product Standard PS-20, establishes nationally recognized requirements for the grading of lumber (NIST 2015, Green and Hernandez 2000, FPL 2010). The provisions of PS-20 were developed and administered by the American Lumber Standards Committee (ALSC). Grading rules and allowable properties for both softwood and hardwood structural lumber are developed and administered through ALSC's National Grading Rule Committee and Board of Review. Grading rules and design values for eastern hardwoods are given in the current edition of the Standard Grading Rules of the Northeastern Lumber Manufacturers' Association (NeLMA 2013. Allowable properties for all species, including hardwoods, are also summarized in the National Design Specification (NDS) for Wood Construction (AF&PA 2015). For dimension lumber (lumber 4 in. and less in thickness), grades and properties are given for Structural Framing (lumber 2 in. and wider), Stud (lumber 2 in. and wider), and Light Framing (also 2 in. and wider). (Structural Framing is usually further separated into Structural Light Framing (lumber 2 to 4 in. thick and 2 to 4 in. wide) and Structural Joist and Plank (lumber 2 to 4 in. thick and 6 in. and wider).) Structural Framing grades are Select Structural, No. 1, No. 2, and No. 3. Light Framing grades are Construction, Standard, and Utility. Virtually all recent information on yield and properties of hardwood lumber are for Structural Framing grades. These are the only visual grades discussed in this chapter.

Yield

Studies on hardwood lumber usually express results either as total volume of lumber from a given grade that may be obtained from a total volume of log (called "recovery" in this chapter) or as total volume of lumber of a given grade relative to total volume of all lumber cut from the log or cant (called "grade yield" in this chapter). Most studies in the literature report only grade yield.

Table 4.1—Grade yield[a] of hardwood structural lumber from ungraded logs and cants

Species and size	Number of pieces	Grade yield (%) Select Structural	No. 1	No. 2	No. 3	Econ.
Sweetgum						
2 by 4[b]	403	—[b]	18.0	53.5	18.9	9.6
2 by 8[b]	423	—[b]	9.9	41.2	33.1	15.8
Yellow-poplar						
2 by 4[b]	366	—[b]	39.7	37.8	21.8	0.7
2 by 8[b]	362	—[b]	50.9	35.0	13.4	0.7
2 by 4[c]	—	30.4	19.9	38.0	11.7	—
2 by 6[c]	—	24.6	20.7	45.0	9.7	—
2 by 8[c]	—	37.2	11.4	43.0	8.4	—
Hybrid poplar						
2 by 4[d]	243	23.0	23.0	20.2	19.8	14.0
Hard maple						
2 by 6[e]	925	4.2	1.9	41.6	35.4	16.9

[a]Because of the way some studies reported their yield of lumber, all estimates of percentage grade yield are based on the board feet (or number of pieces) of lumber of a given size reported in the cited literature. See text for additional discussion.
[b]Faust 1990. For sweetgum and yellow-poplar, Select Structural and No. 1 grades were not separated and would more appropriately be classified as No. 1 and Better.
[c]Moody et al. (1993). Yield of Economy lumber not reported separately from "trim," sawdust, etc. Number of pieces also not reported.
[d]Kretschmann et al. (1999).
[e]Unpublished data of D.W. Green, R.J. Ross, J.W. Forsman, and J. Erickson.

Faust (1990) evaluated grade yield of Structural Light Framing from ungraded sweetgum and yellow-poplar logs. The 12-ft- (3.7-m-) long logs were sawn into nominal 8- by 8-in. cants and then resawn into four 2 by 8's. Two 2 by 4's were produced by ripping one of the 2 by 8's. Several things should be noted about how grade yield for this study is reported in this chapter. The arbitrary selection of one 2 by 8 to be cut into two 2 by 4's makes basing grade yield on the total number of pieces of lumber rather meaningless. Therefore, in Table 4.1 grade yield is based on the total number of pieces of a given size that were obtained (board feet of lumber was not reported), thus the sum of the grade yields for 2 by 4's (or 2 by 8's) is 100%. Also, because of some problems with overdrying of the lumber, only grades based on maximum strength-reducing defects in the piece (such as knots and slope of grain) are discussed here. Finally, because the lumber was graded following usual practices for grading southern pine dimension lumber, the No. 1 grade reported in the original publication was really a combination of No. 1 and Select Structural and is called "No. 1 and Better" in this chapter. Table 4.1 shows grade yield for individual grades and sizes of lumber based on number of pieces produced. Only lumber that makes No. 3 or Better grades may be used for structural purposes, and most of the profit comes from lumber that is No. 2 or Better. Some 90% of the sweetgum 2 by 4's and 84% of the 2 by 8's made No. 3 or Better, and 71% of the 2 by 4's and 51% of the 2 by 8's made No. 2 or Better. For yellow-poplar, about 99% of both sizes made No. 3 or Better, and 77% of the 2 by 4's and 85% of the 2 by 8's made No. 2 or Better. These high yields for yellow-poplar suggest that the logs may have been very high quality.

Grade yields for visually graded yellow-poplar dimension lumber were also reported as part of a study to develop specifications for hardwood glulam beams (Moody et al. 1993). In this study, logs were obtained from southwestern West Virginia. The trees were 12 to 24 in. (305 to 610 mm) in diameter at breast height and ranged in age from 25 to more than 50 years old. Cant sawing was used to obtain maximum yield from the logs. Although recovery of lumber from the logs is reported in the paper, some discrepancies appear in the tabulated numbers. Grade yields discussed here are based on board foot yield of No. 3 and Better lumber for each size of lumber reported in table 7 of Moody et al. (1993) after the lumber had been trimmed for maximum grade (Table 4.1). To be consistent with other studies summarized in Table 4.1, grade yields sum to 100% for each individual size. (Grade yields based on board feet, trimmed, of all sizes sawn from the logs are 2.8, 1.9, 3.6, and 1.1 for Select Structural, No. 1, No. 2, and No. 3 2 by 4's, respectively. For 2 by 6's, percentage grade yields based on total board feet of all sizes are 7.6, 6.4, 13.9, and 3.0, respectively, for 2 by 6's, and 22.2, 6.8,

Table 4.2—Grade yield of dry 2 by 4's from factory grade logs[a]

Species and grade	Grade yield (%)				
	Select Structural	No. 1	No. 2	No. 3	Econ.
Red oak					
F2	11	5	17	18	49
F3	4	1	11	10	75
Const.	5	4	30	14	46
Red maple					
F1	18	1	36	18	27
F2	5	0	22	16	56
F3	3	0	16	18	62

[a]From McDonald and Whipple (1992) and McDonald et al. (1993).

25.7, and 5.0, respectively, for 2 by 8's.) In general, grade yields, by size, of the yellow-poplar in this study are similar to those reported by Faust (1990), with some allowance made because Economy lumber was not reported separately by Moody et al. (1993). Thus 50.3% of the 2 by 4's in this study would make No. 1 and Better, whereas 39.7% made No. 1 and Better in the study by Faust (1990). For 2 by 8's, the comparisons are 48.6% in the Moody et al. (1993) study and 39.7 in the Faust (1990) study.

Kretschmann et al. (1999) evaluated grade yield of "Wisconsin-5" hybrid poplar, a variety previously extensively planted in Wisconsin. Material for this study was obtained from three plots of 20-year-old hybrid poplar growing near Hancock, in central Wisconsin. The 50 logs used in this study were about 9 ft (2.7 m) long and had small-end diameters that ranged from 6.75 to 11.5 in. (171 to 292 mm). Recovery was reported in the report for two different sawing patterns but was not given by lumber grade. Eighty-six percent of the 2 by 4's made No. 3 or Better grade, and 66% made No. 2 and Better (Table 4.1).

An unpublished study (D.W. Green, R.J. Ross, J.W. Forsman, and J. Erickson) examined mechanical grading options for structural lumber cut from hard maple. In this study, 2 by 6 dimension lumber was cut from ungraded hard maple cants obtained from the Upper Peninsula of Michigan. The lumber was dried using a schedule developed for hardwood structural lumber (Simpson et al. 1998) and graded as Structural Joist and Plank by a representative of the Southern Pine Inspection Bureau (SPIB). Grade yield was low in the two upper grades but was good for No. 2 and No. 3 grades (Table 4.1). Thus 83% of the lumber made No. 3 or Better, but only 48% made No. 2 or Better.

Two studies evaluated the yield of 2- by 4-in. (51- by 102-mm) structural lumber from USDA Forest Service factory-grade logs, one with red oak and another with red maple. In the first study (McDonald and Whipple 1992), 95 12-ft- (3.7-m-) long logs were obtained from central Wisconsin and sorted into USDA Forest Service standard hardwood log grades F2, F3, and hardwood Construction grade (Carpenter et al. 1989, Rast et al. 1973, Vaughn et al. 1966). F1 grade oak logs were excluded from the study because those logs are primarily used for veneer. All logs were 10 in. (254 mm) or more in scaling diameter. Logs were sawn by log grade and scaling diameter. The sawing pattern specified a 4-in. (102-mm) cant through the center of each log and 7/4 flitches on each side of the center cant. If possible, another 7/4 flitch was taken outside these flitches, otherwise 4/4 side lumber was sawn. 7/4 lumber was resawn from the center cant. Only the 7/4 lumber was retained for further study. The lumber was kiln-dried to an average moisture content of 15% and planed to 1.5 by 3.5 in. (38.1 by 88.9 mm). The 2 by 4's were graded by a SPIB Inspector as Structural Light Framing (chapter 7, FPL 2010).

Grade yield, expressed as a percentage of total sawn volume of 2 by 4's, is given in Table 4.2. Yield of merchantable (No. 3 and Better) lumber from the lower valued Construction grade red oak logs was comparable to yield from the higher valued F2 grade, with about 50% yield of No. 3 or Better. Yield of No. 3 or Better from log grade F3 was only about 25%.

The second study (McDonald et al. 1993) used procedures very similar to those previously discussed for red oak. In this study, 100 red maple logs were selected from central Vermont. The logs were sorted into USDA Forest Service standard hardwood log grades F1, F2, and F3. Construction grade logs were not available and therefore not included in the study. Grade yield of red maple is also shown in Table 4.2. With red maple, factory grade F1 logs yielded almost 75% No. 3 or Better lumber. With the lower quality F2 and F3 logs, less than half the volume graded as No. 3 or Better.

In both studies, an attempt was made to contrast the value of the logs for production of structural lumber versus their value if the log had been sawn into factory lumber. Because there are no established prices for hardwood structural lumber, and any prices for hardwood lumber would have to be competitive with those of other species, the value of southern pine lumber per thousand board feet (MBF) was used to calculate the value of the oak dimension lumber (Table 4.3). Prices from 1990 were: $300 per MBF Select Structural, $280 for No. 1, $260 for No. 2, and $150 for No. 3. Thus, for example, the 2,149 board feet for lumber from log grade F2 of red oak was valued at $506 (Table 4.3). In the original publication, however, the volume of lumber that did not make No. 3 was given a value of $0. Thus the value of the log was determined as the value of the dimension lumber divided by the entire volume of the log. For grade F2 red oak, this meant that the value of the logs for dimension lumber was listed as $119 per MBF (column 2 in Table 4.4). In retrospect, it seems overly severe

Table 4.3—Expected volume[a] and value by log grade for hardwood lumber[b]

Species and log grade	Log volume (BF)	Dimension lumber Volume (BF)	Dimension lumber Value ($)	Factory lumber Volume (BF)	Factory lumber Value ($)
Red oak					
F2	4,249	2,149	506	4,130	2,461
F3	2,844	710	157	3,161	1,460
Const.	1,322	701	166	—	—
Red maple					
F1	3,315	2,427	589	3,729	1,225
F2	2,679	1,169	264	3,012	819
F3	1,850	706	149	1,794	407

[a]BF, board foot.
[b]Adapted from McDonald and Whipple (1992) and McDonald et al. (1993).

Table 4.4—Value per unit volume for hardwood lumber[a]

Species and log grade	Value ($) per MBF[b] based on volumes: Structural lumber: Log	Structural lumber: Dimension lumber	Factory lumber
Red oak			
F2	119	235	596
F3	55	221	462
Const.	126	237	—
Red maple			
F1	178	243	329
F2	99	226	272
F3	81	211	227

[a]Adapted from McDonald and Whipple (1992) and McDonald et al. (1993).
[b]MBF, thousand board feet.

to assume that lumber that did not make No. 3 grade had no value. Even for firewood, dry red oak Economy lumber would have some value. An alternative approach would be to evaluate the lumber based only on the volume of the dimension lumber produced, knowing that some market would have to be found for the material that did not make No. 3 lumber grade. On that basis, the value of the F2 red oak logs is $235 per MBF (column 3 of Table 4.4).

The value of the logs for factory lumber could only be approximated. The expected volume of Factory grades was obtained from percentage yield tables (Vaughn et al. 1966, Hanks et al. 1980) and published market prices (Table 4.3). Note that the volume of No. 3 or Better dimension lumber available from a log was often much less than half the log volume. Thus, there are sometimes big differences in volumes of dimension and Factory grades given in Table 4.3. On this basis, the value of F2 grade logs from red oak for Factory lumber was estimated as $596 per MBF (Table 4.4). In the original publications (McDonald and Whipple 1992, McDonald et al. 1993), the value of logs for production of dimension lumber never came close to the value for factory lumber ($596 per MBF for F2 red oak factory lumber compared with $199 for dimension lumber). Assuming the value of dimension lumber is based on volume of dimension lumber produced, the value of red oak dimension is still not comparable to the value of oak factory lumber ($235 per MBF for dimension compared with $596 per MBF for factory in Table 4.4). At the time, however, red maple was worth a lot less than oak for factory lumber. Looking at the value of red maple based on the volume of dimension lumber ($243 for log grade F1, Table 4.4) compared with the value as factory lumber ($329 for log grade F1) makes using the maple logs to produce dimension lumber more competitive. In fact, for a grade F3

Table 4.5—Yield of green 2 by 6 pieces from heart-centered cants[a]

		Lumber yield (%)				
Species	Source[b]	Select Structural	No. 1	No. 2	No.3	Econ.
Beech	Mill run	8	2	14	41	35
	Switch ties	10	5	31	36	18
Hickory	Mill run	23	2	16	25	34
	Switch ties	25	10	43	17	5
Yellow-poplar	Mill run	10	5	32	26	27
	Switch ties	42	22	25	9	2
Red maple	Mill run	3	4	15	28	50
	Switch ties	16	8	32	33	11
Red oak	Mill run	3	4	15	28	50
	Switch ties	16	8	32	33	11
White oak	Mill run	13	5	25	38	19
	Switch ties	10	5	42	24	19

[a]From table 5 of McDonald et al. (1996).
[b]Mill run pieces were ungraded. Switch ties were graded by species and specified as "sound square edge."

red maple log, the value of the log for factory lumber was only about 8% higher than it was for producing dimension lumber, and the value of the lumber that did not make No. 3 lumber grade is not included. Still, these data assume the best (highest value) wood—wood from the outside of the hardwood log—is going into the production of dimension lumber. McDonald and Whipple (1992) and McDonald et al. (1993) postulated that it might be better to cut clear 1-in.-thick boards from the outside of the log and cut dimension lumber only from the center portion of the log.

Following up on their earlier hypothesis, McDonald et al. (1996) evaluated the potential for producing structural lumber from log heart cants, including graded switch ties and mill run (ungraded) pallet cants. This option could be attractive to mills already producing products from log heart cants. The option of cutting structural lumber from heart-centered cants might also be attractive to mills that remove higher quality wood from the outside portion of the log for sale as appearance grade lumber and then use the lower quality inner portion for structural products. A survey of manufacturers in West Virginia found that a range of lumber sizes could be produced from cants in lumber widths up to 9 in. (229 mm) without incurring a premium price for the cants. The survey also found that a common practice for grading cants was for the buyer to specify species and stipulate only that the cants be "Sound Square Edge" (Railway Tie Association 2015). This specification was used for the "graded" switch ties tested in this study. Freshly sawn and graded 7- by 9-in. (178- by 229-mm) switch ties were ripped into nominal 2- by 7-in. (51- by 178-mm) pieces of dimension lumber. This process generally yielded four boards per tie. The mill run 6- by 8-in. (152- by 203-mm) cants were sawn from logs available at the mill log yard. Four boards were also sawn from each mill run cant.

The lumber from all cants was graded by certified agency graders as Structural Joist and Plank. The results clearly show that the quality of the cants makes a difference (Table 4.5). As would be expected, lumber yield from graded switch ties was higher than that from mill run cants. For all species sampled, yields from graded switch ties of No. 3 or Better lumber exceeded 80%. The biggest difference in the yield of No. 3 or Better lumber between graded and ungraded cants was with red maple (39% lower yield with mill run cants than with graded switch ties), whereas with the oaks there was little difference. Except for the oaks, the graded cants produced more Select Structural and No. 1 grades of lumber, whereas the grade yield from the ungraded cants shifted to the lower grades.

Properties

Currently nine hardwood species, or species groups, have allowable design strengths for dimension lumber listed in the National Design Specification (NDS) for Wood Construction (AF&PA 2015). The properties of these species are derived by the "clear wood" procedures of ASTM D2555/D245 (ASTM 2015, chapter 7 of FPL 2010). As with softwood species, most hardwoods are marketed in a grouping of species. With many of these hardwood groupings, it is difficult or impossible to visually identify individual species after the logs have been processed into lumber. For these species groups, allowable properties of the group are controlled by the weakest species in the grouping.

Table 4.6—Mean property values for green, clear wood[a]

Grouping and species	Modulus of elasticity ($\times 10^6$ lb/in^2)	Modulus of rupture ($\times 10^3$ lb/in^2)
Red oak		
Black oak	1.182	8.820
Cherry bark oak	1.790	10.850
Laurel oak	1.393	7.940
Northern red oak	1.353	8.300
Pin oak	1.318	8.330
Scarlet oak	1.476	10.420
Southern red oak	1.141[b]	3.923[b]
Water oak	1.552	8.910
Willow oak	1.286	7.400
Mixed maple		
Black maple	1.328	7.920
Sugar maple	1.546	9.420
Red maple	1.386	7.690
Silver maple	0.943[b]	5.820[b]

[a]From ASTM D2555.
[b]Species whose properties control the assignment of allowable properties for the group.

For example, as shown in Table 4.6, the properties of Mixed Maple are controlled by the properties of silver maple. Although this procedure may have validity from marketing and technical perspectives, it may make for inefficient resource utilization.

Recent studies of hardwood properties for visually graded lumber have generally been limited to 2 by 4’s and 2 by 6’s. These studies have shown that hardwoods have excellent strength and stiffness values. Properties determined from lumber tests often exceed those assigned by the clear wood procedure (Table 4.7). For individual species, establishment of properties by the full-size testing procedures of ASTM D1990 (ASTM 2015) might improve hardwood property assignments. However, the inability to identify many individual species in a species grouping would still limit property assignment and lead to inefficient utilization. For most species groupings, more precise property assignments can be achieved only through mechanical grading.

Mechanically Graded Dimension Lumber

Mechanically graded lumber is 2-in.-thick structural lumber evaluated nondestructively by a machine, followed by visual assessment of certain growth characteristics that the machine cannot or may not properly evaluate (FPL 2010, Smulski 1997, Galligan and McDonald 2000). The use of two types of sorting criteria allows more precise sorting of lumber for specific applications in engineered structures such as metal-plate-connected wood trusses and wood I-joists. Mechanical grading of 2-in.-thick dimension lumber has been conducted commercially for softwood species in the United States since the 1960s. In 1993, research studies evaluated the relationship between bending strength and tensile strength parallel to the grain and between bending strength and compression strength parallel to the grain for red oak, red maple, and yellow-poplar dimension lumber (Green and McDonald 1993a,b). This research showed that the relationships between lumber strength properties for domestic hardwood species were the same as those used to assign properties to mechanically graded softwood species (ASTM D6570) (ASTM 2015). This research removed remaining technical barriers to the mechanical grading of hardwood structural lumber. (Note, however, that interlocked grain, common in such domestic hardwoods as black gum, sweetgum, cottonwood, sycamore, and tupelo, remains a technical issue. Research on tropical hardwoods has shown that interlocked grain does not alter the relationship between bending strength (modulus of rupture, MOR) and tensile strength parallel to the grain (UTS) but does alter the relationship between MOR and compression strength parallel to the grain (UCS) (Green and Rosales 1996). Some property relationships would have to be justified before machine stress rated (MSR) lumber could be produced with species that generally have interlocked grain.)

In late 1993, the concept of mechanically grading hardwood was put to the test. With the cooperation of the Northeastern

Table 4.7—Comparison of allowable properties assigned to visually graded hardwood lumber to test results on structural lumber

Species and size	Grade[a]	Experimental/allowable Modulus of elasticity	Modulus of rupture	Source
Red maple				
2 by 4	SS	1.07	0.89[b]	Green and McDonald (1993b)
	No. 2	1.14	1.45	
	No. 3	1.27	2.16	
Mixed maple				
2 by 6	SS	1.44	1.72	Unpublished data of D.W. Green, M.P. Wolcott, and D.C. Hassler
	No. 1	1.55	1.83	
	No. 2	1.53	1.75	
	No. 3	1.68	1.47	
Red oak				
2 by 4	SS	1.22[b]	1.54[c]	Green and McDonald (1993a)
	No. 2	1.16	1.17	
	No. 3	1.22	1.74	
2 by 6	SS	1.42	2.27	Unpublished data of D.W. Green, M.P. Wolcott, and D.C. Hassler
	No. 1	1.37	1.89	
	No. 2	1.45	1.67	
	No. 3	1.53	2.31	
Yellow-poplar				
2 by 4	SS	1.03	1.67	Green and Evans (1987)
	No. 2	1.13	1.33	
2 by 6	SS	1.08	1.33	Unpublished data of D.W. Green, M.P. Wolcott, and D.C. Hassler
	No. 1	1.16	1.56	
	No. 2	1.22	1.11	
	No. 3	1.19	1.33	
Beech				
2 by 6	SS	1.04	1.26	Unpublished data of D.W. Green, M.P. Wolcott, and D.C. Hassler
	No. 1	1.12	1.34	
	No. 2	1.12	1.31	
	No. 3	1.25	1.67	
Hickory				
2 by 6	SS	1.51	1.99	Unpublished data of D.W. Green, M.P. Wolcott, and D.C. Hassler
	No. 1	1.45	1.82	
	No. 2	1.52	1.92	
	No. 3	1.63	3.37	

[a]SS, Select Structural.
[b]Only 46 pieces available.
[c]Only 40 pieces available.

Table 4.8—Results of machine stress rated (MSR) certification of oak 2 by 8's[a]

		Allowable property	
Grade	Yield (%)	Bending strength (×lb/in^2)	Modulus of elasticity (×10^6 lb/in^2)
Visual			
Select Structural	1	1,350	1.4
No. 1	3	990	1.3
No. 2	33	960	1.2
No. 3	63	540	1.2
MSR			
1650f-1.4E	36	1,650	1.4

[a]From Green et al. (1994).

Lumber Manufacturers' Association, the SPIB, the Forest Products Laboratory, and Burke–Parsons–Bowlby Corp. (Spencer, West Virginia), 803 pieces of mixed oak 2 by 8 lumber was graded to meet the MSR lumber requirements for 1650f-1.4E4 (Green et al. 1994). (Grade names for MSR lumber are given in terms of the allowable bending strength (F_b) and allowable modulus of elasticity (MOE, or E) of the grade. Thus 1650f-1.5E MSR lumber has an F_b value of 1,650 lb/in^2 and an average MOE value of 1.5×10^6 lb/in^2.) The procedures followed were the same as those used by SPIB to grade southern pine MSR lumber. Results of this certification showed that although only 1% of the lumber qualified as Select Structural by visual grading, 36% of it could be assigned an MSR grade with properties equal to or greater than those of Select Structural (Table 4.8). Thus, in this instance, the MSR process was able to produce lumber with the properties of Select Structural grade lumber but with a yield similar to that of No. 2 and Better visual grade. The oak MSR lumber was subsequently used in a timber bridge in Jackson County, West Virginia (Fig. 4.1). It has subsequently been shown that a similar MSR process is applicable to oak 7 by 9 structural timbers (Kretschmann and Green 1999).

The relationship between MOR, also called bending strength, and MOE is used in the assignment of MSR grades. This is done by establishing a lower tolerance limit on the MOE–MOR relationship and using the MOE of the grade to determine allowable MOR of the lumber (Fig. 4.2). Several studies evaluated the relationship between MOE and MOR of hardwood lumber (Table 4.9). Two observations may be noted about these results. First, the coefficient of determination on the regression relationship is generally lower for hardwoods than it is for softwoods. This lower coefficient of determination would result in the tolerance limit being further from the mean trend line for hardwoods than it is for softwood (Fig. 4.2). Second, for lumber of equal width, the slope of the MOE–MOR relationship is generally steeper for hardwoods than for softwoods

Figure 4.1—Stress-laminated box section timber bridge located in Jackson County, West Virginia, containing 1650f-1.4E machine stress rated oak decking.

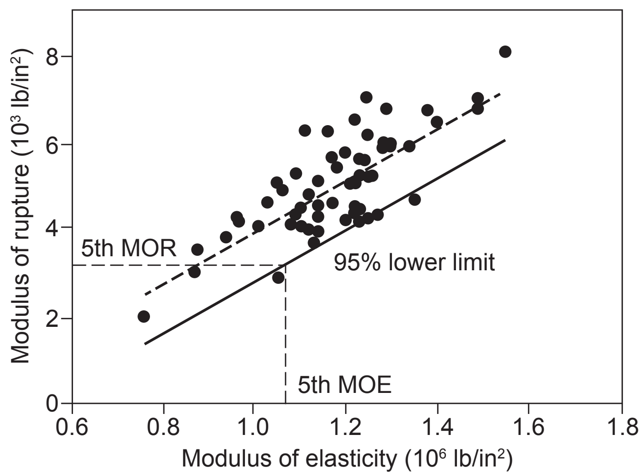


Figure 4.2—Conceptual relationship between 5th percentile modulus of elasticity (MOE) and modulus of rupture (MOR) for establishing grades for machine stress rated lumber.

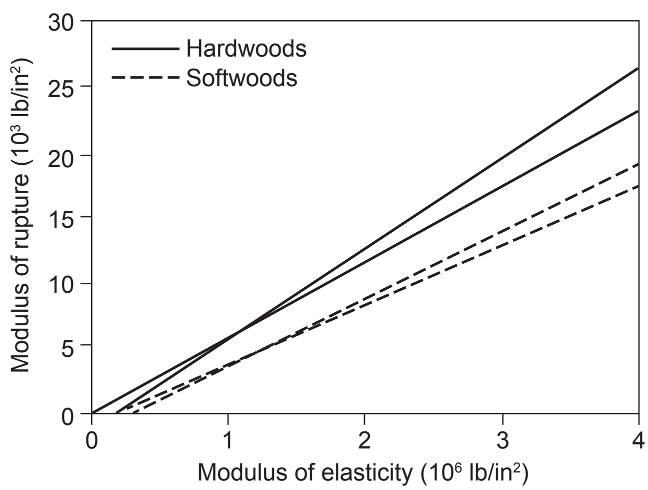


Figure 4.3—Relationship between modulus of rupture (MOR) and modulus of elasticity (MOE) for dry hardwood and softwood 2 by 4's.

Table 4.9—Relationship between MOE and MOR for hardwood and softwood lumber at 12% moisture content

Species	Size	Sample size	MOR = *A* + *B*(MOE) Slope (*B*)	Coefficient of determination (r^2)	Source
Hardwoods					
Red oak	2 by 4	215	7.009	0.46	a
	2 by 6	229	6.568	0.39	b
Red maple	2 by 4	260	5.840	0.31	c
Mixed maple	2 by 6	220	7.602	0.42	b
Yellow-poplar	2 by 4	126	4.763	0.25	d
	2 by 6	230	7.112	0.22	b
Beech	2 by 6	445	6.248	0.30	b
Hickory	2 by 6	464	5.533	0.33	b
Hybrid poplar	2 by 4	243	5.044	0.42	e
Softwoods					
Southern pine	2 by 4	2,161	4.490	0.52	d
Douglas-fir	2 by 4	2,781	4.593	0.56	d
Hem-Fir	2 by 4	903	5.166	0.53	d

[a]Green and McDonald (1993a).
[b]Unpublished study by D.W. Green, M.P. Wolcott, and D.C. Hassler.
[c]Green and McDonald (1993b).
[d]Green and Evans (1987), extracted from data summarized in report.
[e]Kretschmann et at. (1999).

Table 4.10—Allowable properties and grade yield of visually graded hardwood 2 by 6s cut from graded heart-centered cants compared with those estimated for machine stress rated (MSR) lumber[a]

Species or grouping	Visual graded as No. 2 and Btr. Modulus of elasticity ($\times 10^6$ lb/in^2)	F_b ($\times 10^3$ lb/in^2)	Grade yield (%)	MSR Modulus of elasticity ($\times 10^6$ lb/in^2)	F_b ($\times 10^3$ lb/in^2)	Grade yield (%)
Beech	1.5	1.300	55	1.5	1.650	73
Hickory	1.5	1.300	71	1.5	1.650	99
Mixed maple	1.5	1.180	72	1.5	1.650	90
Red oak	1.2	1.040	77	1.2	1.200	99
Yellow-poplar	1.3	0.910	83	1.3	1.450	94

[a]From unpublished study by D.W. Green, M.P. Wolcott, and D.C. Hassler.

(Fig. 4.3). This generally higher slope helps compensate for the lower tolerance limit. Our experience suggests that hardwood MSR lumber can make the same MOR limit for a given MOE value as softwood lumber (Green et al. 1994). Additional information on MOE–MOR relationships for yellow-poplar and sweetgum is presented in Faust et al. (1990). Coefficients of determination for both species are reported at 0.49; unfortunately, the data for 2 by 4's and 2 by 8's are combined in their analysis, and thus the correlation is not compatible with the data presented in Table 4.9.

For the engineer, the advantage of MSR lumber is a more precise assignment of allowable properties. However, for the producer, the advantage is the possibility of achieving higher grade yield for a specified set of allowable properties. As shown in Table 4.8 for mixed oak 2 by 8's, the yield of an MSR grade having an MOE of 1.4×10^6 lb/in^2 was only 1% for Select Structural visual grade but was 36% when mechanically graded. An unpublished study (D.W. Green, M.P. Wolcott, and D.C. Hassler) on grading and properties of Appalachian hardwoods from log heart cants showed that for 2 by 6 lumber of several hardwood species where the lumber was cut from graded cants, the yield of MSR lumber runs 10% to 20% higher than the visual grade having an equivalent MOE value (Table 4.10). Although the latter study was a computer simulation of MSR yield, the former study on oak 2 by 8's was from actual production. Thus, research to date indicates the possibility of achieving higher yields for a specified set of allowable properties using the MSR process. The challenge for the producer would be to find a market for this material that would pay for the increased cost of mechanical grading.

Because MOE is one of the critical criteria for assigning an MSR grade, the producer of MSR lumber must better control moisture content (MC) of the lumber than might be required for visually graded structural lumber. An unpublished study (D.W. Green, R.J. Ross, J.W. Forsman, and J. Erickson) that examined mechanical grading options for structural lumber cut from hard maple estimated that the yield of 2100f-2.0E hard maple MSR was reduced from 88% at an average MC of 13% to 28% at an average MC of 23%. However, the good relationship between MOE and MC (Green and Evans 1989) presented an opportunity to identify the lumber that was suitable for production of a high MSR grade based on its green MOE value and visual inspection of growth characteristics. Only those pieces needed to be dried to a lower MC level. The rest of the lumber could be dried to a higher MC level and sold for uses that did not require such high allowable property assignments.

Discussion

Hardwood mills will find that factory lumber and structural lumber differ in many ways. (Much of this discussion is excerpted from McDonald and Whipple (1992). Valuable additional information on the differences in factory lumber and structural lumber is available in this publication.) For example, thicknesses for factory lumber are rough sawn by quarter-inch classes from 4/4 up to nominal 16/4; structural dimension lumber is usually nominal 2 in. (standard 51 mm) or actual 1.5 in. (38 mm) thickness after drying and planing. Widths are random for factory lumber and vary in 2-in. increments for dimension lumber. Defect limitations allowed on graded products are also much different. More wane and edge knots are accepted in factory lumber than in dimension lumber. Such differences reflect the end use of the grades, and they can produce significant problems to a mill trying to produce both types of products. These problems are further aggravated by different target sizes for green thicknesses and widths. Therefore, getting a stress-graded product on the market involves more than simply providing the means to grade the product. Hardwood logs would need to be sawn like softwood logs to produce a product similar to softwood structural lumber. The simple solution of having one mill saw stress-graded structural lumber is not a likely solution for most hardwood species because of the relatively higher value of factory lumber compared with structural lumber and the efficiency of getting both products from the same logs. The logical solution to the problem is that a portion of the log should be sawn into factory lumber and a portion into dimension lumber.

Results of the studies discussed strongly indicate that success in producing structural lumber will require some sort of sorting scheme. For logs, sorting the logs into groups of those most suitable for production of structural lumber and those most suitable for other (generally higher value) products looks to be essential. The grade of the log was found to have a pronounced effect on grade yield for most species. Not only did higher quality logs produce a higher total yield of structural lumber, but also they tended to produce a better yield in the higher lumber grades. The production of lumber from heart-centered cants seemed particularly attractive for those already purchasing or producing cants, especially if there is a good market for factory lumber for the better quality wood from the outer portions of the log. Results suggest that producing lumber from cants will also require some sort of grading scheme, similar to the grading scheme discussed briefly for railroad ties. In addition, from a mill manager's point of view, the decision to cut structural lumber will involve examining the economic tradeoff between selling cants outright, cutting them into appearance-grade lumber, or cutting them into nominal 2-in.-thick material. For the latter option, the best market will be for lumber that will make No. 2 visual grade or Better.

As in the production of any lumber product, and especially for anyone interested in producing structural lumber from hardwoods, understanding your markets is critical. Because 2-in.-thick hardwood structural lumber is not currently a generally accepted product, it would be best to establish a relationship with specific buyers prior to beginning production. Those considering the production of both mechanically graded and visually graded structural lumber must pay particular attention to the requirements of their buyers.

Another critical factor is kiln-drying. For most structural applications, lumber must be dried to an average MC of either 12% or 15%. The typical drying schedule for structural lumber such as southern pine is 1 to 2 days, as opposed to 40 to 90 days for 7/4 oak. The effect of drying degrade on the assignment of structural grades is less restrictive than for most traditional uses of hardwood species, thus drying schedules can generally be accelerated. Recommendations on the drying of hardwood lumber for structural use is discussed in the next chapter.

Literature Cited

AF&PA. 2015. National design specification (NDS) for wood construction. Washington, DC: American Forest & Paper Association.

ASTM. 2015. Annual book of ASTM standards. Volume 04.10, Wood. West Conshohocken, PA: American Society for Testing and Materials.

D6570-04. Standard practice for assigning allowable properties for mechanically-graded lumber.

D2555-06. Standard practice methods for establishing clear wood strength values.

D245-06. Standard practice for establishing structural grades and related allowable properties for visually graded lumber.

D1990-14. Standard practice for establishing allowable properties for visually graded dimension lumber from in-grade tests of full size specimens.

Carpenter, R.D.; Sonderman, D.L.; Rast, E.R.: Jones, M.J. 1989. Defects in hardwood timber. USDA Agricultural Handbook AH-678. Washington, DC: U.S. Department of Agriculture. 88 p.

DeBonis, A.L.; Bendtsen, B.A. 1988. Design stresses for hardwood structural grades create new opportunities. In: Executive summaries from the 43rd annual meeting of the Forest Products Society. Madison, WI: Forest Products Society. pp. 48-50.

Erickson, R.W.: Peterson, H.D.; Larson, T.D.; Maeglin, R. 1986. Producing studs from paper birch by saw-dry-rip. Research Paper FPL–RP–480. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Faust, T.D. 1990. Grade distribution and drying degrade of sweetgum and yellow poplar structural lumber. Forest Products Journal. 40(5): 18–20.

Faust, T.D.; McAlister, R.H.; Zarnoch, S.J. 1990. Strength and stiffness properties of sweetgum and yellow poplar structural lumber. Forest Products Journal. 40(10): 58–64.

FPL. 2010. Wood handbook—wood as an engineering material. General Technical Report FPL–GTR–190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Galligan, W.L.; McDonald, K.A. 2000. Machine grading of lumber: practical concerns for lumber producers. General Technical Report FPL–GTR–7. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Gerhards, C.C. 1983. Effect of high-temperature drying on bending strength of yellow poplar 2x4's. Forest Products Journal. 33(2): 61–67.

Green, D.W.; Evans, J.W. 1987. Mechanical properties of visually graded lumber: Volume I, a summary. Publication 88-159-389. Springfield, VA: Department of Commerce, National Technical Information Service. 131 p.

Green, D.W.; Evans, J.W. 1989. Moisture content and the mechanical properties of dimension lumber: decisions for the future. In: Proceedings of the workshop on in grade testing of structural lumber. Proc. 47363. Madison, WI: Forest Products Research Society. pp. 44–55.

Green, D.W.; Evans, J.W. 2001. Evolution of standardized procedures for adjusting lumber properties for change in moisture content. General Technical Report FPL–GTR–127. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Green, D.W.; McDonald, KA. 1993a. Investigation of the mechanical properties of red oak 2 by 4's. Wood and Fiber Science. 25(1): 35–45.

Green, D.W.; McDonald, K.A. 1993b. Mechanical properties of red maple structural lumber. Wood and Fiber Science. 25(4): 365–374.

Green, D.W.; Hernandez, R. 2000. Codes and standards for structural wood products and their use in the United States. In: North America Forestry Commission. Proceedings of the forest products study group workshop. Madison, WI: Forest Products Society. pp. 3–16.

Green, D.W.; Rosales, A. 1996. Property relationships for tropical hardwoods. In: Gupu, V.K.A., ed. Proceedings of the International Wood Engineering Conference. Baton Rouge, LA: Louisiana State University. Vol. 3: 516–521.

Green, D.W.; Ross, R.J.; McDonald, K.A. 1994. Production of hardwood machine stress rated lumber. In: Proceedings of the 9th international symposium on nondestructive testing. Madison, WI: Forest Products Society. pp. 141–150.

Hanks, L.F.; Gammon, G.L.; Brisbin, R.L.; Rast, E.D. 1980. Hardwood log grades and lumber grade yields for factory lumber logs. Research Paper NE–RP–468. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeast Forest Research Station.

Kretschmann, D.E.; Green, D.W. 1999. Mechanical grading of oak timbers. Journal of Materials in Civil Engineering. 11(2): 91–97.

Kretschmann, D.E.; Isebrands, J.G.; Stanosz, G.; Dramm, J.R.; Olstad, A.; Cole, D.; Samsel, J. 1999. Structural lumber properties of hybrid poplar. Research Paper FPL–RP–573. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Maeglin, R.R.; Boone, S. 1983. Manufacturing quality structural lumber from hardwoods using the saw-dry-rip process. In: Proceedings of the 9th annual hardwood symposium. Memphis, TN: Hardwood Research Council.

Maeglin, R.R.; Boone, S. 1985. Evaluation of mixed hardwood studs manufactured by the saw-dry-rip process. Research Note FPL–RN–0249. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

McDonald, K.A.; Whipple, J.W. 1992. Yield of 2 by 4 red oak stress-graded dimension lumber from factory-grade logs. Forest Products Journal. 42(6): 5–10.

McDonald, K.A.; Green, D.W.; Dwyer, J.; Whipple, J.W. 1993. Red maple stress-graded 2 by 4 dimension lumber from factory-grade logs. Forest Products Journal. 43(11/12): 13–18.

McDonald, K.A.; Haler, C.C.; Hawkins, J.E.; Timothy, L.P. 1996. Hardwood structural lumber from log heart cants. Forest Products Journal. 46(6): 55–62.

Moody, R.C.; Hernandez, R.; Davalos, J.E.; Sonti, S.S. 1993. Yellow poplar glulam timber beam performance. Research Paper FPL–RP–520. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

NIST. 2015. American softwood lumber standard. Voluntary product standard PS-20. Gaithersburg, MD: U.S. Dept. of Commerce, National Institute of Standards and Technology.

NeLMA. 2013. Standard grading rules for northeast species. Cumberland Center, ME: Northeast Lumber Manufacturers' Association.

Railway Tie Association. 2015. Specifications for timber crossties. Fayetteville, GA: Railway Tie Association.

Rast, E.D.; Sondermann, D.L.; Gammon, G.L. 1973. A guide to hardwood log grading. General Technical Report NE-1 (rev.). Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 32 p.

Simpson, W.T.; Forsman, J.W.; Ross, R.J. 1998. Kiln-drying maple structural lumber from log-heart cants. Forest Products Journal. 48(6): 70-76.

Smulski, S. 1997. Machine-graded lumber. Wood Design Focus. 8(2):1-24.

Vaughn, C.L.; Wollin, A.C.; McDonald, K.A.; Bulgrin, E.H. 1966. Hardwood log grades for standard lumber. Research Paper FPL–RP–63. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Chapter 5

Drying and Heat Sterilization of Hardwood Lumber for Structural Uses

Xiping Wang, Research Forest Products Technologist
William T. Simpson, Research Forest Products Technologist (retired)
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

Traditional hardwood lumber drying processes were developed for appearance-type products such as furniture, cabinetry, and millwork (FPL 1991). This means that air-drying practices were managed to minimize chemical and fungal stains, which occur in white woods such as maple, and surface checking, which is common in some species. It also means that the kiln schedules that were developed are conservative, slow, and designed to virtually eliminate even minor drying defects, such as small surface checks or discolorations. In structural products, surface checks and discoloration do not detract from utility, and they are not considered defects in softwood structural lumber grading rules. Therefore, for hardwood structural lumber, air-drying and pre-drying practices can be relaxed and kiln schedules can be more severe, faster, and more efficient than traditional hardwood schedules.

Additional factors that will shorten kiln-drying times compared with traditional hardwood schedules are higher final moisture content (MC) and wider allowable MC distribution—15% to 19% for structural products, 6% to 8% for traditional hardwood appearance products. This additional drying—from 15% to 19% MC to 6% to 8% MC—is a significant portion of total drying time and would be eliminated in lumber for structural uses. Efficient drying methods would make a positive contribution to the economics of producing structural wood products from undervalued hardwoods.

Several options are available for drying hardwood lumber for structural uses. The most basic option is the exclusive use of air drying. Exclusive use of air drying is not an option for appearance products because MC levels of 6% to 8% are not possible in areas of the country where hardwoods are a significant timber resource. However, when desired MCs are as high as 19%, air drying is possible. On the negative side, air drying can be a long process, with time requirements that may be difficult to estimate, making production planning difficult. Nevertheless, it is a drying option some producers might consider.

Another option is to combine air-drying to some level, such as 30% MC, followed by kiln-drying to final MC. The rationale for this approach is that air-drying from green to approximately 30% MC is the fastest part of drying; below 30% MC, the air-drying rate slows significantly. The drying rate for kiln-drying can be considerably increased with the higher temperatures and lower relative humidity available. Pre-dryers can also be used either exclusively or, similar to air drying, in combination with final-stage kiln-drying. Because pre-dryers are at temperatures in the 80 to 90 °F range and relative humidity in the 65% or lower range, their exclusive use results in a final MC of approximately 19%. Combining the use of pre-dryers with final-stage kiln-dryers at a MC of less than 30% works as well. Finally, it is also possible to employ kiln-drying from green MC to a final MC of 15% to 19%, although this method may not be wise economically.

Structural hardwood products can include such items as dimension lumber (as used in light-frame construction) and engineered wood products (such as I-joists, CLT). Another type of structural product already in common use and sometimes engineered is wood packing material (such as pallets). A current concern involving wood packing material is its role in transporting insects and pathogens between countries in international trade. Because of this concern, many countries require wood packing material to be heat-sterilized before it is allowed to enter. One issue in heat sterilization is the time required for the center of any of a variety of wood sizes and configurations to reach the temperature necessary to kill the insect or pathogen.

This chapter focuses on drying studies conducted at the Forest Products Laboratory and at Michigan Technological University with 2- by 6-in. sugar and red maple lumber and on heating time studies associated with heat sterilization for killing insects and pathogens.

Drying Options

Air Drying

Air drying is a viable option because it is possible, although lengthy, to air-dry to below 19% MC. It is also viable when used as a predecessor to kiln drying. One problem with air drying, either alone or as a predecessor, is difficulty in estimating the time required to reach the desired MC level, which makes production planning and inventory control difficult. Several factors influence air-drying time. Wood species and lumber thickness are important factors, but they remain constant in the case of a specific product such as nominal 2-in.-thick maple structural lumber. Two other important factors are geographical location of the air-drying operation and time of year when the lumber is stacked for air drying. In general, air drying takes longer in northern locations of the United States than in southern U.S. locations. If lumber is stacked for air drying in late summer or early fall, it is subjected to cold winter weather before it reaches the target final MC. If lumber is stacked in early spring, it will very likely be air-dried before it can be subjected to cold winter weather. Simpson and Hart (2000, 2001) developed a method for estimating air-drying times based on various influencing factors. They also presented a series of graphs showing how air-drying time depends on wood species, lumber thickness, final target MC, geographical location, and time of year the lumber is stacked. Figure 5.1 shows a series of such graphs for nominal 2- by 6-in. maple lumber air-dried in various locations in the maple growing range, from as far north as Duluth, Minnesota, to as far south as Montgomery, Alabama. Each graph shows estimated drying time according to stacking date and to several final MCs ranging from 18% to 30%.

Pre-Drying

Pre-dryers offer a way to dry lumber that is a compromise between air drying and kiln drying in terms of drying time. It offers controlled drying that avoids long air-drying times associated with rainy weather and cold winter temperatures. Pre-dryers are typically large warehouse-type structures where temperature is controlled at relatively low levels, in the 80 to 90 °F range, relative humidity is controlled, and venting and air circulation are provided. Pre-drying is typically used as a substitute for air drying, and MC is lowered to about 25% before going into a dry-kiln for final drying to 6% to 8% MC for use in traditional hardwood products. However, for structural lumber, for which the required final MC is 15% to 19%, pre-dryers could accomplish the entire drying process. Figure 5.2 shows estimated drying times (same method as Simpson and Hart (2000, 2001)) in a pre-dryer controlled at three typical temperatures (80, 85, and 90 °F) and 65% relative humidity. Drying times vary from about 24 to 38 days, depending on temperature. The important contrast here is that in northern states, air-drying time could be 200 days or more if stacking is done in late summer or fall, compared with a constant 24 to 38 days year round in a pre-dryer.

Kiln Drying

Studies have been conducted to develop kiln schedules especially designed for maple used as structural lumber (Simpson et al. 1998, Simpson and Wang 2001). These schedules are more severe than maple schedules intended for the traditional appearance-type end use and thus are faster and more efficient. Simpson et al. (1998) developed an accelerated MC-based maple schedule. The starting point in the study was the maple schedule intended for traditional appearance-type products. This schedule starts with a dry-bulb temperature of 120 °F and a wet-bulb depression of 7 °F and ends with a dry-bulb temperature of 180 °F and a wet-bulb depression of 50 °F. In the study, the starting dry-bulb temperature was increased in increments of 10 °F up to 160 °F, while keeping the same final dry-bulb temperature of 180 °F. The result was that even the most severe schedule that started with a dry-bulb temperature of 160 °F caused no more structural grade loss than did the mildest schedule that started with a dry-bulb temperature of 120 °F. About 12% of maple 2 by 6's lost grade because of warp or end splits. Drying time from 60% to 15% MC with the severe schedule that started at 160 °F was about five days.

In the MC-based kiln schedule just described, kiln conditions are changed when the lumber reaches various MCs during drying. This requires some method of estimating MC. Because of the lower quality requirements of structural lumber compared to appearance grade lumber, traditional kiln schedules for softwood structural lumber are usually based on time. In these time-based schedules, changes in kiln conditions are made at predetermined time intervals rather than at predetermined MC levels. Thus, periodic estimates of MC during kiln drying are not necessary. Time-based schedules are therefore more efficient than MC-based schedules. Using drying rate data from the study on the MC-based schedule, a time-based schedule was developed to dry maple 2 by 6's in approximately 5 days (Simpson and Wang 2001), and that schedule is shown in Figure 5.3. An equalizing period following the kiln drying is advisable.

Figure 5.4 shows comparative estimated drying times to 15% MC for kiln-drying alone, pre-drying alone, and combined pre-drying (to 30% MC) and kiln-drying. Kiln-drying alone is estimated to take 5 days, pre-drying to 30% MC followed by kiln-drying about 17 days, and pre-drying alone about 30 days.

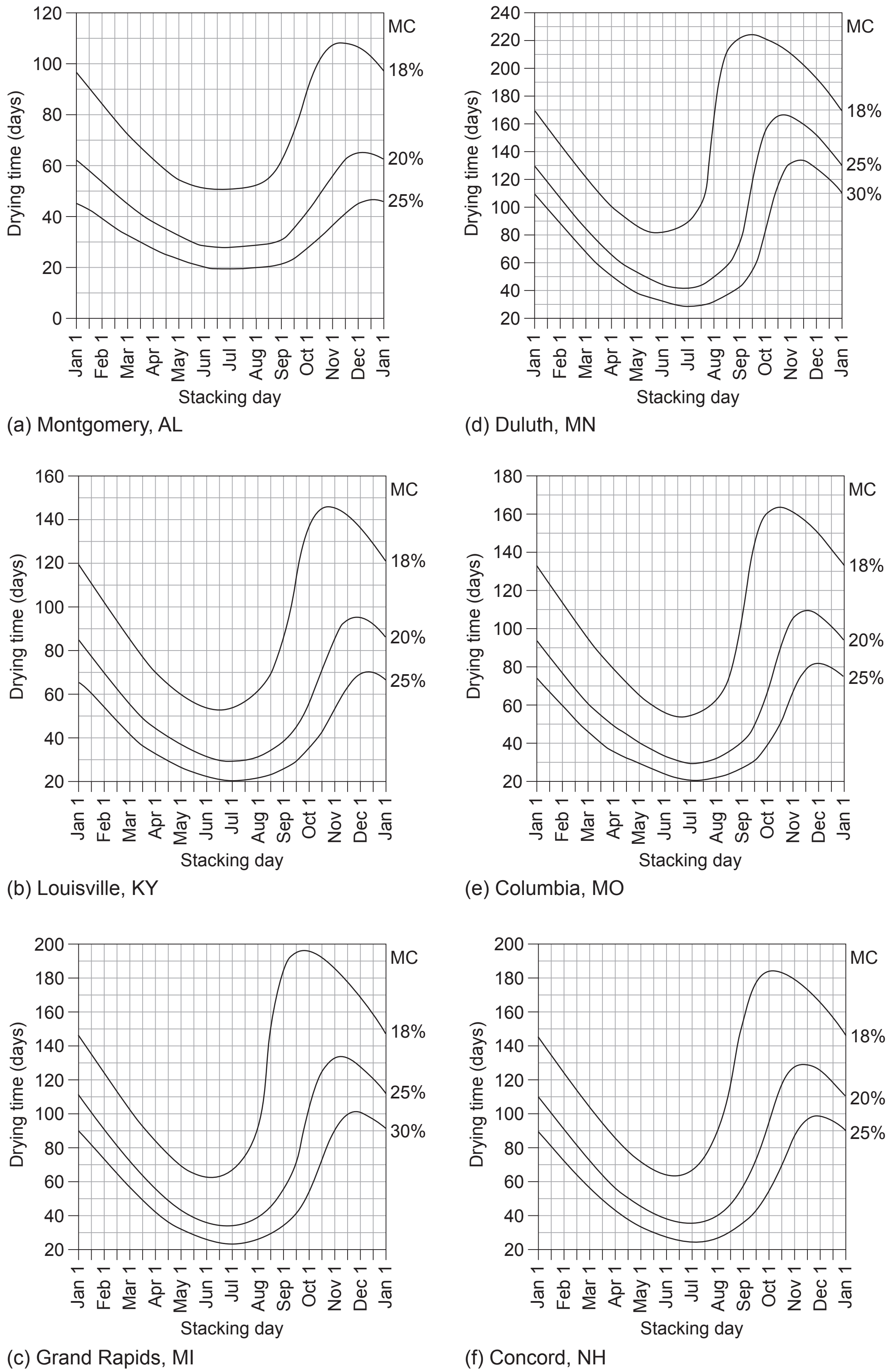
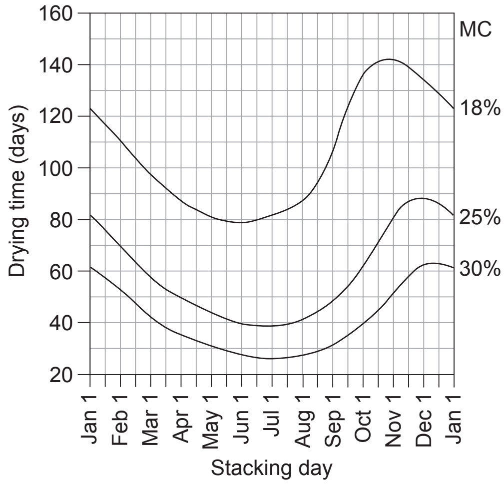
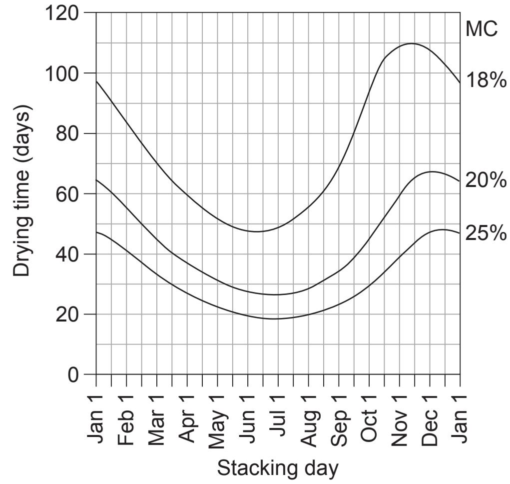


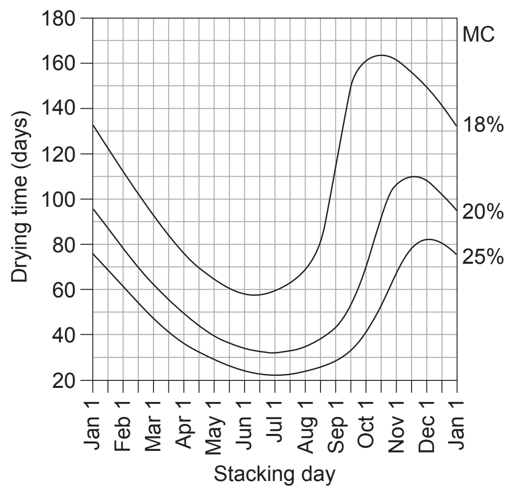
Figure 5.1—Estimated air-drying times for nominal 2- by 6-in. maple lumber as they depend on geographical location, stacking date, and final moisture content (Simpson and Hart 2000, 2001).



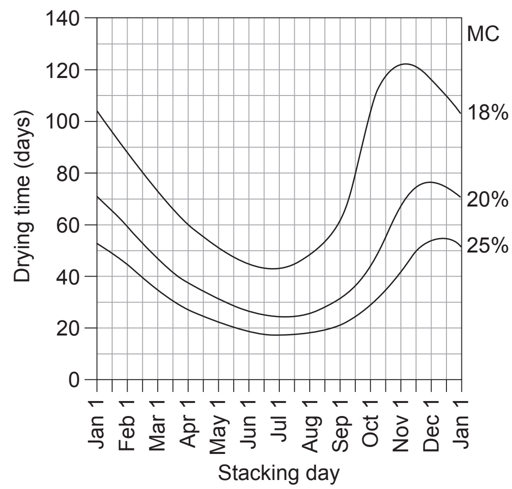
(g) Asheville, NC



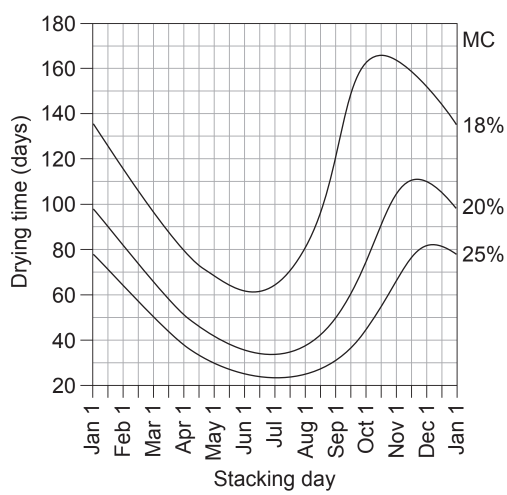
(j) Columbia, SC



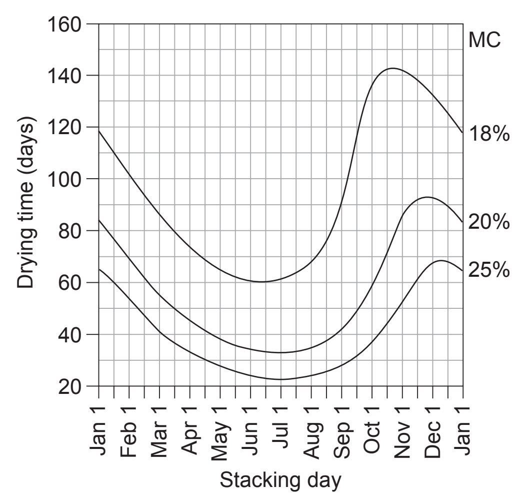
(h) Columbus, OH



(k) Memphis, TN



(i) Williamsport, PA



(j) Charleston, WV

Figure 5.1—Estimated air-drying times for nominal 2- by 6-in. maple lumber as they depend on geographical location, stacking date, and final moisture content (Simpson and Hart 2000, 2001). (con.)

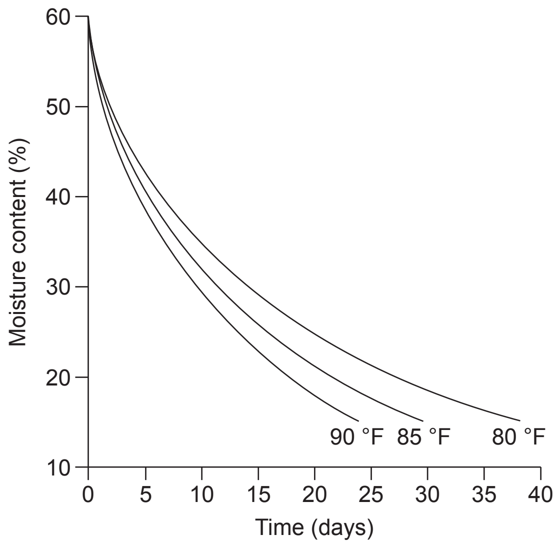


Figure 5.2—Moisture content as a function of time for 2- by 6-in. maple lumber in a pre-dryer at three temperature levels (80, 85, and 90 °F) and 65% relative humidity.

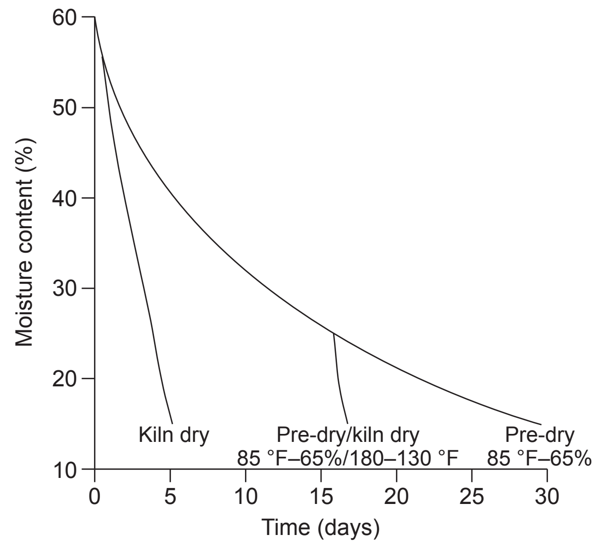


Figure 5.4—Moisture content as a function of time for 2- by 6-in. maple lumber dried in a kiln, in a pre-dryer, and sequentially in a pre-dryer and then a dry kiln.

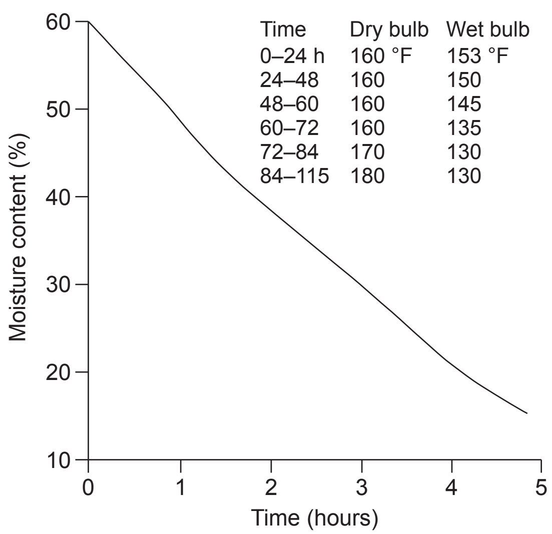


Figure 5.3—Moisture content as a function of time for 2- by 6-in. maple lumber kiln-dried by a time-based schedule (Simpson and Wang 2001).

Table 5.1—Warp limits for 8-ft-long southern pine 2 by 6's[a]

	Southern pine warp limits (in.)			
Grade	Crook	Bow	Twist	Cup
Select Structural	0.250	0.500	0.563	0.063
No. 1	0.250	0.500	0.563	0.063
No. 2	0.313	0.750	0.750	0.063
No. 3	0.500	1.000	1.125	0.125

[a]From SPIB (1994). 1 in. = 25.4 mm.

Table 5.2—Observed average warp for maple 2 by 6's dried to 19% and 12% target moisture contents[a]

Final target MC (%)	Observed maple warp (in.)			
	Crook	Bow	Twist	Cup
19	0.050	0.045	0.065	0.056
12	0.042	0.066	0.100	0.051

[a]From Simpson and Forsman (1999). 1 in. = 25.4 mm.

Warp

One possible serious defect in structural lumber is warp that develops during drying. Crook, bow, twist, and cup can interfere with the utility of a board, and grading rules for softwood structural lumber impose limits on allowable warp. Warp developments in sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), and yellow birch (*Betula alleghaniensis*) 2 by 6's were investigated by Simpson and Forsman (1999). Table 5.1 shows warp limits for southern pine Structural Light Framing 2- by 6-in., 8-ft-long lumber (SPIB 1994) as an example of warp limits that could be applied to hardwood structural lumber. Table 5.2 shows observed warp for maple 2 by 6's dried to 19% and 12% target MCs. The data indicate that serious warp did not develop in maple 2 by 6's. Table 5.3 shows the percentage of boards that meet the southern pine No. 2 grade warp limits immediately after drying and surfacing and also after equilibration. The percentages are shown according to type of warp, drying method, species, and final target MC (in the case of kiln drying). Although commercial planing equipment and methods probably differ from the laboratory capabilities, the data show that the planing operation is capable of greatly reducing downgrade from warp that occurs during drying. Surfacing out warp to meet grade requirements requires larger target dimensions for sawn lumber, which reduces yield and wastes resource. However, considering the poor use potential of this type of material, reduced yield may still be economically justifiable.

The results in Table 5.3 are somewhat varied. In all cases, the percentage of hardwood boards meeting grade warp requirements after drying and planing was high, from 97% to 100%. In many cases, the percentage was still high after equilibrating to 12% MC. The worst case was red maple equilibrated to 12% after pre-drying to 27% MC—the percentage of boards meeting grade warp requirements was only 38.6%, and no reason for this outlying result was apparent. One concern is that cup might be a problem in equilibration. For kiln-dried sugar maple, the percentage of boards that met grade warp requirements based on cup dropped into the 80% range (82.9% to 85.6%) during equilibration to 12% MC. The percentage of red maple boards pre-dried to 27% MC that met grade warp requirements after equilibration also dropped into the 80% range.

Currently, most structural lumber is kiln-dried to 15% to 19% MC. Because of post-kiln drying to ambient equilibrium moisture content (EMC) conditions of 12% MC or below and the potential danger of warp during that drying, some are suggesting that structural lumber be dried closer to these ambient EMCs (Koch 1971, Markstrom et al. 1984). The concern with this approach is that warp, and thus grade loss, during kiln drying may be increased, and kiln residence time, and thus required kiln capacity, will certainly be increased. At the other extreme, drying to final MCs higher than 19% would be desirable to reduce required kiln capacity and residence time, even though the danger of post-kiln drying warp exists. This study provides data to help make a decision on optimum final MC of hardwoods for structural purposes. However, results suggest that even though increased warp develops when final MC immediately after drying is reduced to 12%, it probably can be surfaced out in most planing operations. However, because additional warp that develops during equilibration of sugar maple kiln-dried to only 27% may not reduce grade appreciably, it may also be appropriate to rethink and further investigate the idea of increasing final MC to some level above the common 15% to 19%. However, before a higher final MC could be recommended, the effects of post-kiln drying shrinkage in terms of variable size and fastener integrity would have to be investigated.

Table 5.3—Percentage of hardwood boards that meet southern pine grade requirements for warp in No. 2 grade[a]

Experimental variables[b]	Percentage of boards			
	Crook	Bow	Twist	Cup
SM kiln-dried to 27%				
AD-AP	100	100	100	100
AE to 12%	97.3	100	100	82.9
SM kiln-dried to 19%				
AD-AP	100	100	100	100
AE to 12%	99.1	100	100	84.7
SM kiln-dried to 12%				
AD-AP	100	99.1	97.3	100
AE to 12%	98.2	100	100	85.6
SM pre-dried to 27%				
AD-AP	100	100	100	100
AE to 12%	95.1	99.0	87.3	100
SM air-dried to 27%				
AD-AP	100	100	100	100
AE to 19%	100	100	100	100
AE to 12%	86.1	100	96.0	92.1
RM pre-dried to 27%				
AD-AP	100	100	100	100
AE to 12%	38.6	100	89.1	85.1
RM air-dried to 27%				
AD-AP	100	99.0	99.0	100
AE to 19%	98.0	100	93.1	100
AE to 12%	96.0	100	94.1	100
YB pre-dried to 27%				
AD-AP	100	100	100	100
AE to 12%	88.1	100	100	100
YB air-dried to 27%				
AD-AP	100	99.0	100	100
AE to 12%	99.0	100	97.0	100

[a]From Simpson and Forsman (1999).
[b]SM, sugar maple; RM, red maple; YB, yellow birch; AD-AP, after drying, after planing; AE, after equilibration.

Heat Sterilization

Heat sterilization of lumber, timbers, and pallets is currently used to kill insects and thus prevent their transfer between countries in international trade. Current regulations for heat sterilization of these wood products require holding a center temperature of 133 °F for 30 min (FAO 2002). An important factor in heat sterilization is the additional time required for the center of any wood configuration to reach that temperature. This additional time can vary depending on several variables. Wood species, specific gravity, MC, and initial temperature are factors that have a moderate influence on heating time (Simpson et al. 2005). One of the most significant factors is wood configuration. A 4-in.-square pallet runner requires a much longer heating time than the 1- by 4-in. deck boards of the pallet. Heating medium can also have a significant effect on heating time. Heating in the water-saturated atmosphere of live steam (that is, wet heat) results in the shortest heating times. The use of dry heat can significantly extend heating time because in a dry atmosphere the wood is also drying at the same

Table 5.4—Summary of heating times (min) for six sizes of five hardwood species heated at two wet-bulb depressions (WBDs)[a]

		1	2	3	4	5	6	7	8
WBD	Species and size	Unadjusted T_{133}	Adjusted (157 °F) T_{133}	99% confidence interval	MacLean specific gravity–moisture content	Finite difference specific gravity–moisture content	MacLean wet-bulb temperature (°F)	Deviation from unadjusted (%)	99% confidence interval
	Red maple (specific gravity (SG) = 0.531; MC = 65%)								
	1.0	13.2	13.5	12.5–14.5	11.8	13.4	12.9	−2.3	12.1–14.4*
0 °F	1.5	29.3	28.8	27.2–30.5	27.5	29.4	29.1	−0.7	27.1–30.8*
	2.0	49.1	49.6	46.9–52.3	46.8	49.6	49.4	−0.6	46.0–52.1*
	3×3	53.9	59.4	54.9–63.9	56.5	59.6	59.0	9.5	49.9–57.9
	4×4	108.1	114.6	110.1–119.2	103.0	107.0	107.6	−0.5	104.5–111.7*
	6×6	254.9	264.6	246.0–283.3	237.3	245.5	247.1	−3.1	237.1–272.6*
10 °F	1.0	16.7	16.5	15.4–17.6	12.3	17.1	18.3	9.6	15.3–18.2
	1.5	36.9	36.3	34.4–38.2	27.5	34.8	35.8	−3.0	34.9–38.8*
	2.0	58.4	58.8	55.7–62.0	46.8	57.2	58.3	−0.2	54.8–61.9*
	3×3	84.5	85.3	74.7–95.9	60.4	85.6	72.8	−13.8	72.8–96.3*
	4×4	133.7	136.7	130.2–143.1	106.1	122.5	126.6	−5.3	126.8–140.6
	6×6	294.4	294.4	284.7–304.1	245.4	280.7	294.1	−0.1	283.3–305.4*
	Sugar maple (SG = 0.582; MC = 50%)								
	1.0	12.2	12.9	11.8–13.9	11.7	13.4	12.3	0.8	11.3–13.0*
0 °F	1.5	27.1	28.0	26.4–29.6	26.7	28.6	27.6	1.8	26.0–28.3*
	2.0	45.2	47.7	44.1–48.6	46.0	48.1	47.3	4.6	41.1–49.2*
	3×3	55.5	57.8	54.1–61.4	60.9	63.2	62.3	12.3	50.7–60.4
	4×4	103.9	107.4	101.7–113.1	108.9	110.6	111.4	7.2	97.0–110.8
	6×6	250.2	255.0	233.1–276.9	248.4	250.8	254.2	1.6	226.6–273.8*
10 °F	1.0	13.9	13.8	13.1–14.6	12.3	15.3	15.7	12.9	12.6–15.1*
	1.5	32.8	31.1	28.6–33.6	29.5	35.7	35.4	7.9	30.6–34.9
	2.0	55.1	52.6	49.3– 55.9	50.9	61.0	60.6	10.0	50.5–59.8
	3×3	64.0	62.7	58.4–67.0	64.4	74.9	75.8	18.4	59.9–68.2
	4×4	124.4	120.7	114.2–127.2	115.9	133.1	135.6	9.0	116.7–132.1
	6×6	295.0	283.6	267 9–299.2	263.7	295.6	308.9	4.7	279.3–310.7*
	Red oak (SG = 0.551; MC = 75%)								
	1.0	13.9	14.0	13.3–14.7	11.8	13.7	12.7	−8.6	12.8–15.0
0 °F	1.5	27.5	26.3	24.9–27 7	26.4	28.8	27.8	1.1	26.1–29.0*
	2.0	49.4	49.2	45.4–52.9	46.7	50.6	48.6	−1.6	44.9–53.9*
	3×3	56.0	56.9	53.4–60.4	60.7	63.2	62.6	11.8	52.9–59.1
	4×4	106.4	108.8	105.9–111.7	106.3	110.4	109.9	3.3	100.2–112.5*
	6×6	256.6	251.9	244.7–259.0	249.7	256.6	258.5	0.7	246.4–266.7*
10 °F	1.0	14.5	15.2	14 .0–16.3	11.1	14.2	14.3	−1.4	12.6–16.4*
	1.5	31.6	31.7	30.1–33.3	26.3	32.5	32.1	1.6	27.7–35.4*
	2.0	56.0	56.3	53.5–59.1	46.1	56.0	55.2	−1.4	51.7–60.3*
	3×3	66.7	65.5	62.0–69.0	61.8	72.5	72.8	9.1	63.0–70.3
	4×4	126.0	124.0	118.5–129.4	109.7	127.0	128.3	1.8	117.8–134.3*
	6×6	294.7	283.6	269.6–297.6	253.5	288.6	296.9	0.7	274.5–314.9*
	Basswood (SG = 0.327; MC = 115%)								
	1.0	12.7	12.3	11.1–13.6	10.5	12.1	11.1	−12.6	10.6–14.7*
0 °F	1.5	22.9	26.1	24.2–28.0	19.8	21.5	20.6	−10.0	20.6–25.1*
	2.0	43.6	45.6	42.8–48.3	38.3	40.7	39.6	−9.2	40.4–46.7
	3×3	45.8	51.3	44.8–57.7	47.2	49.5	48.7	6.3	38.6–53.1*
	4×4	92.3	100.0	92.2–107.7	85.8	89.2	88.8	−3.8	84.0–100.7*
	6×6	206.3	226.0	209.5–242.5	191.2	195.8	198.4	−3.8	188.8–223.7*
10 °F	1.0	15.1	14.8	12.9–16.6	10.8	13.3	13.2	−12.6	12.7–17.5*
	1.5	27.9	29.2	27.0–31.4	21.9	26.6	26.5	−5.0	25.7–30.1*
	2.0	58.0	53.8	49.8–57.9	44.9	53.0	53.2	−8.3	53.9–62.1
	3×3	62.1	62.6	56.3–68.9	52.4	60.9	61.3	−1.3	57.2–67.1*
	4×4	113.7	113.9	108.3–119.6	94.0	108.1	109.7	−3.5	105.9–121.5*
	6×6	258.5	262.0	240.3–283.8	208.5	234.2	243.6	−5.8	233.8–283.2*
	Aspen (SG = 0.398; MC = 88%)								
	1.0	13.0	12.9	11.5–14.3	11.5	13.1	12.3	−5.4	11.5–14.6*
0 °F	1.5	28.1	29.1	26.5–31.6	24.0	26.1	25.1	−10.7	23.9–32.2*
	2.0	48.8	50.2	46.8–53.6	41.5	44.2	43.3	−11.3	45.6–52.0
	3×3	60.0	61.4	59.0–63.9	55.6	58.3	57.5	−4.2	56.7–63.3*
	4×4	108.9	112.7	108.7–116.8	97.9	100.6	100.9	−7.3	104.6–113.2
	6×6	253.9	261.5	245.3–277.5	221.3	224.6	228.0	−10.2	236.2–271.5
10 °F	1.0	14.6	15.1	14.1–16.2	10.7	13.2	13.5	−7.5	13.3–15.9*
	1.5	29.8	31.5	30.5–32.5	23.3	28.4	28.4	−4.7	28.9–30.7
	2.0	54.8	57.3	52.6–62.0	41.5	49.7	49.5	−9.7	49.0–60.7*
	3×3	66.8	69.2	64.7–73.7	54.5	63.4	63.8	−4.5	61.7–71.9*
	4×4	125.1	128.5	123.9–133.1	98.2	113.4	114.6	−8.4	120.3–130.0
	6×6	276.5	284.8	274.9–294.7	220.6	247.7	257.0	−7.1	267.3–285.8

[a]From Simpson et al. (2005). Calculated times in columns 4–6 are based on actual sizes, initial temperatures, and heating temperatures, and should be compared with unadjusted times. The * in column 8 indicates that the times calculated by MacClean's equations using the wet-bulb temperature as the heating temperature fall within the 99% confidence interval of the unadjusted times.

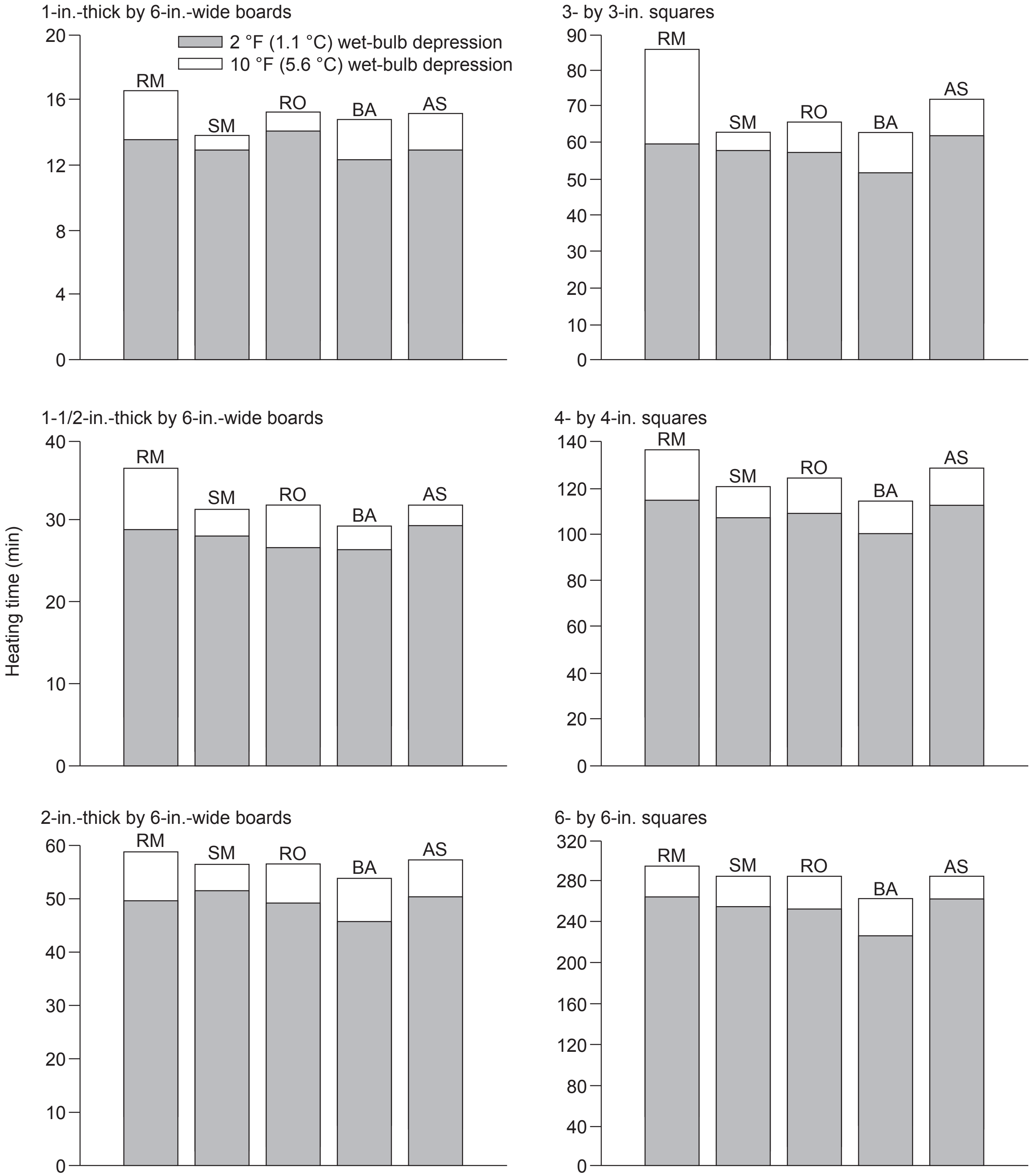


Figure 5.5—Effect of species and wet-bulb depression on heating times of boards and squares (Simpson et al. 2005). (RM, red maple; SM, sugar maple; RO, red oak; BA, basswood; AS, aspen.)

Table 5.5—Estimated times to heat the center of various wood configurations as they depend on heating temperature, target center temperature, and initial wood temperature[a]

Heating temperature (T_h)	160 °F				180 °F			
Target center temperature (T_c)	133 °F		158 °F		133 °F		158 °F	
Initial wood temperature (T_i)	35 °F	70 °F	35 °F	70 °F	35 °F	70 °F	35 °F	70 °F
Sample size (in.)	Time needed to heat center of wood (min.)							
0.625 by 4	5	4	13	11	4	3	6	5
1.0 by 4	13	10	32	29	10	8	15	13
1.5 by 4	29	23	68	61	22	17	34	28
2.0 by 4	48	38	110	98	37	29	55	47
2.0 by 6	52	41	123	110	40	31	61	51
3 by 3	67	54	154	138	53	42	77	66
4 by 4	120	97	274	246	94	75	138	118
6 by 6	269	217	616	553	210	168	310	264
8 by 8	478	386	1,095	982	374	299	551	470
10 by 10	747	604	1,712	1,535	584	467	860	735
12 by 12	1,076	869	2,465	2,210	842	673	1,239	1,058

[a]From Simpson et al. (2005). Assumed wood moisture content and specific gravity are 60% and 0.53, respectively.

time it is heating up. Evaporation of water from the wood surface cools the surface and thus slows the rate of heat transfer from the surface of the wood to the center. Little evaporation, and thus little surface cooling to slow heat transfer, occurs with wet heat. Heating times of softwood lumber have been studied extensively (Simpson 2001, 2002, 2003; Simpson et al. 2003).

One study explored the effects of species, cross-sectional dimensions, and heating medium on time required to heat the center of five hardwoods (red maple, sugar maple, red oak, basswood, and aspen) to 133 °F (Simpson et al. 2005). Table 5.4 summarizes heating times of the various experimental groups. Columns 1 to 3 show (1) unadjusted heating times, (2) heating times adjusted to an initial wood temperature of 60 °F, a heating temperature of 157 °F, and the common sizes, and (3) the 99% statistical confidence interval for the adjusted heating times. Adjusted heating times are also shown in Figure 5.5 for comparing the relationship of heating times between species and wet-bulb depression. As expected, size has a significant effect on heating time, ranging from about 15 min for 1-in.-thick boards to almost 300 min for 6- by 6-in. squares. Heating time was longer with the 10 °F wet-bulb depression heating than with the 2 °F wet-bulb depression heating. The overall average increase in heating time for all species and all sizes because of greater wet-bulb depression was 15%. Overall, hardwood species had a statistically significant effect on heating time, but not all individual comparisons were statistically significant. However, the actual effect of species was insignificant in the practical sense (apparent from Fig. 5.5). Although some species differences were statistically significant, differences have little practical significance. Because differences in heating time are so small, there is no practical reason to heat-treat these five species separately; the differences are of magnitude similar to the expected natural variability between individual boards and squares.

When heating is done in a saturated steam atmosphere, equations of heat transfer may be applied to estimate heating times as they depend on wood specific gravity, MC, size, initial temperature, heating temperature, and target center temperature (Simpson 2001). Table 5.5 lists estimated heating times for various board and square sizes common to wood pallets, other packing containers, and timbers that might be imported or exported for any purpose. Heating times are shown for two heating temperatures (160 and 180 °F), two target center temperatures (133 and 158 °F), and two initial temperatures (35 and 70 °F). The different sizes range from 0.625- by 4-in. boards to 12- by 12-in. square timbers.

Summary

Hardwood lumber for engineered and nonengineered structural wood products requires different drying strategies than hardwood lumber used for more traditional hardwood appearance-type products, such as furniture, cabinetry, and millwork that require drying. The application of air drying and pre-dryers can be expanded from their current hardwood applications, and kiln drying can be accelerated to be faster and more efficient than current practices for appearance-type products because of the irrelevance of discolorations and minor surface checking in structural products. Heat sterilization to kill insects and pathogens in wood packaging is becoming a requirement in international trade. Manufacturers and users of wood packaging need to know the time necessary to heat the center of any wood configuration to the temperature required to kill the insect or pathogen of concern, and research has offered guidelines to do this.

Literature Cited

FAO. 2002. International standards for phytosanitary measures: guidelines for regulating wood packaging material in international trade. Publ. No. 15. Rome, Italy: Food and Agriculture Organization of the United Nations.

FPL. 1991. Dry kiln operator's manual. Agric. Handb. 188. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 274 p.

Koch, P. 1971. Process for straightening and drying southern pine 2x4s in 24 hours. Forest Products Journal. 21(5): 17–24.

Markstrom, D.C.; Shuler, C.E.; King, R.M. 1984. Warpage of studs from young growth ponderosa pine from northern New Mexico. Res. Pap. RM–RP–257. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station.

Simpson, W.T. 2001. Heating times for round and rectangular cross-sections of wood in steam. Gen. Tech. Rep. FPL–GTR–130. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 103 p.

Simpson, W.T. 2002. Effect of wet bulb depression on heat sterilization time of slash pine lumber. Res. Pap. FPL–RP–604. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 6 p.

Simpson, W.T. 2003. Mechanism responsible for the effect of wet bulb depression on heat sterilization time of slash pine lumber. Wood and Fiber Science. 35(2): 175–186.

Simpson, W.T.; Forsman, J.W. 1999. Effect of moisture content on warp in hardwood 2 by 6's for structural use. Res. Pap. FPL–RP–580. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 8 p.

Simpson, W.T.; Hart, C.A. 2000. Estimates of air-drying times for several hardwoods and softwoods. Gen. Tech. Rep. FPL–GTR–121. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 70 p.

Simpson, W.T.; Hart, C.A. 2001. Method for estimating air drying times of lumber. Forest Products Journal. 51(11/12): 56–63.

Simpson, W.T.; Wang, X. 2001. Time-based kiln drying schedule for sugar maple for structural uses. Res. Note FPL–RN–0279. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 4 p.

Simpson, W.T.; Forsman, J.W.; Ross, R.J. 1998. Kiln drying maple structural lumber from log heart cants. Forest Products Journal. 48(6): 70–76.

Simpson, W.T.; Wang, X.; Verrill, S. 2003. The effect of wet bulb depression on the heat sterilization time of ponderosa pine and Douglas-fir boards and square timbers. Res. Paper FPL–RP–607. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Simpson, W.T.; Wang, X.; Forsman, J.W.; Erickson, J.R. 2005. Heat sterilization times of five hardwood species. Res. Pap. FPL–RP–626. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 10 p.

SPIB. 1994. Grading Rules. Pensacola, FL: Southern Pine Inspection Bureau. 214 p.

Chapter 6

Engineered Trusses from Undervalued Hardwoods

Robert J. Ross, Supervisory Research General Engineer
Brian K. Brashaw, Program Manager
John R. Erickson, Former Director (deceased)
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

Kurt Grundahl, Executive Director
Wood Truss Council of America, Madison, Wisconsin

John W. Forsman, Assistant Research Scientist (retired)
College of Forest Resources and Environmental Science, Michigan Technological University, Houghton, Michigan

A significant volume of softwood lumber is used in engineered truss assemblies. Metal plate connected (MPC) trusses are commonly used in residential construction for both roof and floor applications. Currently, no truss manufacturers produce MPC trusses with hardwood lumber, primarily because of supply chain and logistics challenges.

This chapter presents information that is critical to using hardwood lumber in MPC trusses. It summarizes results from several testing and demonstration studies and includes information on estimated design values for various metal plate connectors used with hardwood lumber, results of tests conducted on full-size trusses manufactured from hardwood lumber, and demonstration of hardwood trusses in residential construction.

Laboratory Testing of Metal Plate Connectors and Full-Size Trusses

Testing Program for Metal Plate Joints

Knowledge of the metal plate connector/lumber joint is essential in the design of wood trusses. The strength of this joint is determined by tests that measure the lateral withdrawal resistance of metal plate connectors from wood.

An extensive testing program was conducted to develop baseline information on the lateral withdrawal resistance of common types of metal plate connectors from hardwood lumber. Nineteen types of metal connector plates from eight manufacturers were included in the testing program. Nominal 2- by 4-in. lumber sections were prepared from sugar maple, red maple, and yellow birch cants. Each section was selected to be straight grained and free of knots. The specific gravity of each section was calculated based on weight and dimension measurements. Parallel- and perpendicular-to-grain test specimens were then prepared using the lumber sections and various metal plate connectors. Specimen dimensions and testing protocols utilized are summarized in ANSI-TPI 1-1995. Data obtained from this test program were reported by Forsman and Erickson (2000).

Note that the goal of this program was not to develop a new or optimized plate design for hardwood lumber. The primary goal was to provide data on the performance of connector plates currently used with hardwood lumber and then use this information to derive design values that will allow truss designers to use hardwood lumber in their designs. A secondary goal was to compare derived design values with those used in the design of trusses whose lumber is from the Southern Pine and Spruce–Pine–Fir (SPF) lumber groupings.

Demonstration Study for Full-Size Trusses

In the demonstration study, 54 full-size trusses were manufactured and tested to failure to compare the performance of trusses made from red and sugar maple lumber with similar trusses made from Southern Pine and SPF lumber (Brashaw et al. 2001, 2002). Tables 6.1 and 6.2 summarize key elements of this study. Figures 6.1 and 6.2 illustrate designs tested. The pitched chord trusses were manufactured from nominal 2- by 4-in. lumber. They were designed to span 24 ft and had a 4:12 pitch. The parallel chord trusses were also constructed from nominal 2- by 4-in. lumber. For the pitched chord trusses, a 1.8E-2100fb machine stress rated (MSR) grade of lumber from the SPF lumber grouping was specified for chord members. A visual grade of No. 3 SPF was specified for the web members. The lumber specified for the parallel chord trusses was 1.4E-1650f_b MSR SPF for the chords and visual grade No. 3 SPF for the webs.

Table 6.1—Description of pitched chord truss groups that were manufactured for testing

		Chord lumber			Web lumber		
Group	No. of trusses	Species[a]	Grade	Moisture content (%)	Species[a]	Grade	Moisture content (%)
1	6	SM	2,100f_b 1.8E	12 to 15	SM	No. 3 or Btr.	12 to 15
2	6	RM	2,100f_b 1.8E	12 to 15	RM	No. 3 or Btr.	12 to 15
3	6	DRM	2,100f_b 1.8E	12 to 15	DRM	No. 3 or Btr.	12 to 15
4	6	SYP	2,100f_b 1.8E	12 to 15	SYP	No. 3 or Btr.	12 to 15
5	6	SPF	2,100f_b 1.8E	12 to 15	SPF	No. 3 or Btr.	12 to 15
6	6	SPF	2,100f_b 1.8E	12 to 15	RM	No. 3 or Btr.	12 to 15
7	3	SPF	2,100f_b 1.8E	12 to 15	RM	No. 3 or Btr.	50 to 60

[a]SM is sugar maple; RM is red maple; DRM is Delaware red maple; SYP is southern yellow pine species classification; SPF is Spruce–Pine–Fir species classification.

Table 6.2—Description of parallel chord truss groups that were manufactured for testing

		Chord lumber			Web lumber		
Group	No. of trusses	Species[a]	Grade	Moisture content (%)	Species[a]	Grade	Moisture content (%)
8	6	SM	1,650f_b 1.4E	12 to 15	SM	No. 3 or Btr.	12 to 15
9	6	DRM	1,650f_b 1.4E	12 to 15	DRM	No. 3 or Btr.	12 to 15
10	6	SPF	1,650f_b 1.4E	12 to 15	SPF	No. 3 or Btr.	12 to 15
11	6	SPF	1,650f_b 1.4E	12 to 15	RM	No. 3 or Btr.	12 to 15
12	3	SPF	1,650f_b 1.4E	12 to 15	RM	No. 3 or Btr.	50 to 60

[a]SM is sugar maple; RM is red maple; DRM is Delaware red maple; SYP is southern yellow pine species classification; SPF is Spruce–Pine–Fir species classification.

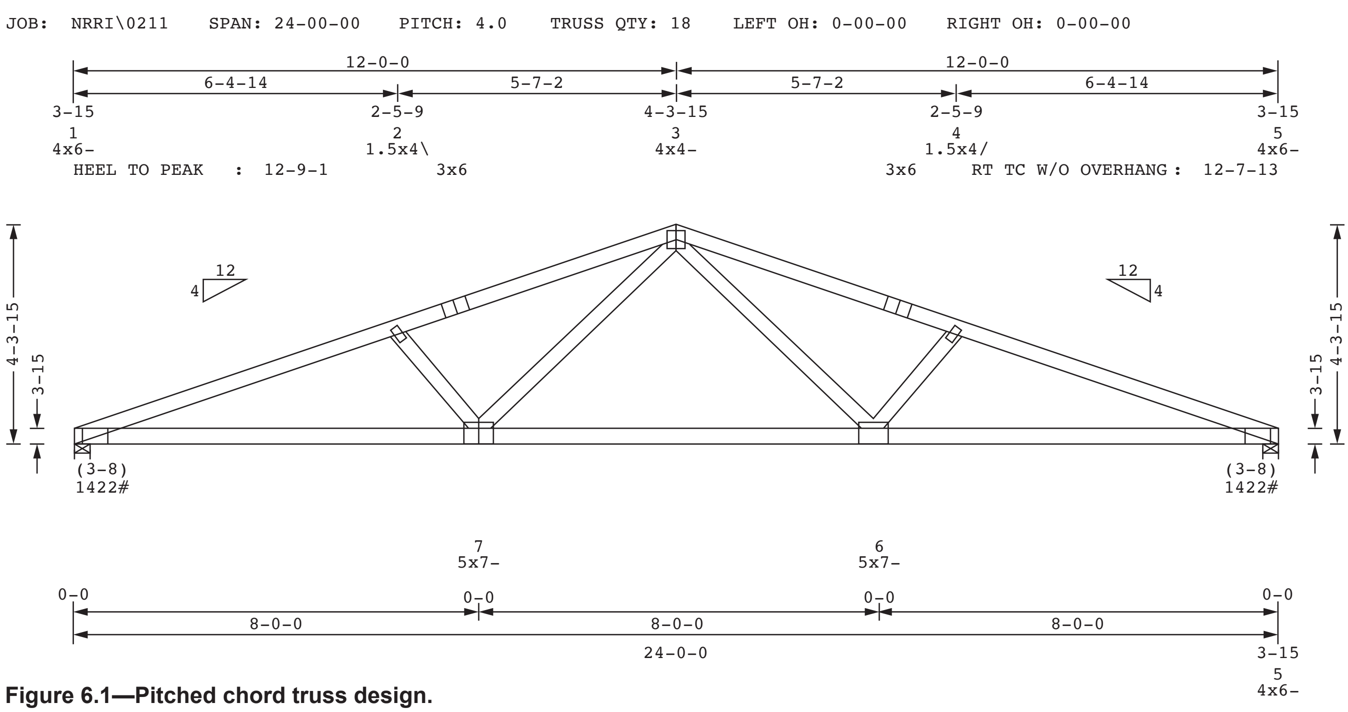


Figure 6.1—Pitched chord truss design.

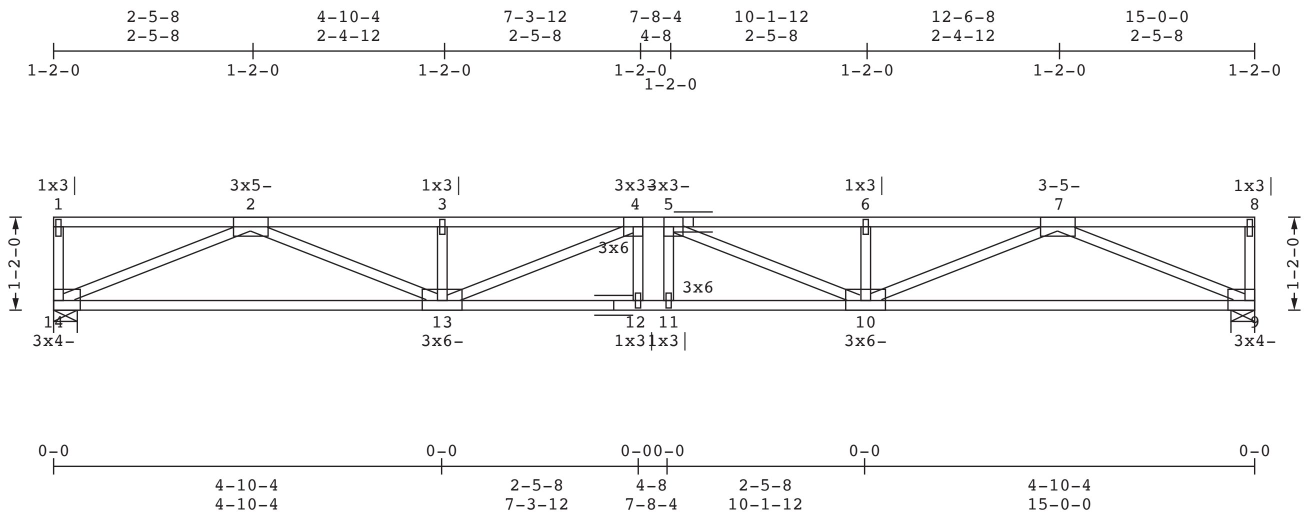


Figure 6.2—Parallel chord truss design.

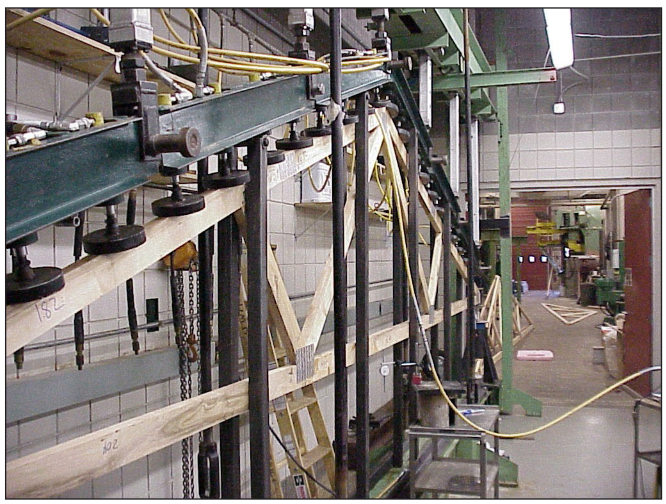


Figure 6.3—Hardwood pitched chord truss during full-scale testing.

Figure 6.4—Parallel chord truss testing setup.

Table 6.3—Summary of pitched chord truss testing results[a]

	Species[b]			Mean deflection and strength results			
Group	Chord	Web	No. of trusses tested	Deflection at dead load (in.)	Deflection at design load (in.)	Total ultimate load (lb)	Failure load/design load
1	SM	SM	5	0.117 (0.009)	0.319 (0.015)	6,739 (202)	2.37 (0.07)
2	RM	RM	5	0.119 (0.016)	0.349 (0.032)	7,063 (1,148)	2.48 (0.40)
3	DRM	DRM	5	0.123 (0.015)	0.363 (0.065)	6,805 (1,023)	2.39 (0.36)
4	SYP	SYP	5	0.118 (0.014)	0.345 (0.025)	5,360 (470)	1.88 (0.17)
5	SPF	SPF	5	0.129 (0.010)	0.350 (0.017)	5,545 (806)	1.95 (0.28)
6	SPF	RM	5	0.115 (0.015)	0.342 (0.023)	6,050 (413)	2.13 (0.15)
7	SPF	GRM	2	0.139 (0.013)	0.380 (0.001)	5,190 (127)	1.82 (0.04)

[a]Standard deviations are shown in parentheses.
[b]SM is sugar maple; RM is red maple; DRM is Delaware red maple; SYP is southern yellow pine species classification; SPF is Spruce–Pine–Fir species classification; GRM is green red maple.

Table 6.4—Summary of parallel chord truss testing results[a]

	Species[b]			Mean deflection and strength results			
Group	Chord	Web	No. of trusses tested	Deflection at dead load (in.)	Deflection at design load (in.)	Total ultimate load (lb)	Failure load/design load
8	SM	SM	4	0.091 (0.010)	0.305 (0.016)	3,775 (752)	2.2 (0.4)
9	DRM	DRM	5	0.107 (0.006)	0.384 (0.010)	2,988 (312)	1.7 (0.2)
10	SPF	SPF	5	0.118 (0.007)	0.427 (0.027)	2,694 (182)	1.6 (0.1)
11	SPF	RM	5	0.106 (0.005)	0.388 (0.023)	2,755 (146)	1.6 (0.1)
12	SPF	GRM	3	0.100 (0.007)	0.390 (0.034)	2,834 (326)	1.6 (0.2)

[a]Standard deviations are shown in parentheses.
[b]SM is sugar maple; RM is red maple; DRM is Delaware red maple; SYP is southern yellow pine species classification; SPF is Spruce–Pine–Fir species classification; GRM is green red maple.

Figures 6.3 and 6.4 show pitched and parallel chord trusses under test. Tables 6.3 and 6.4 summarize test results obtained for pitched and parallel chord truss tests, respectively. Two important points were observed:

1. A typical failure mode for trusses manufactured from hardwood lumber was a tearing (failure) of the metal plate at a joint. Typical failure modes for trusses manufactured from softwood lumber was withdrawal of the fingers of the metal plate from the wood at a joint.
2. Trusses manufactured from hardwood lumber performed at levels equivalent to or better than comparable softwood trusses.

Testing was conducted according to ANSI/TPI2-1995 guidelines.

Estimated Design Values

Estimated design values derived from this testing program are summarized in Table 6.5. Note that

- these values were derived from results of the lateral withdrawal testing program,
- all joint specimens exhibited withdrawal of the connector teeth on both sides of the specimen, and
- design values were derived for a species grouping of sugar maple, red maple, and yellow birch.

It was assumed that, in practice, no separation of species would occur. Before using these values, it is imperative to examine the technical information available from specific plate manufacturers. Of significant importance is a comparison of these values with those used in the design of trusses where the lumber is from the Southern Pine or SPF lumber groupings. Table 6.6 illustrates such a comparison for one type of connector plate. Note that the design values derived for use with the sugar maple–red maple–yellow birch lumber grouping were, in essence, significantly greater than values used for lumber from the SPF lumber grouping.

Table 6.5—Estimated design values for metal connector plates from eight manufacturers for wood from the sugar maple–red maple–yellow birch lumber grouping

Manufacturer and metal connector plate designation	Test configuration	Metal connector plate orientation (°)	Design value (lb/in^2)
Alpine Engineered Products			
A 20	Parallel to grain	0	273
		90	149
	Perpendicular to grain	0	134
		90	165
A20H	Parallel to grain	0	222
		90	128
	Perpendicular to grain	0	126
		90	122
Cherokee Metal Products			
CA20	Parallel to grain	0	188
		90	145
	Perpendicular to grain	0	110
		90	141
CB20	Parallel to grain	0	214
		90	146
	Perpendicular to grain	0	125
		90	145
CC205	Parallel to grain	0	173
		90	158
	Perpendicular to grain	0	149
		90	141
Computrus			
C20	Parallel to grain	0	198
		90	190
	Perpendicular to grain	0	148
		90	147
Eagle Metal Products			
E20	Parallel to grain	0	211
		90	194
	Perpendicular to grain	0	147
		90	152

Table 6.5—Estimated design values for metal connector plates from eight manufacturers for wood from the sugar maple–red maple–yellow birch lumber grouping (con.)

Manufacturer and metal connector plate designation	Test configuration	Metal connector plate orientation (°)	Design value (lb/in^2)
MiTek Industries			
M20	Parallel to grain	0	210
		90	210
	Perpendicular to grain	0	142
		90	165
M20H	Parallel to grain	0	180
		90	160
	Perpendicular to grain	0	129
		90	140
M18	Parallel to grain	0	245
		90	251
	Perpendicular to grain	0	154
		90	160
M16	Parallel to grain	0	202
		90	144
	Perpendicular to grain	0	144
		90	163
Robbins Engineering			
RA20	Parallel to grain	0	244
		90	172
	Perpendicular to grain	0	129
		90	157
RB20H	Parallel to grain	0	221
		90	170
	Perpendicular to grain	0	139
		90	148
Truswal			
TW20	Parallel to grain	0	197
		90	181
	Perpendicular to grain	0	129
		90	156
TW16	Parallel to grain	0	199
		90	163
	Perpendicular to grain	0	136
		90	148

Table 6.5—Estimated design values for metal connector plates from eight manufacturers for wood from the sugar maple–red maple–yellow birch lumber grouping (con.)

Manufacturer and metal connector plate designation	Test configuration	Metal connector plate orientation (°)	Design value (lb/in^2)
TeeLok Corporation			
TL20	Parallel to grain	0	229
		90	204
	Perpendicular to grain	0	143
		90	163
TL20H	Parallel to grain	0	222
		90	175
	Perpendicular to grain	0	131
		90	165
TL18	Parallel to grain	0	256
		90	220
	Perpendicular to grain	0	148
		90	180
TL16	Parallel to grain	0	197
		90	153
	Perpendicular to grain	0	143
		90	141

Table 6.6—A comparison of metal connector plate design values (estimated) for the sugar maple–red maple–yellow birch lumber grouping to design values for lumber from the southern pine and spruce–pine–fir lumber groupings. Design values are for metal connector plates manufactured by MiTek Industries.

			Design value (lb/in^2)		
Plate designation	Test configuration	Metal connector plate orientation[a]	Sugar maple–red maple–yellow birch	Spruce–Pine–Fir	Southern pine
M20	Parallel to grain	0	210	197	249
		90	210	144	190
	Perpendicular to grain	0	142	144	184
		90	165	137	200
M20H	Parallel to grain	0	180	148	187
		90	160	108	143
	Perpendicular to grain	0	129	108	138
		90	140	103	150
M18	Parallel to grain	0	245	141	196
		90	251	138	188
	Perpendicular to grain	0	154	134	159
		90	160	109	152
M16	Parallel to grain	0	202	127	174
		90	144	82	126
	Perpendicular to grain	0	144	75	147
		90	163	107	122

[a]Relative to application of load.

Figure 6.5—Habitat for Humanity house.

Figure 6.6—Metal plate trusses containing red maple web lumber.

It is also important to note that the values for the sugar maple–red maple–yellow birch grouping are slightly lower than those currently used when designing trusses that use Southern Pine lumber.

Demonstration of Hardwood Trusses in Residential Construction

Several structures were constructed using trusses made from hardwood lumber. Two houses with attached garages were constructed in Duluth, Minnesota, by the Duluth Chapter of Habitat for Humanity International. Red maple lumber was used as webs, and the trusses used in the garage were made entirely from red maple lumber. Figures 6.5 shows one of the houses during construction, and Figure 6.6 is a close-up of the maple webs in the trusses.

A large garage was constructed utilizing trusses manufactured from low-grade sugar maple lumber. The trusses were designed as modified storage trusses with a 26-ft span. The pitch was 6:12 with a 1-ft overhang at the truss ends. The trusses were hand set 24 in. on center.

Conclusions

Based on the demonstration studies summarized in this chapter, the following can be concluded:

1. Design values for various metal plate connectors used with a species grouping of sugar maple–red maple–yellow birch have been established. These values are greater than published values for lumber from the SPF lumber grouping. They are slightly lower than values for lumber from the Southern Pine lumber grouping.
2. Laboratory tests of full-size trusses manufactured using low-value hardwood lumber revealed performance comparable to or greater than equivalent softwood trusses.
3. Hardwood trusses were installed in three buildings. Monitoring revealed outstanding performance.

Literature Cited

Brashaw, B.K.; Vatalaro, R.J.; Lackore, M.; Ross, R.J.; Wang, X.; Forsman, J. 2001. Advancing technology to manufacture trusses from hardwood lumber. Technical Report NRRI/TR-2001/26. Duluth, MN: Natural Resources Research Institute, University of Minnesota, Duluth.

Brashaw, B.K.; Ross, R.J.; Vatalaro, R.J. 2002. Demonstration of hardwood trusses in residential construction projects. Technical Report NRRI/TR-2002/05. Duluth, MN: Natural Resources Research Institute, University of Minnesota, Duluth.

Forsman, J.; Erickson, J. 2000. Final report to USDA Forest Products Laboratory on the lateral strength of metal connector plate teeth joining sugar maple, red maple, and yellow birch species grouping. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Chapter 7

I-Joists and Headers

Brian K. Brashaw, Program Manager
Robert J. Ross, Supervisory Research General Engineer
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

Prefabricated wood I-joists and headers are widely used in wood construction throughout the world. They are used in roof and floor systems in both residential and commercial applications. These structural members consist of flanges, which are made from either solid-sawn or laminated veneer lumber, that are adhesively bonded to a web, which is made of plywood or oriented strandboard (OSB). Approximately a billion linear feet of wood I-joists and headers are manufactured annually. Currently, softwood species are predominately used for flanges. The work presented in this chapter was conducted to demonstrate the use of undervalued hardwood lumber for flanges in structural I-joists and headers (Brashaw and Vatalaro 2000).

Manufacture and Grading of Lumber for Flanges

A hardwood lumber manufacturer in northern Michigan provided approximately 100 nominal 2-by 6-in. hardwood lumber specimens for this demonstration study. The lumber was sawn from center cants and kiln-dried to a target moisture content (MC) of 15%. It was then planed and edged to a final thickness of 1.5 in. and width of 5.5 in.

The modulus of elasticity (MOE) of each lumber specimen was determined using transverse vibration nondestructive testing methods. Each specimen was then visually graded by a certified grader from the Southern Pine Inspection Bureau. Note that the visual override criteria for machine stress rated (MSR) lumber requires that all lumber meet No. 2 or Better visual grade rules.

Based on current I-joist manufacturing standards, the following MSR grade categories were utilized:

- 2.0E Sugar maple, yellow birch
- 1.8E Sugar maple, yellow birch, soft maple, aspen

The MSR grade category used to manufacture headers was 1.5E red maple, aspen.

Prior to manufacturing I-joists and headers, the lumber was defected according to additional requirements provided by the I-joist manufacturer. Knot size was limited to a maximum diameter of 1.0 in., split depth was limited to 1/4 in., and wane to 3/8 in. Lumber defects were then removed. Sixteen-foot lengths of defect-free material were then manufactured by finger-jointing shorter lengths together with a phenol-resorcinal adhesive.

Lumber Yield

Table 7.1 shows the yield loss for each evaluated species of hardwood lumber. There were substantial levels of deep drying splits in the sugar maple groups. This precluded their use for manufacturing I-joists and headers. Several other pieces of sugar maple lumber were excluded because of warp and other dimensional problems. The lumber used for I-joists and headers had been stored for almost 18 months. It is suspected that some of these splits and dimensional problems occurred during the storage period.

Table 7.1—Yield loss of hardwood lumber used for manufacturing I-joists and headers

		Loss by defect type (%)				
Species	MSR grade	Knots	Splits	Bark inclusion	Misc.	Total
Sugar maple	1.8E	6.1	10.5	1.5	20.7	38.8
	2.0E	5.4	38.4	3.0	—	46.8
Yellow birch	1.8E	7.6	3.9	1.7	2.7	15.9
	2.0E	2.9	—	—	—	2.9
Red maple	1.8E	3.0	12.2	3.5	—	18.7
	2.0E	5.7	10.0	1.8	0.4	18.0
Aspen	1.8E	8.5	13.6	—	1.9	23.9
	2.0E	4.1	5.5	—	—	9.6

Manufacture and Performance of Demonstration I-Joists and Headers

Flange stock was manufactured from the 2-by 6-in. lumber by ripping the lumber into two sections and milling a rout into each section. The flange stock was then used to manufacture I-joists and headers. A phenol-formaldehyde adhesive was placed into the rout and OSB web material inserted. The assembled members were then pressed together in a continuous press. The finished members (I-joists and headers) were then placed into storage for 10 days prior to mechanical testing.

Shear Resistance

Testing was completed according to ASTM D5055-99, Standard Specification for Establishing and Monitoring Structural Capacities of Prefabricated Wood I-Joists (ASTM 1999). Seven-foot shear test specimens were cut, with an OSB web joint located 12 to 18 in. from both ends of the joist. Each specimen was tested to failure. Maximum load was recorded, and failure type and location were determined.

Tables 7.2 and 7.3 show the maximum load observed from the shear tests that were completed for the I-joist and header specimens, respectively. The results shown for the hardwood I-joists and headers were based on experimental testing. These results were compared against minimum acceptable quality control (QC) values that the industrial cooperator uses as part of their quality assurance program.

The sugar maple and yellow birch test specimens failed in horizontal shear between the lumber flange and the OSB. There appeared to be a lack of bonding in these joints. The amount of wood failure was extremely low. Examination of the failed specimens revealed that the sugar maple flange material appeared to be sufficiently wetted by the adhesive, yet a poor bond was evident. It is possible that the adhesive did not reach high enough temperatures during curing to obtain an optimum bond, or there was too large a gap between the lumber flange and the OSB. The lower density red maple and aspen showed excellent bonds between the lumber flange and the OSB.

Each of the alternate species evaluated for header stock showed that minimum acceptable performance was obtained for the limited sample set.

Moment Resistance

Moment testing was completed in accordance with ASTM D5055-98. Each sample was laterally supported to minimize off-axis buckling. Due to the short flange length, the span-to-depth ratio for these joists was 16:1; the recommended ratio is 17:1–21:l. Moment capacity was determined for each specimen.

Results are shown in Table 7.4. The 16:1 span-to-depth ratio resulted in shear-type failures, when typical failures are bending moment failure types. This may have occurred because a poor bond existed between the sugar maple and OSB and the yellow birch and OSB.

The sugar maple (1.8E) I-joist moment capacity was equivalent to the Spruce–Pine–Fir (SPF) lumber flanges, even though relatively poor bonds existed between the sugar maple and the OSB. There were not enough other data points for the other species evaluated to draw any specific conclusions.

Table 7.2—I-joist shear test results for hardwood and SPF lumber

Species	MSR grade	No. of samples	Mean ultimate load (lb)	Pass QC requirements
Sugar maple	1.8E	11	6,049	4 of 11
	2.0E	1	4,603	0 of 11
Yellow birch	1.8E	5	5,652	2 of 5
	2.0E	3	6,258	1 of 3
Red maple	1.8E	7	6,720	7 of 7
Aspen	1.8E	3	6,934	3 of 3
Spruce–Pine–Fir	1.8E	QC	6,600 minimum	na

Table 7.3—Header shear test results

Species	MSR grade	No. of samples	Mean ultimate load (lb)	Pass QC requirements
Red maple	1.5E	2	11,984	2 of 2
Aspen	1.8E	3	14,167	4 of 4
Spruce–Pine–Fir	1.8E	QC	11,000 to 13,000 10,250 minimum	na

Table 7.4—I-joist moment testing results

Species	MSR grade	No. of samples	Maximum load (lb)	Moment capacity (ft-lb)
Sugar maple	1.8E	5	4,651	12,403
	2.0E	1	5,010	13,360
Yellow birch	2.0E	1	4,372	11,659
Red maple	1.8E	1	4,117	10,979
Aspen	1.8E	1	4,455	11,880
Spruce–Pine–Fir	1.8E	6	4,732	12,619

Table 7.5—Nailing performance of hardwood I-joists at 5 to 6 percent moisture content using 8d and 10d nails[a]

		Nailing location				
Species	MSR grade	Flange end (8d)	Flange midspan (8d)	Rimboard (8d)	Rimjoist top flange (10d)	Rimjoist bottom flange (10d)
Sugar maple	1.8E	4 of 12	3 of 6	0 of 6	2 of 3	2 of 3
Yellow birch	1.8E	1 of 12	0 of 6	0 of 6	2 of 3	2 of 3
	2.0E	3 of 12	0 of 6	0 of 6	3 of 3	2 of 3
Red maple	1.8E	1 of 12	0 of 6	0 of 6	2 of 3	1 of 3
Aspen	1.8E	1 of 12	0 of 6	0 of 6	1 of 3	0 of 3
Spruce–Pine–Fir	1.8E	1 of 12	0 of 6	0 of 6	2 of 3	2 of 3

[a]Values indicate the number of splits that occurred out of the total number of nails that were driven.

Table 7.6—Nailing performance of hardwood I-joists at 12 to 13 percent moisture content using 8d and 10d nails[a]

		Nailing location				
Species	MSR grade	Flange end (8d)	Flange midspan (8d)	Rimboard (8d)	Rimjoist top flange (10d)	Rimjoist bottom flange (10d)
Sugar maple	1.8E	2 of 12	0 of 6	0 of 6	2 of 3	0 of 3
	2.0E	2 of 12	0 of 6	0 of 6	1 of 3	2 of 3
Yellow birch	1.8E	1 of 12	0 of 6	0 of 6	0 of 3	2 of 3
	2.0E	5 of 12	0 of 6	0 of 6	2 of 3	1 of 3
Red maple	1.8E	1 of 12	0 of 6	0 of 6	2 of 3	1 of 3
Aspen	1.8E	1 of 12	0 of 6	0 of 6	1 of 3	0 of 3
Spruce–Pine–Fir	1.8E	1 of 12	0 of 6	0 of 6	2 of 3	2 of 3

[a]Values indicate the number of splits that occurred out of the total number of nails that were driven.

Nailing Performance

An important performance characteristic for prefabricated I-joists and headers is their response to nailing. Significant splitting of the flange in response to application of nails may result in unacceptable performance. To examine the performance of I-joists manufactured using hardwood flange stock, a study was designed and conducted to compare their performance relative to those made using SPF lumber as flange stock. A commercially available nail application system was used with 8d and 10d nails to simulate nailing patterns as specified in construction drawings provided by an industrial cooperator. Small joist sections were conditioned to two moisture conditions (5% to 6% and 12% to 13%). 8d nails were inserted 1.5 in. from the joist end, at mid-span of the joists, and through a rimjoist into a joist end. 10d nails were inserted through the top joist at the joist end and at mid-span. Each nailing location was evaluated for the number of joists that split.

Table 7.5 shows the nailing test results for hardwood and SPF lumber at 5% to 6% MC, and Table 7.6 shows the results at 12% to 13% MC. Each table shows the number of splits that occurred out of the total number of nails that were driven. The data show that the majority of the splits occurred at the ends of the I-joists and when driven through the top of the joists into another joist. Very few splits occurred when the nails were located at midspan 18 in. away from a cut end. Slightly fewer nailing splits occurred at the higher MC level.

Conclusions

A significant volume of lumber tested met the criteria for several grades of MSR softwood lumber. This included MOE values and visual grading criteria. Additional defecting was completed prior to using the lumber for prefabricated wood I-joists and headers. Deep checking in the sugar maple lumber caused the largest amount of downgrade.

I-joists and headers that were manufactured using red maple and aspen lumber for flange stock had shear strength values that were equivalent to or greater than values required for comparable I-joists manufactured using lumber from the SPF lumber grouping. I-joists manufactured using sugar maple and yellow birch lumber exhibited marginal bonding between the flanges and OSB webs. It was not clear whether the poor bonding was caused by lack of contact between the flanges and the webs, insufficient temperatures during curing of the adhesive, or some other factor.

During moment testing, a large number of the specimens failed in a shear mode rather than in bending mode. Two factors contributed to this phenomenon:

1. The span-to-depth ratio used was shorter than suggested.
2. There was poor bonding between the hardwood lumber flanges and the OSB webs.

The nailing study showed that the dense sugar maple and yellow birch lumber resulted in slightly more splits when the nails were inserted 1.5 in. away from the joist end as compared with SPF. The other results were comparable between red maple, aspen, and SPF.

Literature Cited

ASTM. 1999. Standard specification for establishing and monitoring structural capacities of pre-fabricated wood I-joists. ASTM D5055-99. West Conshohocken, PA: American Society for Testing and Materials.

Brashaw, B.; Vatalaro, R. 2000. Hardwood I-joist manufacturing. Technical Report NRRI/TR-2000/56. Duluth, MN: Natural Resources Research Institute, University of Minnesota Duluth.

Chapter 8

Ultrasonic Grading of Hardwood Veneer

Brian K. Brashaw, Program Manager
Robert J. Ross, Supervisory Research General Engineer
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

The purpose of this chapter is twofold: to provide background information on the use of ultrasonic grading technologies for wood veneer and to provide results from a study that successfully demonstrated use of these technologies to evaluate red maple veneer. The section on ultrasonic grading technologies draws from Brashaw (2015). The section that describes the demonstration study was originally reported by Ross et al. (2004).

Ultrasonic Grading Technologies for Wood Veneer

The development and growth of the laminated veneer lumber (LVL) industry has been a direct result of the application of ultrasonic nondestructive evaluation (NDE) methods for assessing the properties of wood veneer. Individual veneer sheets are fed through opposing transducers that send and receive a wave. This wave travels longitudinally through the veneer. The time it takes for the wave to travel between the transducers is referred to as the propagation time and is used to calculate the velocity of the wave. With previously determined empirical relationships that relate wave velocity to wood stiffness and strength, each sheet of veneer is assigned to a strength category based on the velocity of the wave traveling through it. These relationships were derived from fundamental research studies in which samples of veneer were tested to determine the velocity at which a wave traveled through them and were then destructively tested to determine their strength and stiffness. Knowing the properties of each sheet of veneer enables manufacturers to design and produce engineered wood products that have properties with predictable performance characteristics.

Ultrasonic veneer grading is based on elementary one-dimensional stress wave theory, which states that the dynamic modulus of elasticity (MOE_d) of a material is a function of the velocity *C* of stress wave propagation and mass density ρ as defined by

$$MOE_d = C^2 \rho$$

Figure 8.1—Metriguard 2600.

Metriguard Technologies, Inc. (Pullman, Washington, USA) is the only commercial manufacturer of ultrasound veneer grading equipment. Their first commercial system was installed in 1977 at Trus Joist Corporation's first LVL plant in Eugene, Oregon, USA (Pieters 1979). This system was capable of production speeds of 100 ft/min (30.5 m/min). Douglas-fir veneer was sorted into three grades based on veneer propagation time in the longitudinal grain direction. Figure 8.1 shows an original Metriguard Model 2600 commercial ultrasonic veneer grader.

Technical advances have coupled the velocity of the wave with the use of a radiofrequency probe to determine specific gravity and moisture content of each veneer sheet (Logan 2000). Research resulted in the development of better relationships between the temperature of wood and wave velocity. These improvements resulted in the ability to sort veneer on the basis of calculated MOE based on the wave velocity and specific gravity (Logan 2000).

Figure 8.2 shows the Metriguard Model 2800 DME, capable of achieving production speeds of 300 to 425 ft/min (91.4 to 129.5 m/min). It is equipped with wood temperature compensation, radiofrequency measurement of specific gravity and moisture content, and sheet width and thickness detection capabilities.

Figure 8.2—Metriguard 2800 DME.

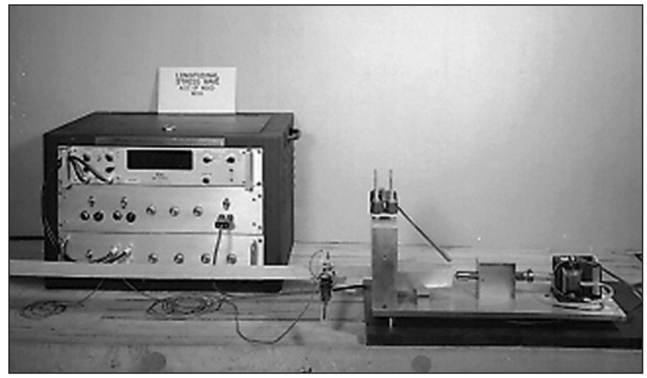


Figure 8.3—Washington State University stress wave timer.

Laminated Veneer Lumber Production

In 2000, approximately 150 ultrasonic veneer graders were in use around the world, resulting in a grading capacity of 15 million m^3 of veneer for LVL (Logan 2000). Today the number of ultrasonic veneer graders in use exceeds 200. Laminated veneer lumber is manufactured from C and D grade rotary-peeled veneer that is typically 0.17 to 0.10 in. (4.3 to 2.5 mm) thick. Species that are used for LVL include Douglas-fir, southern yellow pine, lodgepole pine, western hemlock, western larch, aspen, black spruce, paper birch, and red pine. After drying, the veneer is graded through a commercial ultrasonic veneer grader into several grades. Adhesive is applied to the veneer, which is oriented in the longitudinal direction prior to pressing. Typically, LVL is manufactured in continuous length billets (1.25 to 3 in. (3.2 to 7.6 cm) thick, 52 in. (1.3 m) wide). The LVL is then sawn into sizes based on customer requirements. This LVL is used in many structural products including prefabricated wood I-joists, truss chords, headers, and beams.

Trus Joist Corporation (Boise, Idaho, USA) was the initial entrant into the LVL industry in the early 1970s. They pioneered the manufacturing and grading technology that allowed for the exponential growth of LVL since 1992. The annual estimate for LVL production was approximately 9 million ft^3 (255,000 m^3) from six engineered wood products manufacturers in 1992 (Guss 1994). Laminated veneer lumber production increased to 51.9 million ft^3 (1.5 million m^3) in 1999 (APA 2000). Approximately 61% of the LVL production was used as flanges for wood I-joists in 1999, followed by 31% as headers and beams, and 8% for other applications (APA 2000). Although it would be difficult to estimate current production statistics, LVL production has increased considerably in recent years.

Technology Development

The concept for determining wave propagation time, stress wave velocity, and MOE for veneer was based on lumber studies that were completed at Washington State University (Pullman, Washington, USA) (Galligan and Courteau 1965; Pellerin and Galligan 1973). The presence of stress waves in softwood lumber was detected using a probe that was sensitive to the piezoelectric charge in wood in response to strain caused by impact. The MOE for a sample set of 40 pieces of Douglas-fir lumber was determined through stress wave velocity and density and compared with the corresponding static MOE. A correlation coefficient of 0.95 was reported, which shows excellent potential for using the stress wave timing technique to grade lumber based on MOE.

An effort to apply this technology to veneer was initiated by Roy Pellerin of Washington State University (WSU) and Peter Koch of U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station (New Orleans, Louisiana, USA). Rotary cut southern yellow pine veneer for this study was shipped to WSU for evaluation of MOE using a laboratory-built experimental stress wave timer. Modulus of elasticity for each veneer sheet was determined from static tests conducted on samples obtained from each veneer sheet. There was a strong relationship between static tensile MOE and ultrasound MOE, as evidenced by a correlation coefficient of 0.92 (Koch 1967).

Based on this success, a faster stress wave grading apparatus was constructed by WSU and sent to the Southern Experiment Station for an extensive study of 10,350 southern yellow pine veneers that were to be manufactured into laminated beams. The goal was to determine the MOE of each veneer and use this information to place the stiffest veneer in the highly stressed tension and compression zones and to place the lowest stiffness near the neutral axis (Koch and Woodson 1968). Figure 8.3 shows the WSU stress wave timer used in that study. The stress wave was introduced through an anvil impact system and captured by a piezoelectric probe.

Each piece of southern yellow pine veneer was 0.17 in. (4.3 mm) thick by 2.75 in. (7 cm) wide and 100 in. (2.5 m) long. The stress wave velocity was determined across a 92-in. (2.3-m) span as an average of three consecutive time readings for each veneer. This was the basis for sorting the veneer into groups for manufacturing laminated beams. Every 50th veneer was also tested to determine the

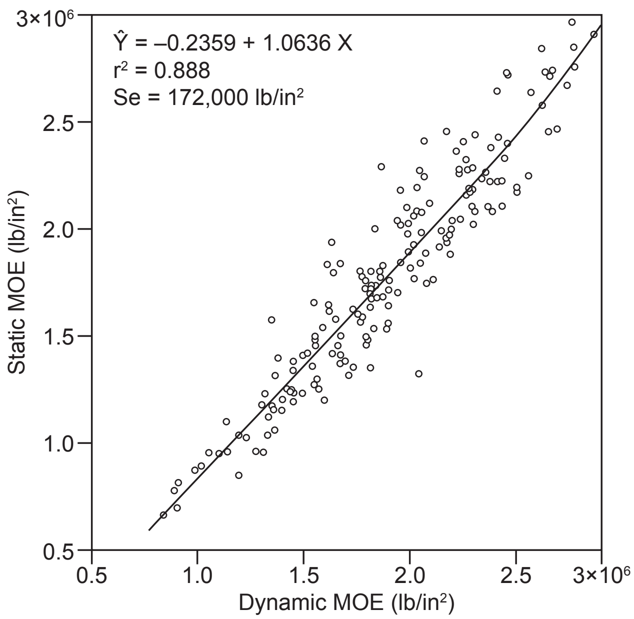


Figure 8.4—Regression of static and ultrasound MOE of southern yellow pine veneer (Koch and Woodson 1968).

static tensile MOE for comparison against the ultrasound MOE. Figure 8.4 shows the regression of static MOE and ultrasound MOE for these veneers. The correlation coefficient was 0.94 for the 177 veneers evaluated.

The veneer was then strategically placed during beam layup with the stiffest veneers on the outside and those with the lowest stiffness near the neutral axis. The resulting beams had predictably high static MOE values with low standard deviations. These beams were essentially the first experimental LVL manufactured from stress wave graded veneer.

Subsequent laboratory studies (Hunt et al. 1989; Jung 1979; Jung 1982) were conducted to investigate the concept for use in evaluating veneer strands, in addition to examining the effect that naturally occurring defects have on wave behavior.

Metriguard, Inc., was founded in 1973 to commercialize the use of stress wave timing technology for lumber, wood composites, paper, and veneer. Metriguard's first system was the portable 239 stress wave timer, designed to measure the transit time of an impact-induced wave. The wave was introduced with a pendulum impactor to a clamp attached to the sample. Piezoelectric transducers were placed at two points of the specimen and used to sense the passing of the wave. The time it takes for the wave to travel between the sensors was measured and displayed. This time was then used to compute wave propagation speed through the material.

Concurrently, Trus Joist was developing commercial LVL for use as a flange material for open web wood and steel trusses and wood I-joists. They began manufacturing LVL in 1972 but experienced wide variation in mechanical properties of the LVL they manufactured. They found that there was no relationship between the visual grade mix of the Douglas-fir veneer and the strength properties of the LVL (Kunesh 1978).

Trus Joist approached Metriguard, Inc., about their portable stress wave timer to grade veneer. Robert Kunesh of Trus Joist Corporation and Roy Pellerin of WSU used a Metriguard Model 239 to grade 0.10-in.- (2.5-mm-) thick Douglas-fir C and D visual grade veneer. The veneer was sorted into several groups based on stress wave velocity. Laminated veneer lumber was then manufactured from these groups and tested to determine the relationships between the veneer stress wave velocity and bending and tension properties of the LVL billets. Correlation coefficients were 0.92 between ultrasound MOE and tension MOE and 0.91 between ultrasound MOE and static bending MOE. The use of stress wave NDE technology allowed Trus Joist to accurately assess veneer sheet quality and translate it into LVL with predictable properties with low variability (Kunesh 1978; Pieters 1979).

Based on the success of stress grading veneer, Metriguard focused development efforts on building an automated production line ultrasonic veneer grading system for Trus Joist. The Metriguard 2600 system used rolling ultrasonic transducers to input and receive stress waves that traveled along the longitudinal length of each veneer sheet. Approximately 60 ultrasonic pulses per second were sent into the material, resulting in 50 to 100 time measurements for each sheet of 27-in.- (68.6-cm-) wide veneer. These measurements were averaged for each sheet of veneer and used to sort the veneer into one of several grades based on transit time. Low transit time corresponded to high velocities, which is indicative of veneers with high stiffness as defined by fundamental one-dimensional wave theory.

The first commercial machine developed had a production speed of about 100 ft/min (30.5 m/min), which was limited by acoustic noise emissions produced by the veneer and by ultrasonic intensity of the sending transducer (Logan 1987; Logan 2000). Improvements in transducers and signal processing allowed production speeds to increase to 200 ft/min (61 m/min) by the early 1990s (Uskoski et al. 1993).

Metriguard continued to refine and develop ultrasonic veneer grading technology and equipment and introduced the Model 2650 DFX and 2800 DME in 2000. Digital signal processing coupled with continued noise reduction has increased the stress wave sampling rate by 60%, up to 200 ultrasonic pulses per minute. This resulted in increased production speeds of 300 to 425 ft/min (91.4 to 129.5 m/min) of veneer through the ultrasound veneer graders (Logan 2000). Newer models can operate up to 600 ft/min. This system also includes temperature correction for stress wave propagation time and radio frequency measurement of specific gravity, moisture content, and

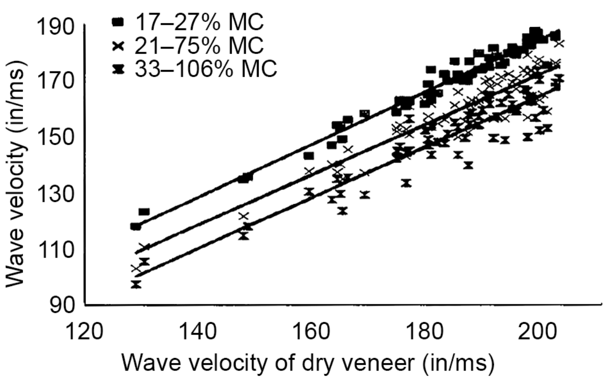


Figure 8.5—Stress wave velocities of southern yellow pine veneer at several moisture content (MC) ranges compared with stress wave velocity of dry veneer measured with a digital oscilloscope (1 in/ms = 25.4 m/s) (Brashaw et al. 1996).

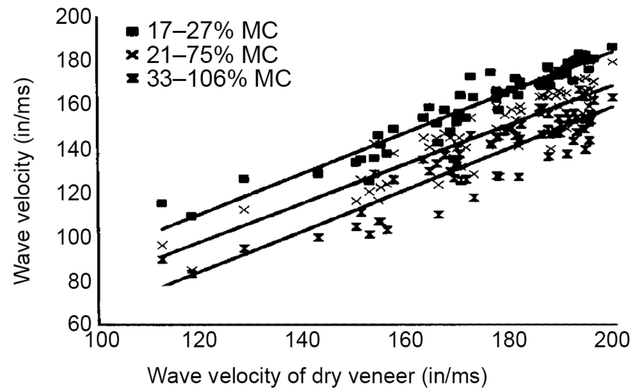


Figure 8.6—Stress wave velocities of southern yellow pine veneer at several moisture content (MC) ranges compared with stress wave velocity of dry veneer measured with a stress wave timer (1 in/ms = 25.4 m/s) (Brashaw et al. 1996).

veneer sheet width and thickness and computes the MOE of each sheet of veneer. Because many veneer manufacturers evaluate hot veneer directly after the dryer outfeed, the temperature effect on stress wave velocity is important. The temperature correction factors are based on research completed at the Forest Products Laboratory and Metriguard (Green et al. 1999; Logan 2000). The ability to determine specific gravity allows for the determination and sorting by MOE instead of only by transit time and should allow for improved utilization of the resource (Logan 2000). Current equipment models provide ultrasonic propagation measurements along with specific gravity measurements and MOE determination and allow sorting veneer based on MOE. MOE sorting and corresponding LVL layup allow for very precise control of the MOE in the final LVL product (Moore and Bier 2002). In addition, studies have been conducted to couple optical techniques with ultrasonic grading (DeVallance et al. 2011).

Ultrasonic Grading of Green Veneer

The initial application of ultrasonic methods to sort veneer for LVL manufacture was restricted to dry veneer. By the time the veneer is sorted into stress grades, significant drying costs have been incurred. If a similar sorting procedure for green veneer could be developed, it would be possible to dry material with similar strength and stiffness together in customized drying schedules. These custom drying cycles, based on veneer strength and stiffness, could lead to increased efficiency, energy savings, and lower costs by reducing or eliminating veneer redrying.

Laboratory investigations of the use of ultrasonic methods for assessing the quality of green veneer have yielded promising results. Brashaw et al. (1996) evaluated the potential of using these methods to sort green southern yellow pine and Douglas-fir veneer into stress grades. Stress wave transit times were measured on a sample of veneer using both a digital oscilloscope and a commercial grading device. The stress wave transmission times were measured in both green (wet) and dry conditions. They found that wave velocities in green and dry veneers were strongly correlated. Figure 8.5 compares longitudinal wave velocities of southern yellow pine veneer at several moisture content ranges to the velocity of dry veneer measured with an oscilloscope. Figure 8.6 shows longitudinal wave velocities of southern yellow pine veneer at several moisture content ranges compared with the velocity of dry veneer as measured with a commercial stress wave timer. This research effort indicated that it is possible to sort green veneer prior to drying.

Radio frequency measurements for density and moisture content of green veneer can be made with the Metriguard veneer grading equipment. The lack of physical sorting capability in green veneer lines is currently limiting implementation of these processes in manufacturing facilities.

Ultrasonic Evaluation of Red Maple Veneer—Results from a Demonstration Study

A major shift is occurring in the ecology of eastern deciduous forests. There is an aggressive proliferation of red maple (*Acer rubrum*) as a consequence of past forest harvesting and use. Prior to the 20th century, red maple was confined to lowlands. Fire suppression and forest fragmentation triggered by urban sprawl have enabled red maple to become an increasingly significant component of the forest. Additionally, wildlife such as deer and turkeys rely heavily on oaks for food. Burgeoning populations of these species have a negative impact on oak generation, thereby providing opportunities for red maple. To provide for greater diversity in these forests, markets for red maple wood must be found so that cost-effective, active management can take place.

Research has shown that red maple has excellent potential as a structural material. For example, solid sawn red maple can perform well in commonly used engineered components such as trusses and prefabricated I-joists (Brashaw et al. 2001). Red maple lumber can also be used in glued-laminated timber (Janowiak et al. 1995). These efforts were based on earlier research that showed the good to excellent mechanical properties of red maple wood (Green and McDonald 1993).

Engineered composite materials represent one of the fastest growing segments of the wood products industry. Wood composite I-joists are used in more than 40% of new residential construction in North America, and LVL is the primary material in I-joist manufacture. LVL is made in large billets from veneer sheets that are bonded together with an adhesive system. The billets can be produced to a specified thickness and cut to a desired width. One of the most significant technical advantages of LVL is the adaptability of its design to specific performance characteristics. By strategically placing selected veneer sheets within the composite, it is possible to manufacture a wood-based product that has well-controlled physical and mechanical properties. This enables LVL to be used in a variety of products, including commodity structural components, wind turbine blades, and other specialty products. The dominant raw materials used in current LVL production are Southern Pine and Douglas-fir, but LVL can be manufactured from a wide range of wood species.

Of critical importance to using a specific species in LVL is the ability to accurately assess the mechanical properties of individual veneer sheets. Also important is knowledge of the range of mechanical properties obtained from available sources. A study by Kimmel and Janowiak (1995) showed that red maple can be used in LVL and that available ultrasonic veneer grading equipment used in LVL manufacturing facilities can be used to effectively grade red maple veneer. More importantly, the results from their testing showed that red maple would produce veneer that has good potential for LVL. The red maple veneer used in the study by Kimmel and Janowiak was obtained from a small sample of logs from one location. The purpose of the study reported here was to expand on their positive results by investigating the ultrasonic grade yield from a larger sample of red maple veneer obtained from a range of sites throughout the Eastern and Lake States regions of the United States.

Materials and Methods

Red maple logs were obtained from cooperating sawmills in six states (Table 8.1) and were graded according to Forest Service specifications (Rast et al. 1973). An attempt was made to secure two logs from visual grades No. 1, No. 2, and No. 3 from each state, but only the log suppliers from Vermont, West Virginia, and Wisconsin provided at least two sawlogs of each visual grade (Table 8.2). In total, 48 suitable logs were obtained. Because of the inconsistency in the number of logs supplied from each State, veneer yield could be compared only on the basis of geographic region of origin. The logs were grouped into either the Lake States region (Michigan and Wisconsin) or Eastern States region (New York, Pennsylvania, Vermont, and West Virginia). The number of logs by region and grade is given in Table 8.2.

Table 8.1—Log suppliers by State

State	Supplier
Michigan	College of Forest Resources and Environmental Science Michigan Technological University Houghton, MI 49931
New York	Potter Lumber Co., Inc. PO Box 10 Allegany, NY 14706
Pennsylvania	Kane Hardwoods, A Collins Pine Co. PO Box 807 Kane, PA 16735
Vermont	Mill River Lumber, Ltd. PO Box 100 North Clarendon, VT 05759
	Killington Wood Products PO Box 696 Rutland, VT 05701
West Virginia	Cranberry Hardwoods 263 White Oak Drive Beckley, WV 25801
Wisconsin	Kretz Lumber Co., Inc. W11143 Highway G PO Box 160 Antigo, WI 54409

Table 8.2—Red maple sawn logs by state and visual grade

		Number of logs by visual grade			
State	Total	Grade 1	Grade 2	Grade 3	Other
Lake States	23	10	4	5	4
Michigan	14	7	1	2	4
Wisconsin	9	3	3	3	—
Eastern States	25	5	12	8	—
New York	7	0	4	3	—
Pennsylvania	6	1	4	1	—
Vermont	6	2	2	2	—
West Virginia	6	2	2	2	—

The average diameter (calculated from inside the bark at each end of the log) and length were used to estimate total wood volume in each log. The logs were then debarked, steamed for 72 h, and rotary peeled into nominal 1/8-in.- (standard 3-mm-) thick veneer. The diameter of the peeler core was set at 4 in. (102 mm). Individual sheets, strips, and fishtails were numbered to identify the log from which they were derived. To avoid mislabeling the veneer, one log was completely processed and labeled before another was rotary peeled. The veneer was dried to approximately 10% to 12% moisture content and shipped to the USDA Forest Service, Forest Products Laboratory (FPL) in Madison, Wisconsin, USA, for ultrasonic testing.

At FPL, the 36- and 54-in.- (91- and 137-cm-) wide veneer sheets were hand fed through an ultrasonic veneer grader (Metriguard Model 2600) (Fig. 8.1). Three stress wave time (SWT) readings (parallel to grain) were collected for the 36-in. (91-cm) sheets. Four measurements of SWT were taken on the 54-in.- (137-cm-) wide sheets. The SWT values were averaged to arrive at a single value for each sheet, and the MOE was calculated using the following equation (Pellerin and Ross 2002):

$$\mathrm{MOE} = c^2\rho = 2.156\,(10^8)\left(\frac{1}{\Delta t^2}\right)\rho$$

in which Δt represents stress wave time (µs/ft) and ρ represents density of the veneer sheet (lb/ft^3).

Data obtained from the ultrasonic veneer grader was verified by independently testing randomly selected sheets with a portable stress wave timer (Metriguard Model 239A). Moisture content samples were also randomly selected during veneer measurement and ultrasonic grading process; moisture content was measured by the oven-dry method (ASTM D4442–92, ASTM 1999). Average moisture content was 6.3%, and standard deviation was 1.15%.

Results and Discussion

Veneer Yield

The veneer from each log was grouped into four categories: 54-in.- (137-cm-) wide sheets, 36-in.- (91-cm-) wide sheets, strips, and fishtails. Measurements of length, width, thickness, and weight were used to calculate the volume and density of each sheet. The volume of strips and fishtails was estimated by weighing the veneer and using the average density of the 54-in. (137-cm) sheets from the same log to calculate volume.

Total veneer volume by region, visual log grade, veneer type, and veneer density is presented in Table 8.3. The density values found in this experiment were higher than those reported in the *Wood Handbook* (Forest Products Laboratory 2010). Average density values for the red maple veneer were between 34.6 and 37.0 lb/ft^3 (554 and 542 kg/m^3), whereas the density of red maple reported in the *Wood Handbook* is 33.7 lb/ft^3 (539 kg/m^3). The higher density values of the experimental data are likely caused by errors in drying or dimension measurements of the veneer.

The veneer volumes in Table 8.3 were converted to percentages based on corresponding total log volumes (Table 8.4). In general, the largest portion of veneer was recovered as 54-in. (137-cm) sheets, followed by strips, fishtails, and 36-in. (91-cm) sheets. The only exception occurred in the case of No. 1 logs from the Eastern States, where more veneer was recovered as 36-in. (91-cm) sheets than as fishtails.

Close examination of the yields and regional comparisons between the same log grades revealed that the Eastern States logs consistently yielded between 4% and 8% more veneer than yielded by the Lake States logs. When these comparisons are restricted to the amounts of veneer recovered in each of the four forms, there was an obvious difference between the No. 2 logs from the Lake States and the Eastern States. There is a large disparity in the amount of veneer recovered as 54-in. (137-cm) sheets: 41.4% of the log volume from the Eastern States logs was converted to full-size sheets compared with only 28.4% of the log volume from the Lake States logs. Correspondingly, the Lake States logs yielded higher percentages of strips and fishtails.

It may be expected that the highest overall yield would come from the logs with the fewest defects (No. 1 logs) and that the lowest yield would come from logs with the greatest number of defects (No. 3 logs). This would almost certainly be expected when considering veneer yield in the form of 54-in. (137-cm) sheets, where defects may limit sheet length. The overall veneer yield from the Eastern States logs did decrease with log quality, but this trend was not observed for the Lake States logs (Table 8.5). Furthermore, when only the yield of 54-in. (137-cm) veneer sheets was considered, two distinct groups of logs were observed:

1. No. 1 logs from Lake and Eastern States and No. 2 logs from Eastern States (veneer yield of 41% to 42% as 54-in.- (137-cm-) wide sheets)
2. No. 2 logs from Lake States and No. 3 logs from Lake and Eastern States (veneer yield of 24% to 26% as 54-in.- (137-cm-) wide sheets).

A possible explanation for the lower yield from the Lake States logs is that the Eastern States logs were larger, on average (Table 8.6). The mean diameter of all three visual grades of the Eastern States logs was greater than that of the Lake States logs, especially for the No. 3 logs. Because all logs were peeled to the same 4-in. (102-mm) core diameter, a constant volume was lost from each log. This constant core volume constitutes a larger percentage of a small log's volume and therefore could result in the recovery of a lower percentage of veneer (by overall log volume) from the smaller logs. Statistical hypothesis tests on our data support this logical explanation for No. 3 logs only.

Two-sample Student's t-tests were used to test the hypothesis that the mean diameters of the No. 1, No. 2, and No. 3 logs from the Lake States were smaller than the mean diameters of the corresponding logs from the Eastern States. At the 5% level of significance, the mean diameters of No. 1 and No. 2 logs were not significantly different ($p = 0.550$ and 0.306, respectively). Nevertheless, the yield from the Eastern States logs was approximately 5%

Table 8.3—Red maple veneer yield from visual log grades[a]

Region and log grade	Veneer volume (ft^3) 54-inch sheets	36-inch sheets	Strips	Fishtails	Total from tree	Veneer density (lb/ft^3)
Lake States						
1	34.3	2.8	11.3	5.0	53.3	36.7
2	9.0	0.0	5.6	2.7	17.2	34.7
3	6.5	0.3	6.9	1.7	15.4	37.0
Eastern States						
1	23.8	3.3	8.7	2.3	38.1	35.0
2	49.0	1.3	15.8	8.2	74.2	34.6
3	21.7	3.1	16.8	6.5	47.9	35.4

[a]1 ft^3 = 0.028 m^3; 1 lb/ft^3 = 16.0 kg/m^3; 1 inch = 25.4 mm.

Table 8.4—Red maple veneer yield by log volume

Region and log grade	Total log volume (ft^3)	Total % yield (by log volume)	Breakdown of yield (% yield from original log volume) 54-inch sheets	36-inch sheets	Strips	Fishtails	Waste and core
Lake States							
1	84.1	63.4	40.7	3.4	13.4	5.9	36.6
2	31.7	54.4	28.4	0.0	17.6	8.4	45.7
3	28.0	54.9	23.1	0.9	24.8	6.2	45.1
Eastern States							
1	55.9	68.2	42.6	5.8	15.6	4.1	31.8
2	118.3	62.7	41.4	1.1	13.3	6.9	37.3
3	80.7	59.4	26.8	3.8	20.8	8.0	40.6

Table 8.5—Combined Eastern and Lake States red maple veneer yield

Log grade	Total log volume (ft^3)	54-inch sheets	36-inch sheets	Strips	Fishtails	Total from tree
		Veneer volume (ft^3)				
1	140.0	58.1	6.1	20.0	7.3	91.4
2	150.0	58.0	1.3	21.3	10.8	91.4
3	108.7	28.1	3.3	23.7	8.2	63.3
		Percentage of yield (by log volume)				
1	—	41.5	4.4	14.3	5.2	65.3
2	—	38.6	0.9	14.2	7.2	60.9
3	—	25.9	3.0	21.8	7.5	58.3

Table 8.6—Average diameter of red maple sawlogs

	Log diameter (in.)					
	No. 1 Logs		No. 2 Logs		No. 3 Logs	
	Lake	Eastern	Lake	Eastern	Lake	Eastern
	11.5	13.3	11.8	12.0	9.8	12.5
	12.1	13.3	12.8	12.3	10.0	12.5
	13.3	15.5	13.5	13.0	10.8	13.5
	13.5	16.8	14.4	13.5	11.6	13.8
	13.8	18.5	—	13.8	12.8	14.0
	14.8	—	—	14.5	—	15.0
	15.0	—	—	14.5	—	16.5
	15.0	—	—	14.8	—	19.5
	18.3	—	—	15.5	—	—
	—	—	—	16.3	—	—
	—	—	—	16.8	—	—
	—	—	—	17.8	—	—
(Mean)	14.1	15.5	13.1	13.8	11.0	14.7

higher for No. 1 logs and 7% higher for No. 2 logs. The mean diameter of the Lake States No. 3 logs was smaller than that of the Eastern States No. 3 logs ($p = 0.018$), but the total veneer yield was only approximately 4.5% lower, despite a 3.7-in. (94-mm) difference in diameter. These results suggest that the observed yield differences may have been due to other factors, such as the presence of defects or differences in roundness (leading to loss when logs are squared to a constant diameter on the lathe).

Veneer Modulus of Elasticity

Figures 8.7 and 8.8 are histograms of MOE distributions of veneer by region and log grade. The MOE values of veneer from the Lake States logs follow a normal distribution with a mean of 1.80×10^6 lb/in^2 (12.4 MPa) and standard deviation of 0.22×10^6 lb/in^2 (1.5 MPa). The MOE distribution of veneer from the Eastern States logs was skewed to the left, with a mean of 1.79×10^6 lb/in^2 (12.3 MPa) and standard deviation of 0.37×10^6 lb/in^2 (2.6 MPa).

When comparing the two distributions, it is interesting to note the contribution of veneer from the No. 3 logs. The low MOE tail in Figure 8.8 (Eastern States) can be attributed to veneer from the No. 3 logs. This might be expected because more prevalent knots would lead to lower MOE values. In addition, slope of grain is more prevalent in low visual grade logs, which can cause a decrease in MOE. When the MOE distribution from the Lake States logs is considered (Fig. 8.7), the No. 3 logs contribute to only the upper two-thirds of the distribution. Because of the inconsistency in MOE of veneer from the No. 3 logs, it is interesting to consider the MOE distributions from only the No. 1 and No. 2 logs.

When veneer from only the No. 1 and No. 2 logs is considered, both distributions are normal (Figs. 8.9 and 8.10). The veneer from the Lake States logs had an average MOE of 1.77×10^6 lb/in^2 (12.2 MPa) with a standard deviation of 0.20×10^6 lb/in^2 (1.4 MPa), whereas the average MOE of veneer from the Eastern States was 1.89×10^6 lb/in^2 (13 MPa) with a standard deviation of 0.25×10^6 lb/in^2 (1.7 MPa). Because the MOE values of veneer from both regions appear to be adequately modeled by a normal distribution, a two-sample Student's *t*-test can be used to compare their means. When the hypothesis that the MOE of veneer from the Eastern States logs is greater than that of the veneer from the Lake States logs is tested at the 5% significance level, we conclude that the mean MOE of the Eastern States veneer is higher ($p < 0.000$).

A statistical comparison of the means of the two distributions, not including No. 3 logs, suggests that the difference of 120×10^6 lb/in^2 (8.3 MPa) is significant. However, in reality, this difference is not likely to have a physical consequence in the overall evaluation of the resource. The difference becomes apparent only when the No. 3 logs are ignored so as not to consider the low strength tail in the MOE distribution from Eastern States logs. The MOE of veneer from the No. 3 logs and their yield as 54-in. (137-cm) sheets are actually quite important to this work. These logs are the lowest cost raw material that was studied in this project. They typically sell for pulpwood prices. If a good yield of acceptable quality veneer were obtained, these logs could be a highly valuable resource for LVL manufacture.

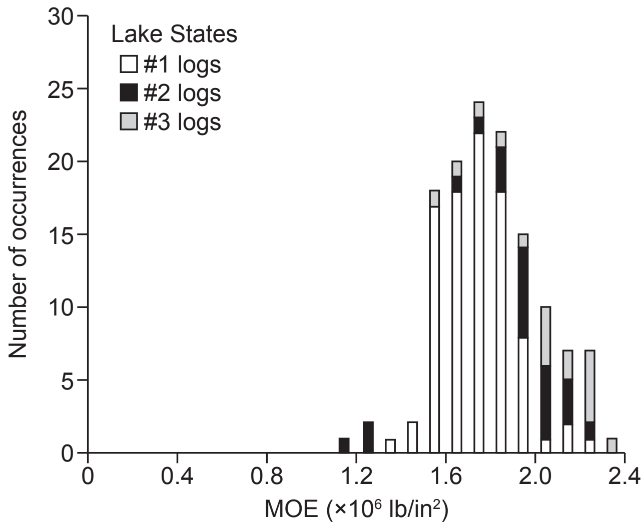


Figure 8.7—Histogram of modulus of elasticity (MOE) results from Lakes States red maple sawlogs.

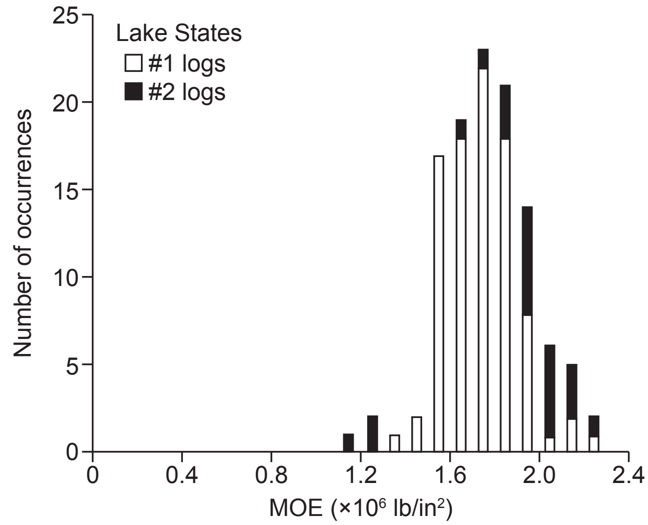


Figure 8.9—Histogram of MOE of veneer from Lake States No. 1 and No. 2 grade red maple sawlogs.

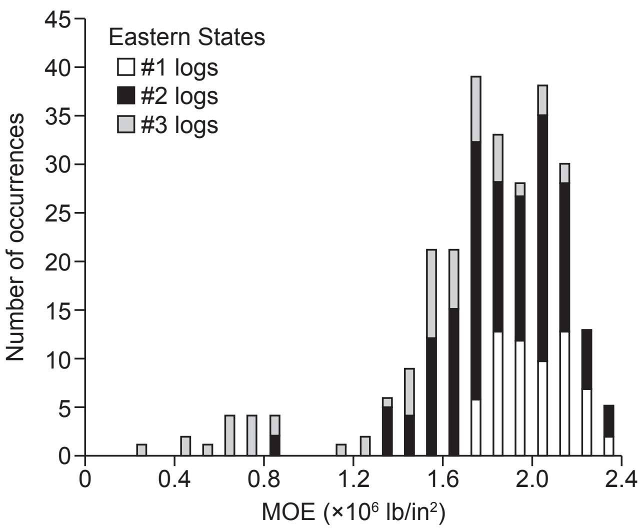


Figure 8.8—Histogram of MOE of veneer from Eastern States red maple sawlogs.

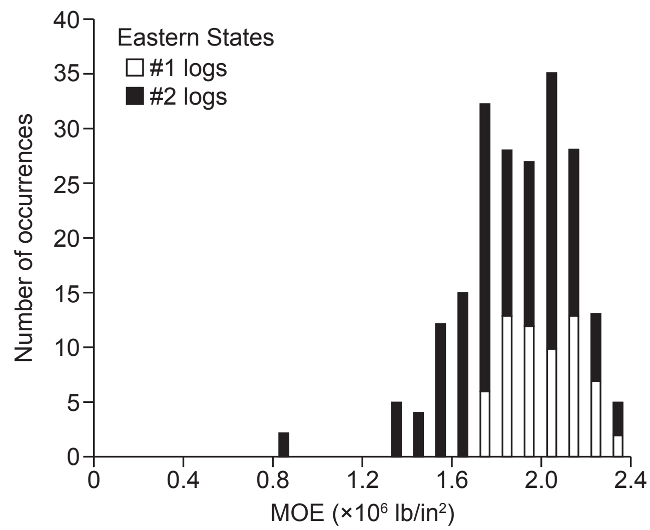


Figure 8.10—Histogram of MOE of veneer from Eastern States No. 1 and No. 2 grade red maple sawlogs.

Although the veneer yield from the Eastern States logs was found to be slightly higher than that from the Lake States logs, it may be best to combine all data. The data set is then a representative sample of the red maple resource, without regional comparison (Fig. 8.11). After all data are pooled, the MOE distribution still has a low MOE tail, with a mean of 1.80×10^6 lb/in^2 (12.4 MPa) and standard deviation of 0.33×10^6 lb/in^2 (2.3 MPa). The combined data set (Table 8.5) suggests that the No. 1 and No. 2 logs yield similar amounts of veneer in the form of 54-in. (137-cm) sheets (41.5% and 38.6%, respectively) and strips (14.3% and 14.2%, respectively). The MOE values of the 54-in. (137-cm) sheets from the No. 1 and No. 2 logs follow a normal distribution with relatively low standard deviation (Fig. 8.11). The No. 3 logs yielded 25.9% of the original volume as 54-in. (137-cm) sheets. The MOE of this veneer varied widely (Table 8.5, Fig. 8.11), but when the low price of these logs is considered, their use may provide an acceptable economic return. During LVL lay-up, the veneer from these logs would be sorted along with the rest of the veneer—low MOE material would go to the core and high strength material would go to the faces. The overall veneer yield generally decreased with decreased log quality, but by only approximately 7% (65.3% to 58.3%) (Table 8.5).

Conclusions

Comparisons of red maple veneer yield and MOE based on geographic region of origin were attempted, but the data were best considered as a whole. In terms of the original log volume, veneer yield decreased with log quality, but only by 7%. The veneer yields from No. 1 and No. 2 logs as 54-in. (137-cm) sheets were actually quite similar—approximately

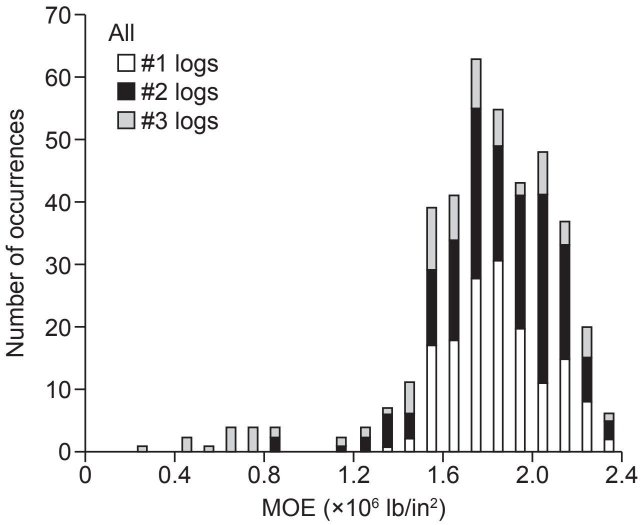


Figure 8.11—Composite histogram of MOE of veneer from all red maple sawlogs.

42% of log volume. Although the No. 3 logs yielded only approximately 26% of the original log volume as 54-in. (137-cm) sheets, the low cost of these logs may make them a viable resource for LVL production. The MOE values of the veneer are normally distributed, with moderate variation: mean = 1.8×10^3 lb/in^2 (12.4 MPa), standard deviation = 0.33×10^3 lb/in^2 (2.3 MPa). These values represent adequate strength properties for LVL manufacture. As may be expected, the distribution had a low strength tail that was attributed to veneer from the No. 3 logs. This material would likely be sorted out and used in the core, where high quality veneer is not needed.

Literature Cited

APA. 2000. Regional production and market outlook for structural panels and engineered wood products, 2000–2005. APA Economics Rep. E66. Tacoma, WA: American Plywood Association.

ASTM. 1999. Standard test methods for direct moisture content measurement of wood and wood-base materials. ASTM D4442–92. West Conshohocken, PA: American Society for Testing and Materials.

Brashaw, B.K. 2015. Ultrasonic veneer grading. In: Nondestructive Evaluation of Wood. Second Edition. R.J. Ross, Ed. General Technical Report. FPL–GTR–238. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 167 p.

Brashaw, B.K.; Ross, R.J.; Pellerin, R.F. 1996. Stress wave nondestructive evaluation of green veneer. In: Proceedings, 10th international symposium on nondestructive testing of wood; 1996 August 26–28; Lausanne, Switzerland: 135–146.

Brashaw, B.K.; Vatalaro, R.J.; Lackore, M.; Ross, R.J.; Wanx, X.; Forsman, J.. 2001. Advancing technology to manufacturing trusses from hardwood lumber. NRR1/T4–2001. Duluth, MN: Natural Resources Research Institute, University of Minnesota, Duluth.

DeVallance, D.B.; Funck, J.W.; Reeb, J.E. 2011. Evaluation of laminated veneer lumber tensile strength using optical scanning and combined optical–ultrasonic techniques. Wood and Fiber Science. 43(2): 169–179.

Forest Products Laboratory. 2010. Wood handbook—wood as an engineering material. Gen. Tech. Rep. FPL–GTR–190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 508 p.

Galligan, W.L.; Courteau, R.W. 1965. Measurement of the elasticity of lumber with longitudinal stress waves and the piezoelectric effect of wood. In: Proceedings, 2nd symposium on nondestructive testing of wood; 1965 April; Spokane, WA. Pullman, WA: Washington State University: 223–244.

Green, D.W.; McDonald; K.A. 1993. Mechanical properties of red maple structural lumber. Wood and Fiber Science. 25(4): 365–374.

Green, D.W.; Evans, J.W.; Logan, J.D.; Nelson, W.J. 1999. Adjusting modulus of elasticity of lumber for changes in temperature. Forest Products Journal. 49(10): 82–94.

Guss, L. 1994. Engineered wood products: a bright future or a myth. In: Proceedings, 28th international particleboard/composite materials symposium. 1994 April 12–14; Pullman, WA: Washington State University: 71–88.

Hunt, M.O.; Triche, M.H.; McCabe, G.P.; Hoover, W.L. 1989. Tensile properties of yellow poplar veneer strands. Forest Products Journal. 39(9).

Janowiak, J.J.; Manbeck, H.B.; Hernandez, R.: Moody, R.C.; Blankenborn, P.R.; Labosky, P. 1995. Efficient utilization of red maple in glued-laminated timber beams. Researh Paper FPL–RP–541. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 23 p.

Jung, J. 1979. Stress wave grading techniques on veneer sheets. General Technical Report FPL–GTR–27. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 10 p.

Jung, J. 1982. Properties of parallel-laminated veneer from stress-wave-tested veneers. Forest Products Journal. 32(7): 30–35.

Kimmel, J.D.; Janowiak, J.J. 1995. Red maple and yellow-poplar LVL from ultrasonically graded veneer. Forest Products Journal. 45(7–8): 54–58.

Koch, P. 1967. Location of laminae by elastic modulus may permit manufacture of very strong beams from rotary-cut Southern pine veneers. Research Paper SO–30. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station.

Koch, P.; Woodson, G.E. 1968. Laminating butt-jointed, log-run southern yellow pine veneers into long beams of uniform high strength. Forest Products Journal. 18(10): 45–51.

Kunesh, R.H. 1978. Using ultrasonic energy to grade veneer. In: Proceedings, 4th symposium on nondestructive testing of wood; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 275–278.

Logan, J.D. 1987. Continuous ultrasonic veneer testing: sorting veneer for structural applications. Sawmill Clinic, Portland, OR.

Logan, J.D. 2000. Machine sorting of wood veneer for structural LVL applications. In: Proceedings, 34th international particleboard/composite materials symposium. Pullman, WA: Washington State University: 67–77.

Moore, H.W.; H. Bier. 2002. Predicting laminated veneer lumber properties from the sonic propagation time and density of dried veneer in the production environment. In: Proceedings of the 13th international symposium on nondestructive testing of wood. Berkeley, CA: University of California: 89–96.

Pieters, A.R. 1979. Ultrasonic energy: a new method for veneer grading. In: Proceedings, ASCE convention; 1979. Preprint #3534. Reston, VA: American Society of Civil Engineers.

Pellerin, R.F.; Galligan, W.L. 1973. Nondestructive method of grading wood materials. Canadian Patent 918286.

Pellerin, R.F.; Ross, R.J., eds. 2002. Nondestructive evaluation of wood. Madison, WI: Forest Products Society. 129 p.

Rast, E.D.; Sonderman, D.L.; Gammon G.L. 1973. A guide to hardwood log grading. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 5 p.

Ross, R.J.; Erickson, J.R.; Brashaw, B.K.; Wang, X.; Verhey, S.A.; Forsman, J.W.; Pilon, C.L. 2004. Yield and ultrasonic modulus of elasticity of red maple veneer. Forest Products Journal. 54(12): 220–225.

Uskoski, D.A.; Bechtel, F.K.; Gorman, T.M. 1993. Ultrasonic stress graded veneer. In: Proceedings, 1st international panel and engineered wood technology exposition; 1993 October 19–21; Atlanta, GA. San Francisco, CA: Miller Freeman.

Chapter 9

Properties of Hardwood Laminated Veneer Lumber

Xiping Wang, Research Forest Products Technologist
Robert J. Ross, Supervisory Research General Engineer
Brian K. Brashaw, Program Manager
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

Steven A. Verhey, Research Assistant Professor
John W. Forsman, Assistant Research Scientist (retired)
College of Forest Resources and Environmental Science, Michigan Technological University, Houghton, Michigan

John R. Erickson, Former Director (deceased)
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

This chapter is intended to serve as a primer on use of hardwoods for laminated veneer lumber (LVL). It presents a pilot study that was conducted to evaluate the flexural properties of LVL manufactured from ultrasonically graded red maple veneer and was originally published by Wang et al. (2003):

The purpose of the pilot study reported here was to examine the flexural properties of LVL manufactured from ultrasonically rated red maple veneer sheets. The specific objectives were as follows:

1. To determine the flatwise and edgewise bending properties of 1/2-in.- and 2-in.- (1.3- and 5-cm-) thick red maple LVL billets
2. To examine the relationship between nondestructive parameters of red maple veneer and flexural properties of LVL billets
3. To demonstrate the use of ultrasonic veneer grading for improving the structural performance of red maple LVL

Materials and Methods

In the first phase of the study, we determined the flatwise and edgewise bending properties of LVL billets and explored the predictability of their structural performance. The experimental procedure is shown in Figure 9.1. Twelve red maple veneer sheets that had been ultrasonically rated in a previous study (Ross et al. 2004) were manufactured into 12 LVL billets in the laboratory. The sheets were selected on the basis of their corresponding dynamic modulus of elasticity (MOE_d) values. The MOE_d of red maple veneer was calculated from wave propagation time (T), gauge length (L), and veneer density (ρ) using the equation

$$MOE_d = \left(\frac{L}{T}\right)^2 \rho$$

The moisture content of the veneer was 5% to 8% at the time of ultrasonic testing.

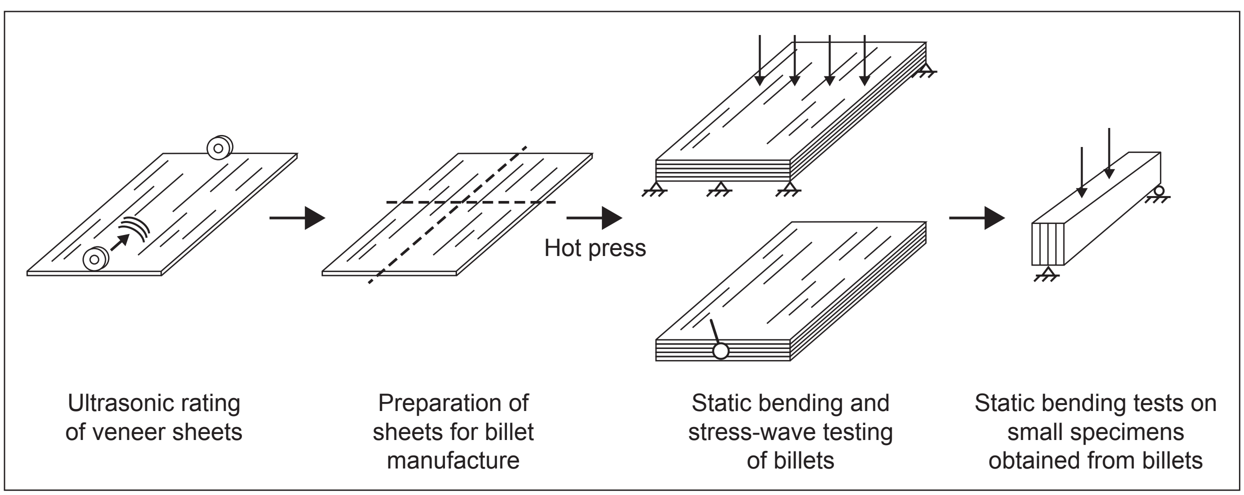


Figure 9.1—Flow chart for phase 1 of the study.

Each 50- by 101- by 1/8-in. (127- by 257- by 0.3-cm) veneer sheet was first cut into four 25- by 50- by 1/8-in. (64- by 257- by 0.3-cm) sheets. The four sheets were then pressed into a 1/2-in.- (1.3-cm-) thick LVL billet (hereafter called "thin" billet). A phenol formaldehyde resin was applied at a rate of 34 lb/10^3 ft^2 (166 g/m^2) in LVL fabrication. Each billet was hot pressed at 175 lb/in^2 (1.21 MPa) for approximately 3 min at a platen temperature of 300 °F (149 °C). After hot pressing, billets were allowed to cool for 24 h. They were then trimmed and tested nondestructively using stress-wave and static bending (center-line loading) test methods to obtain estimates of modulus of elasticity.

Six 1- by 20- by 1/2-in. (2.5- by 51- by 1.3-cm) specimens were cut from each billet, parallel to grain. These specimens were conditioned at 74 °F (23 °C) and 65% relative humidity (12% equilibrium moisture content) for several weeks. Specimens were then tested to failure in edgewise bending using third-point loading. Both edgewise bending MOE (MOE_{ew}) and modulus of rupture (MOR) values were then determined.

In the second phase of the study, we examined the enhancement of structural performance of red maple LVL products. Forty-eight 25-1/2- by 101- by 1/8-in. (65- by 257- by 0.3-cm) ultrasonically rated veneer sheets from a previous study (Ross et al. 2004) were used to make four 2-in.- (5-cm-) thick, 12-ply billets at the laboratory. The veneer sheets were segregated into three MOE classes (low, medium, and high) based on their dynamic MOE values. The procedure of hot pressing in this phase was similar to that used in phase 1. First, four plies of the veneer were pressed to form a 1/2-in.- (1.3-cm-) thick panel. Three of these panels were then pressed to form a nominal 2-in.- (5-cm-) thick billet (actual thickness of 1.5 in. (3.8 cm), hereafter called "thick" billet). The layup patterns for the thick billets and dynamic MOE of the veneer are shown in Table 9.1.

The first three LVL billets were manufactured from veneer that had similar quality based on ultrasonic rating, and had low, medium, and high dynamic MOE values, respectively (Table 9.1). The fourth billet was manufactured from veneer that had mixed quality, with the veneer that had high dynamic MOE values on the outer layers and the veneer that had low dynamic MOE values in the core. The billets were pressed and cooled overnight. Each billet was then cut into five 2- by 4-in. (5- by 10-cm) by 8-ft- (2.4-m-) long specimens. Edgewise bending tests were performed on these specimens through third-point loading (ASTM 1999) to obtain estimates of flexural properties.

Table 9.1—Veneer layup pattern for thick[a] LVL billets and dynamic modulus of elasticity (MOE) of veneer

LVL billet	Layup pattern	Average dynamic MOE of veneer ($\times10^6$ lb/in^2)
1	Homogeneous, low MOE	1.61
2	Homogeneous, medium MOE	1.80
3	Homogeneous, high MOE	2.10
		2.04 (outer 1/3)
4	Nonhomogeneous, mixed quality	1.33 (inner 1/3)
		2.04 (outer 1/3)

[a]2-in. (5-cm) thick.

Table 9.2—Results of tests on thin[a] LVL billets and corresponding small specimens[b]

Billet	Veneer MOE_d ($\times10^6$ lb/in^2)	Billet MOE_{fw} ($\times10^6$ lb/in^2)	Small specimen MOE_{ew} ($\times10^6$ lb/in^2)	Small specimen MOR (lb/in^2)
1	1.51	1.09	1.44	9,930
2	1.80	1.91	1.67	12,034
3	2.32	2.06	1.82	13,605
4	1.67	1.68	1.43	12,210
5	1.75	1.69	1.50	13,637
6	2.10	1.87	1.72	14,414
7	1.37	1.40	1.41	8,265
8	1.34	1.09	1.20	8,600
9	2.04	1.81	1.81	14,218
10	1.44	1.47	1.28	11,296
11	1.64	1.75	1.64	11,204
12	2.13	1.82	1.78	15,564
Average	1.76	1.64	1.56	12,081
STD	0.311	0.299	0.202	2,228.5

[a]1/2-in. (1/3-cm) thick.
[b]MOE_d, dynamic modulus of elasticity.
MOE_{fw}, flatwise bending modulus of elasticity.
MOE_{ew}, edgewise bending modulus of elasticity.
MOR, modulus of rupture.
STD, standard deviation.

Results and Discussion

Thin Billets

Test results for the thin (1/2-in.-, 1.3-cm-thick) billets and corresponding small specimens are summarized in Table 9.2. The average values for billet MOE and small specimen MOE are similar to bending MOE values reported in the *Wood Handbook* for clear red maple (Forest Products Laboratory 2010). The observed MOR values for the small specimens are slightly lower than corresponding clear wood values. These results are encouraging as they indicate that the stiffness and strength of LVL manufactured from red maple would be comparable to that of clear wood. While these results are notable, caution should be exercised because the sample size was small. To explore the predictability of structural performance of LVL billets manufactured from ultrasonically rated red maple veneer, we conducted linear regression analysis to examine the relationship between nondestructive parameters of red

Table 9.3—Results of linear regression analysis of relationship between nondestructive parameters of red maple veneer and flexural properties of thin LVL billets[a]

Nondestructive parameter of veneer (x)	Flexural properties of LVL (y)	$y = a + bx$: a	b	r	S_{yx}
T	MOE_{fw} of billet	4.810	–0.0478	0.78	0.203
	MOE_{ew} of small specimen	3.897	–0.0352	0.86	0.114
	MOR of small specimen	36,480.6	–367.4	0.81	1,435.47
MOE_d	MOE_{fw} of billet	0.217	0.8068	0.84	0.177
	MOE_{ew} of small specimen	0.517	0.5918	0.91	0.090
	MOR of small specimen	956.3	6,324.1	0.88	1,145.36

[a]T, ultrasonic wave propagation time; MOE_d, dynamic modulus of elasticity; MOE_{fw}, flatwise bending modulus of elasticity; MOE_{ew}, edgewise bending modulus of elasticity; r, correlation coefficient; S_{yx}, standard error of estimate.

maple veneer and static bending properties of corresponding LVL billets. The results of regression analysis are summarized in Table 9.3.

Figures 9.2 and 9.3 illustrate typical relationships between non-destructive parameters of red maple veneer and static bending properties of LVL billets and small specimens. Both wave propagation time and dynamic MOE of veneer are significantly correlated to the static bending properties of the LVL billets. The correlation coefficients for the relationships range from 0.78 to 0.86 for T versus $MOE_{fw/ew}$/MOR and 0.84 to 0.91 for MOE_d versus $MOE_{fw/ew}$/MOR. Dynamic modulus of elasticity of red maple veneer, as calculated from wave propagation time, gauge length, and veneer density, is apparently a better predictor of the structural properties of LVL billets than is wave propagation time. This indicates that both ultrasonic wave propagation time and veneer density should be taken into account when using ultrasonic propagation to sort red maple veneer for LVL manufacture.

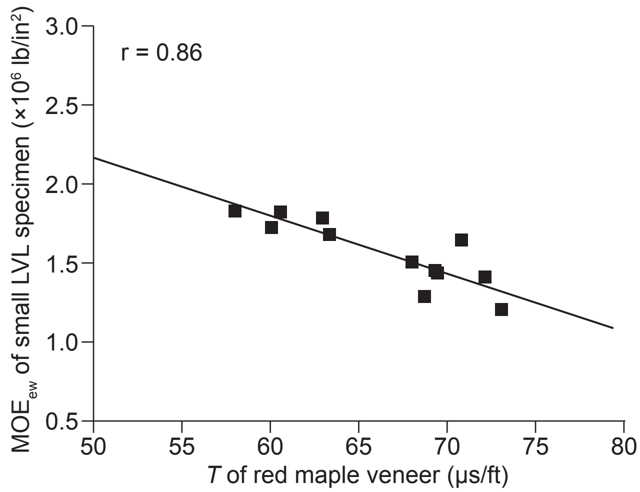


Figure 9.2—Relationship between ultrasonic wave propagation time (T) of red maple veneer and edgewise bending MOE (MOE_{ew}) of small LVL specimens.

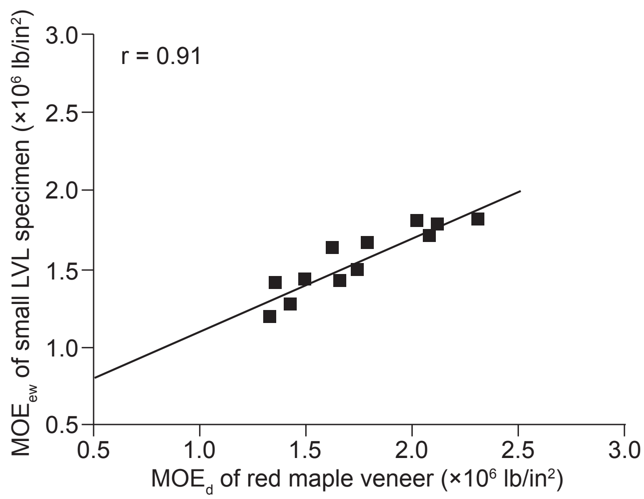


Figure 9.3—Relationship between stress-wave MOE (MOE_{sw}) of red maple veneer and edgewise bending MOE of small LVL specimens.

Thick Billets

The MOE of 2-in.- (5-cm-) thick LVL billets manufactured from ultrasonically rated red maple veneer is shown in Figure 9.4. The error bar indicates the standard deviation (±1 standard deviation). An analysis of variance (at 95% confidence level) of the MOE values indicated that the separation among the low, medium, and high MOE layups was statistically significant. The average dynamic MOE of red maple veneer was 1.61, 1.80, and 2.10 $\times 10^6$ lb/in^2 (11.10, 12.41, and 14.48 GPa) for low, medium, and high MOE layups, respectively. The corresponding edgewise bending MOE of the billets was 1.73, 1.98, and 2.22 $\times 10^6$ lb/in^2 (11.93, 13.65, and 15.31 GPa), respectively. The layups containing veneer with higher dynamic MOE apparently had higher edgewise bending stiffness. The mixed MOE layup yielded an edgewise bending MOE value equivalent to the mean of the medium MOE layup. In addition, note that the edgewise bending MOE of the billets was about 8%, 10%, and 6% higher than the dynamic

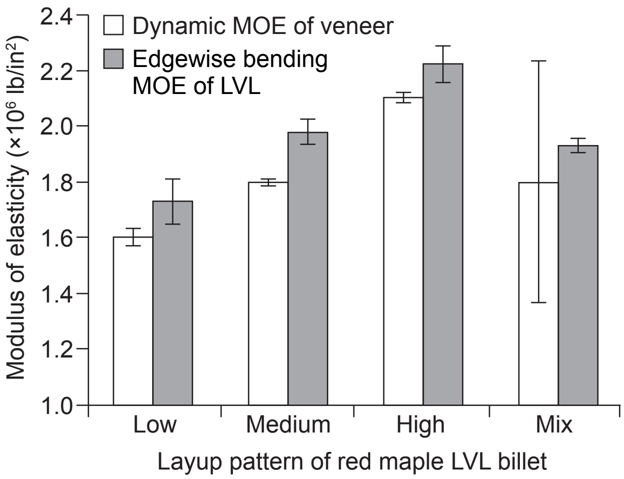


Figure 9.4—Modulus of elasticity of 2-in.- (5-cm-) thick red maple LVL.

MOE of veneer for low, medium, and high MOE layups, respectively. This finding is in agreement with the results reported by Kimmel and Janowiak (1995). It is generally believed that the enhanced stiffness is mainly due to the lamination effect in LVL fabrication. These results suggest that the structural performance of red maple LVL billets might be improved through the application of ultrasonic rating of veneer and the use of optimized layup patterns in LVL fabrication.

Some delamination was found in the thick LVL billets. The delamination usually appeared on one glue line and one edge of the billets. This might have been caused by uneven spread of resin on the veneer sheets, inappropriate resin type (the resin used was designed for Southern Pine plywood), or the not-yet-optimized hot-press schedule. Delamination was not severe overall, but it does require further attention to process variables, such as resin composition, pressing pressure, press temperature, and cycle time.

Conclusions

Ultrasonically rated red maple veneer was fabricated into 1/2-in.- (1.3- cm-) and 2-in.- (5-cm-) thick LVL billets. The flexural properties of the billets and corresponding small specimens cut from the billets were determined through flatwise and edgewise static bending tests. The results of this preliminary study indicate that veneer peeled from low value red maple logs may be used to manufacture high quality LVL products. Ultrasonic wave propagation time and corresponding dynamic MOE of red maple veneer were well correlated to the flexural properties of the LVL billets. The edgewise bending MOE of the LVL billets showed positive relation to the layup pattern in terms of stress-wave rating of veneer. This implies that the performance of red maple LVL can potentially be enhanced through ultrasonic rating of individual veneer sheets.

The experimental data in this study were obtained from a small sample of specimens. To understand the full potential of red maple veneer as a structural material in LVL production, further research is necessary to investigate the effects of veneer layup pattern, grain angle, resin load, and other process variables on LVL structural performance. We also recommend that a mixture of red maple and other hardwood species be included in future study.

Literature Cited

ASTM. 1999. Standard test methods of static tests of lumber in structural sizes. ASTM D 198–98. West Conshohocken, PA: American Society for Testing and Materials.

Brashaw, B.K.; Vatalaro, R.J.; Lackore, M.; Ross, R.J.; Wang, X.; Forsman, J.W. 2001. Advancing technology to manufacturing trusses from hardwood lumber. NRRI/TR–2001/26. Duluth, MN: University of Minnesota, Natural Resources Research Institute.

Forest Products Laboratory. 2010. Wood handbook. Wood as an engineering material. Gen. Tech. Rep. FPL–GTR–190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 508 p.

Green, D.W.; McDonald, K.A. 1993. Mechanical properties of red maple structural lumber. Wood and Fiber Science. 25(4): 365–374.

Janowiak, J.J.; Manbeck, H.B.; Hernandez, R.; Moody, R.C.; Blankenborn, P.R.; Labosky, P. 1995. Efficient utilization of red maple in glued laminated timber beams. Res. Pap. FPL–RP–541. Madison, WI. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 23 p.

Kimmel, J.D.; Janowiak, J.J. 1995. Red maple and yellow-poplar LVL from ultrasonically graded veneer. Forest Products Journal. 45 (7/8): 54–58.

Ross, R.J.; Erickson, J.R.; Brashaw, B.K.; Wang, X.; Verhey, S.A.; Forsman, J.W.; Pilon, C.L. 2004. Yield and ultrasonic modulus of elasticity of red maple veneer. Forest Products Journal. 54(12): 220–225.

Wang, Xiping; Ross, Robert J.; Brashaw, Brian K.; Verhey, Steven A.; Forsman, John W.; Erickson, John R. 2003. Flexural properties of laminated veneer lumber manufactured from ultrasonically rated red maple veneer. Res. Note. FPL–RN–0288. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 5 p.

Chapter 10

Red Maple Lumber Resources for Glued-Laminated Timber Beams

John J. Janowiak, Professor Emeritus
Harvey B. Manbeck, Professor Emeritus
Penn State University, State College, Pennsylvania

Roland Hernandez, Research General Engineer[1]
Russell C. Moody, Supervisory Research General Engineer (retired)
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

Several publications have presented experimental results on the mechanical performance of hardwood glued-laminated (glulam) timbers (Janowiak et al. 1995, Moody et al. 1993, Shedlauskas et al. 1994). These glulam studies are related to broader research efforts in the development of timber bridge systems. Glulam is a vital element for many proposed timber bridge designs. One key issue in bridge research is the use of local, underutilized forest resources. Published performance results of yellow-poplar, red maple, and red oak support the feasibility that hardwood glulam timbers are well-suited for bridge applications. These hardwood species are abundant, with significant saw-timber volume in the northeastern United States, where annual growth accumulations exceed harvest.

This chapter evaluates the performance of red maple glulam beams made from two distinctly different lumber resources:

- Logs sawn using practices normally used for hardwood appearance lumber recovery
- Lower grade, smaller dimension lumber primarily obtained from residual log cants

Cant refers to the remaining log heart or inner log portion after grade sawing removes the higher quality, outer zone material for appearance-type lumber.

Background

Several studies have emerged to explore the yield recovery and lumber properties of structural graded hardwoods (Green and McDonald 1993, Janowiak et al. 1992, McDonald et al. 1993). These study results indicated that hardwood design property values may only be conservatively estimated on the basis of clear wood computational procedures. Another study investigated joist and plank lumber grade yield from railroad switch ties for five hardwood species (McDonald et al. 1996) in an attempt to develop a structural lumber product that does not compete with hardwood sources used by the furniture industry. Preliminary results with red oak, hickory, yellow-poplar, and red maple switch ties indicate yields of nominal 2-by 7-in. lumber to exceed 90% No. 3 and Better lumber.

Railroad switch ties and log cants have significant potential as a source for structural lumber. Hardwood sawmills frequently avoid processing inner log portions because of inadequate appearance grade recovery. Hardwood cants sawn into structural lumber would provide sawmills with an enhanced opportunity for value-added production. In the recovery concept, the sawmill first obtains appearance-type lumber from high quality outer-log portions, then stress-graded dimension lumber from the heart cant. Small 2 by 4 or 2 by 6 nominal cant sawn lumber could be used to manufacture hardwood glulam timbers. Wide-width glulam timber products could be fabricated by manufacturing laminations with two narrow-width lumber specimens laid edge to edge. Using laminations made from lumber placed edge to edge is an accepted practice for glulam beam fabrication (ANSI 1992). More commonly, this practice is reserved where glulam beam width exceeds the largest available dimension lumber. These two-member laminations can include lumber pieces with either a glued or unglued edge joint.

Several publications have reported on the mechanical properties of edge-glued dimension lumber. Edge-glued southern pine lumber was studied to develop a solution to projected shortages of wider dimension construction lumber (McAlister 1973). Another study was conducted with Douglas-fir clear wood that was edge-glued in various combinations with structural No. 3 and L1, L2, and L3 lamination grades of lumber (Johnson 1978). Both studies suggest that edge-to-edge combinations can provide enhanced lumber products or beams with increased mechanical performance. This is due to the reduced influence of width effect in the laminating stock, as a result of using two narrow-width pieces of lumber.

[1]Currently Engineer/Wood Scientist/Mass Timber Consultant, Bell Structural Solutions, San Antonio, Texas.

Table 10.1—Estimated property values of red maple lumber for use in ASTM D3737 procedures

Lamination grade	Modulus of elasticity ($\times10^6$ lb/in^2)	$\bar{x}$[a] (%)	$\bar{x} + h$[b] (%)	SR_{min}[c]	Bending stress index (lb/in^2)
2.0-1/6	2.0	3.0	27.0	0.70	3,250
2.0-1/3	2.0	5.0	35.0	0.60	3,250
1.8-1/3	1.8	5.0	35.0	0.60	2,750
No. 2	1.5	8.0	42.0	0.54	2,470
No. 3	1.4	10.0	50.0	0.39	2,470

[a]$\bar{x}$ is average of sum of all knot sizes within each 1-foot length, taken at 0.2-foot intervals.
[b]$\bar{x} + h$ = 99.5 percentile knot size (ASTM 1993).
[c]SR_{min} is minimum bending strength ratio.

Prior to this study, no research had been reported that thoroughly evaluated the mechanical performance of glulam products composed of unglued two-member laminations. Design stresses for these structural glulam timbers are established according to ASTM D3737 (ASTM 1993). For laminations, this standard specifies that lumber edge joints must be glued unless calculations or experimental data provide verification of structural performance. In addition, no research has been reported on glulam timber made from two-member laminations when tested in the vertically laminated orientation (loads applied parallel to the wide face of the laminations).

Objectives and Scope

Two studies were conducted on two types of material:

- A glulam combination designed with E-rated lumber in 25% of the outer laminations (top and bottom) and visually graded lumber in 50% of the center laminations
- A wide-width glulam combination with laminations made from nominal 2-by 4- and 2-by 6-in. No. 2 grade lumber laid edge to edge having staggered end joints (termed 2 by 4/2 by 6 glulam combination)

In these studies, three objectives were addressed to examine several aspects of red maple glulam product performance. The first objective was to evaluate the performance of an efficient configuration of red maple glulam made with E-rated outer laminations and visually graded No. 2 grade red maple lumber in 50% of the inner laminations, referred to hereafter as Phase I of this research. Lumber for the Phase I portion of this study was obtained by using sawing methods that are common for structural softwood lumber. The second objective was to evaluate a similar combination that utilizes E-rated outer laminations and visually graded No. 3 lumber in the inner laminations; referred to hereafter as Phase II. Lumber for the Phase II portion of this study was obtained by sawing residual log cants obtained from logs that had been processed for removal of furniture-grade stock. The combinations for Phases I and II were developed to provide a target design stress of 2,400 lb/in^2, with a design stiffness of 1.8 $\times10^6$ lb/in^2 (24F-1.8E glulam beam). The second study addressed the third objective, or Phase III, which focused on determining the bending strength, shear strength, and bending stiffness properties of glulam beams made with No. 2 grade laminations having unglued nominal 2 by 4's and 2 by 6's laid edge to edge, hereafter referred to as 2 by 4/2 by 6 beams.

Experimental Design

Previous research (Moody et al. 1993, Shedlauskas et al. 1994) showed that glulam combinations made from hardwood lumber could achieve design stresses of 2,400 lb/in^2 in bending strength and 1.8 × 10^6 lb/in^2 in bending stiffness. Based on these research studies, E-rated hardwood lumber properties were established for ASTM D3737 analytical procedures. Results of these previous studies provided estimates of the lumber properties (Table 10.1).

Phases I and II: 24F-1.8E Glulam Beams

Based on ASTM D3737 analytical procedures and the lumber property information in Table 10.1, the experimental 24F-1.8E beam configurations shown in Figure 10.1a–d were developed. The glulam beam combinations were composed of similar outer zones of E-rated lumber and core zones of visually graded lumber. For the 24F-1.8E combinations, allowable edge knot size of the E-rated lumber for the outermost tension laminations was limited to one-sixth the area of the cross section. Edge knot size in the outer compression laminations was restricted to one-third the area of the cross section. Bending stiffness for the outermost tension and compression zones required E-rated lumber meeting an average MOE of 2.0 × 10^6 lb/in^2. Edge knot size in the next inner tension and compression laminations was restricted to one-third the area of the cross section. Bending stiffness for the next inner zones required average lumber MOE values of 1.8 × 10^6 lb/in^2. In Figure 10.1, note that slight differences exist in the proportion of laminations composed of the E-rated lumber

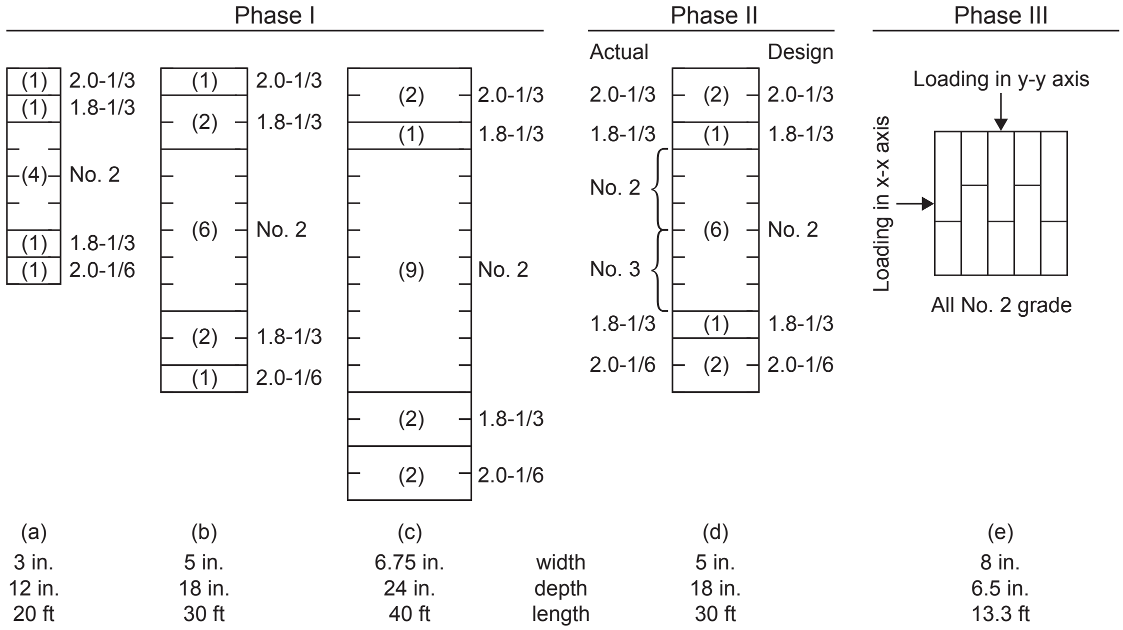


Figure 10.1—Illustration of red maple glulam. Phase I beams (a–c) are 24F-1.8E combinations made from lumber sawn from whole trees. Phase II (d) is a 24F-18E combination made from lumber sawn from log cants. Phase III (e) is a wide-width combination made from cant-sawn 2 by 4 and 2 by 6 lumber.

Table 10.2—Maximum allowable tension lamination criteria for 24F-1.8E glulam beam combinations

	Maximum allowable characteristic[a]			
	Phase I			Phase II
Characteristic	(a)[b]	(b)[b]	(c)[b]	(d)[b]
Edge knot + grain deviation	40%	30%	30%	30%
Center knot + grain deviation	45%	33%	33%	40%
Slope of grain	1:14	1:16	1:16	1:16

[a]Knots plus grain deviations are given in percentages of cross section per ASTM D3737 (ASTM 1993).
[b]Letters correspond to the glulam beam combinations in Figure 10.1.

grades. However, in all configurations, at least 50% of the inner laminations were visually graded lumber. In addition, ASTM D3737 procedures require that 5% of the outermost tension laminations be replaced with a special tension grade lumber. The tension lamination criteria required by Phases I and II of this research are summarized in Table 10.2.

Phase III: 2 by 4/2 by 6 Wide-Width Glulam Beams

Phase III of this research also targeted the evaluation of the 2 by 4/2 by 6 beams for bending strength about the *y-y* beam axis and horizontal shear strength about the same *y-y* beam axis. The dimensions of the 2 by 4/2 by 6 beams in Phase III were designed with a staggered arrangement of nominal 2 by 4's and 2 by 6's (Fig. 10.1), having a total of five laminations. Visually graded No. 2 red maple lumber was used throughout the layup, and the edge interface between the 2 by 4 and 2 by 6 plies was not glued. In the AITC 119 standard (AITC 1996), vertically laminated red maple glulam beams with four or more laminations of No. 2 grade lumber have assigned design bending stresses about the *y-y* beam axis (F_{by}) of 1,450 lb/in^2, and design horizontal shear about the *y-y* beam axis (F_{vy}) of 160 lb/in^2. When laminations are made using edge-to-edge lumber, F_{vy} values are reduced to 65 lb/in^2.

Materials and Methods

The following sections discuss the methods for processing, grading, testing, and laminating the red maple lumber. For additional details of these methods, refer to the comprehensive reports by Manbeck et al. (1993) for material relating to Phase I and by Janowiak et al. (1995) for material relating to Phases II and III.

Lumber Manufacture

Lumber for manufacture of the 24F-1.8E glulam combinations for Phase I was obtained by sawing red maple logs into green 8/4 (2-in.) dimensional material. After drying, the material was rough-planed to a thickness of 1.75 in. The rough-sawn lumber was then visually graded by NELMA (1991) rules to obtain Select Structural, No. 1, No. 2, and No. 3 grades of structural lumber.

Lumber for manufacture of the 24F-1.8E and 2 by 4/2 by 6 glulam combinations evaluated in Phases II and III was processed from residual red maple log cants. Red maple logs were harvested from several north central Pennsylvania sites. Logs were first processed with primary breakdown to recover appearance-grade hardwood lumber. Primary breakdown included sawing of appearance-type lumber to recovery down to a No. 3A Common National Hardwood Lumber Association grade face (NHLA 1991). After appearance material was removed, the log hearts (approximate 6-in. to a minimum 4-1/2-in. dimension cants) were processed through a secondary bandmill resaw operation. Cants were sawn to a heavy 6/4 (final dressed thickness to equal 1.5 in.) hardwood lumber thickness tolerance. Immediately after sawing, the rough lumber was tallied to monitor the amount of 2 by 4 and 2 by 6 material available for experimental beam fabrication and graded green according to NELMA grading rules.

Grading, Sorting, and Stiffness Evaluation

For Phases I, II, and III, the sawn lumber was visually sorted into the desired lumber grades. Both studies included tension-lamination-quality lumber, lumber with one-sixth and one-third edge-knot size restrictions, and the visually graded No. 2 and No. 3 lumber. In both studies, lumber that failed to meet both of the edge-knot requirements was assigned to the visually graded lumber for each study. For Phase III, additional sorting was conducted to separate supplies of nominal 2 by 4 and 2 by 6 No. 2 lumber for fabrication of the 2 by 4/2 by 6 glulam beams.

When the lumber grades were visually sorted, similar procedures were used in both studies to test the lumber for stiffness. Testing was conducted using commercial transverse vibration equipment (Metriguard 1993). Each piece of lumber was marked with an identification number, and the corresponding stiffness was recorded. In each study, a small sample of lumber was tested for flatwise MOE as specified in AITC T116 (AITC 1992) to establish a regression relationship between dynamic and static lumber MOE. Special tension lamination material meeting the criteria in Table 10.2 was selected from the available E-rated 2.0-1/6 lumber.

Knot Properties

After the required amounts of lumber were sorted, knot property data were measured for most of the grades. Knot data were collected for all specimens of special tension lamination material, all 2.0-1/6 pieces, and randomly selected samples of the 2.0-1/3, 1.8-1/3, No. 2, and No. 3 lumber intended for the 24F-1.8E glulam beams. Additional knot data were collected for the No. 2 grade 2 by 4 lumber intended for the 2 by 4/2 by 6 beam fabrication. Knot data were later analyzed according to procedures in USDA Technical Bulletin 1069 (Freas and Selbo 1954).

Glulam Beam Manufacture

24F-1.8E Glulam Beams

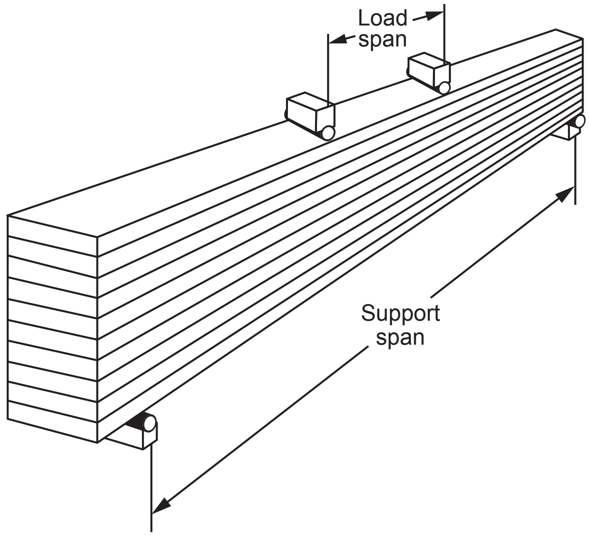
For Phase I, 45 beams (15 of each of three combinations in Fig. 10.1a–c) were manufactured along with extra specimens of finger-jointed lumber. Finger-joint specimens were fabricated for test evaluation purposes. For Phase II, 15 beams of a single combination (Fig. 10.1d) were manufactured along with finger-jointed lumber test specimens.

For Phase I, manufacture of the beams followed production procedures (ANSI 1992) normally used for softwood glulam. This included the types of adhesives for finger jointing and face jointing the lumber, planing speeds of finger-jointed laminations, spread rates for the adhesives, open assembly times for the adhesives, and clamping pressures used during curing. Based on results (discussed later) of the manufacture of Phase I beams, two slight modifications were made to the manufacture of the Phase II beams. The lumber feed rates into the surface planer were reduced, and clamping pressures applied during glulam beam curing were increased.

During Phase II, greater than anticipated drying losses of No. 3 grade lumber resulted; therefore, approximately half the core laminations of No. 3 grade lumber were replaced with No. 2 grade lumber. The No. 3 grade laminations were placed on the more critical tension side of the core, and No. 2 grade laminations were placed in the compression side of the core (Fig. 10.1).

Finger-joints used in both studies were vertically oriented (fingers visible on the wide face of the lumber). Because of the low-quality cant-sawn lumber resource for Phases II and III, it was difficult to obtain adequate sample sizes of lumber specimens meeting the special tension lamination grade requirements for both glulam beam and finger-joint specimen manufacture of Phase II. Thus, beam manufacture was given greater priority for allocation of available tension lamination material compared with finger-joint sampling.

(a)



Combination from Figure 1	Support span (ft)	Load span (ft)
(a)	19	4
(b)	28.5	6
(c)	38	8
(d)	28	6
(e)	12.5	4.17

(b)

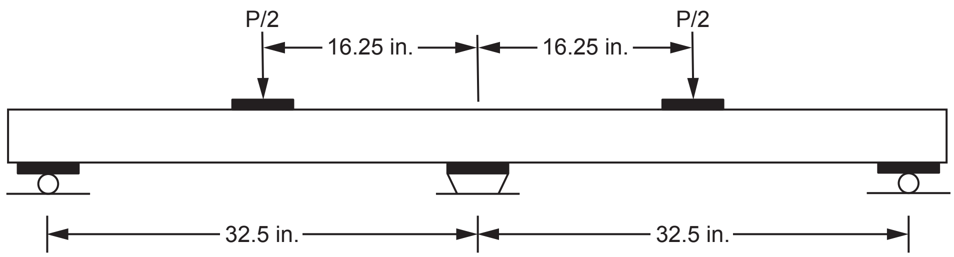


Figure 10.2—Loading configurations for bending (a) and shear (b) tests of red maple glulam beams.

The resulting shortage of tension-lamination-quality material resulted in finger-joint specimens that were heavily weighted toward the maximum characteristics allowed in the grade, which may not have been representative of those used in beam manufacture.

2 by 4/2 by 6 Glulam Beams

The 2 by 4/2 by 6 glulam beams (Phase III) were manufactured with five laminations that resulted in approximately a 6.5-in. depth, 8-in. width, and 13.3-ft length. Procedural steps followed for manufacture of 2 by 4/2 by 6 glulam beams were almost identical to conventional lumber lamination procedures. One major difference was that lumber widths were staggered in adjacent beam lamination layers during final layup (Fig. 10.1e). No attempt was made to bond the lumber on the longitudinal edge-to-edge joint. Some edge-to-edge joints became partially bonded as adhesive flowed into a joint as a result of the application of clamp pressure during beam assembly. Edge-joint quality varied from having tight edge surface contact to open gaps observed along the lamination edge length. Fifteen 13.3-ft-long 2 by 4/2 by 6 beams were fabricated for evaluation of bending strength and 12 7.5-ft-long 2 by 4/2 by 6 beams were fabricated for evaluation of horizontal shear strength.

Evaluation Procedures

Testing equipment and procedures for evaluating the glulam beams and the end-jointed lumber specimens followed criteria in ASTM D198 (ASTM 1993).

Phases I and II: 24F-1.8E Glulam Beams

The glulam beams were destructively evaluated using ASTM D198 procedures. Loading configurations for Phases I and II are shown in Figure 10.2a. Long-span deflection was measured at the neutral axis over the unsupported beam length. Physical properties of weight, moisture content (MC), and dimensions were measured on individual beam specimens. Measurements were recorded for the failure load and time-to-failure tests. Efforts were also made to characterize failure type with sketches of beam failure pattern. MC was determined after failure using a resistance-type moisture meter with measurements on each lamination near a mid-span location. Beam weights were measured prior to testing on a mobile scale to an approximate 10-pound accuracy. Dimensions of width and depth were taken at beam load positions. During loading, full-span deflection readings were recorded at specified incremental loads to compute beam stiffness from a regressed fit of load–deflection data up to design load.

Table 10.3—Modulus of elasticity values of sorted laminating lumber in glulam beams

Lumber section (in.)	Lumber grade	No. of pieces	Average MOE ($\times 10^6$ lb/in^2)	Coefficient of variation (%)
Phase I				
2 by 8	2.0-1/6	141	1.93	9.8
	2.0-1/3	144	1.90	8.5
	1.8-1/3	193	1.74	10.3
	No. 2	50	1.69	14.9
2 by 6	2.0-1/6	52	1.93	7.7
	2.0-1/3	48	1.92	8.9
	1.8-1/3	215	1.74	10.6
	No. 2	50	1.73	14.3
2 by 4	2.0-1/6	39	1.96	5.9
	2.0-1/3	40	1.96	5.8
	1.8-1/3	80	1.72	8.2
	No. 2	50	1.8	16.2
Phase II				
2 by 6	TL[a]	55	2.15	7.8
	2.0-1/6	56	2.05	9.7
	2.0-1/3	113	2.02	9.4
	1.8-1/3	114	1.79	9.1
	No. 3	25	1.68	11.4
Phase III				
2 by 6	No. 2	160	1.84	10.9
2 by 4	No. 2	161	1.82	15.3

[a]TL is tension lamination.

Phases I and II: Finger-Jointed Lumber

The finger-jointed specimens were evaluated to determine their ultimate joint tensile strength. Test specimens were face- and surface-planed prior to testing to dimensions similar to those of the laminations used for beam manufacture. Prior to test, each specimen was evaluated with an E-computer to obtain a dynamic modulus of elasticity (MOE) measurement. Specimens were approximately 8 ft long, with the finger-joint located near mid-length. Tests included a 30-in. gage length centered between machine grips, with increasing tensile load applied until failure. Loading rate was calibrated to achieve an approximate 5- to 10-min time to failure. This loading is longer than the 3- to 5-min test duration recommended by AITC TI19 (AITC 1992) for daily quality control testing. The 5- to 10-min duration used here coincides with the failure times targeted for the full-size glulam beam tests, which followed ASTM D198 procedures.

Phase III: 2 by 4/2 by 6 Glulam Beams

Flexural tests followed ASTM D198 procedures for all 2 by 4/2 by 6 glulam beam specimens. A computerized data-acquisition system was used to monitor load–deflection response. Loading rate for maximum load was adjusted for a 5- to 10-min time-to-failure test duration. Deflection measurements were taken using a linear variable differential transformer (LVDT) on a yoke affixed to the neutral axis of the specimen. The MOE values were computed from a linear regression analysis of load–deflection data up to design load.

The 2 by 4/2 by 6 specimens of 80-in. (7.5-ft) length were also processed from the 2 by 4/2 by 6 glulam material to characterize beam shear strength. Beam shear strength evaluation was conducted using a five-point loading scheme recommended by Soltis and Rammer (1994). The test apparatus consists of three reaction supports, located at either beam end and mid-span, and two loading points, each located equidistant from mid-span (Fig. 10.2b).

Table 10.4—Actual knot sizes of sorted laminating lumber

Nominal lumber size	Lumber grade	Lineal footage (ft)	$\bar{x}$[a] (%)	$\bar{x} + h$[b] (%)
Phase I				
2 by 8	2.0-1/6	304	0.5	11.2
	2.0-1/3	334	0.7	16.6
	1.8-1/3	436	0.1	7.0
	No. 2	666	1.7	33.6
2 by 6	2.0-1/6	572	0.1	13.6
	2.0-1/3	488	0.4	18.5
	1.8-1/3	376	0.1	7.1
	No. 2	362	2.0	35.3
2 by 4	2.0-1/6	386	0.2	14.8
	2.0-1/3	420	0.3	16.8
	1.8-1/3	524	0.6	25.5
	No. 2	442	0.9	29.2
Phase II				
2 by 6	TL[c]	212	0.5	15.0
	2.0-1/6	282	1.5	34.8
	TL and 2.0-1/6	494	0.9	29.3
	No. 3	221	5.2	51.5
Phase III				
2 by 6	No. 2	221	2.3	27.4
2 by 4	No. 2	200	3.0	47.5
2 by 4/2 by 6	No. 2	421	2.7	36.4

[a]$\bar{x}$ is average of sum of all knot sizes within each 1-foot length, taken at 0.2-foot intervals.
[b]$\bar{x} + h$ = 99.5 percentile knot size (ASTM 1993).
[c]TL is tension lamination.

Specimen length was 10 times the member depth, with span between the reaction supports equal to 5 times the depth. Concentrated loads were applied through bearing plates to minimize compressive failure. Test speed was selected so that shear failures would occur between 5 and 10 min after load application. After failure, beam shear failure zones were sketched and MC determined with a resistance-type meter.

ASTM D143 (ASTM 1993) shear block specimens were fabricated using wood samples obtained from locations adjacent to the shear failure zones of the 2 by 4/2 by 6 glulam beams. An evaluation could include one or more observations of shear strength relative to the multiple lumber piece construction. Individual observations were averaged as a measurement of ASTM D143 shear strength for each failed 2 by 4/2 by 6 lamination. Two data sets were developed, with one set tested at ambient or unconditioned MC and the other after conditioning to constant weight at 12% equilibrium MC.

Evaluation Results: Glulam Manufacture

The glulam beam maps compiled during beam manufacture were analyzed to determine if the targeted laminating lumber MOE criteria in Table 10.1 were achieved. Table 10.3 gives a statistical summary of MOE measurements of those lumber specimens used in the fabricated beams for the 24F-1.8E glulam combinations from Phases I and II and the 2 by 4/2 by 6 glulam combinations from Phase III. Note that the special tension lamination and all the E-rated grades (2.0-1/6, 2.0-1/3, 1.8-1/3) were close, met, or slightly exceeded the targeted average MOE values. Both visual grades (No. 2 and No. 3) greatly exceeded the assumed property value in Table 10.1.

The measured knot properties on the sorted lumber grades were also analyzed to determine knot size statistics. Table 10.4 includes a statistical summary of the knot sizes observed in each grade for lumber used in both the 24F-1.8E and 2 by 4/2 by 6 glulam beam combinations.

Table 10.5—Summary of bending test results on red maple glulam beams[a]

	Phase I			Phase II	Phase III
	(a)[b]	(b)[b]	(c)[b]	(d)[b]	(e)[b]
Sample size	15	15	12	15	15
Moisture content (%)	12	12	12	13	9
Modulus of rupture[c]					
Average (lb/in^2)	9,080	7,980	7,860	7,980	6,630
Coefficient of variation (%)	14.4	12.1	15.8	12.1	10.8
5th percentile at 75% tolerance (lb/in^2)	6,760	6,230	5,630	6,230	5,320
Adjusted to design[d] (lb/in^2)	3,020	3,180	3,140	3,180	2,360
Modulus of elasticity					
Horizontally laminated					
Average (lb/in^2)	1.78	1.77	1.78	1.77	1.86
Coefficient of variation (%)	4.3	3.0	2.7	3.0	8.3
Vertically laminated					
Average (lb/in^2)					1.87
Coefficient of variation (%)					7.1

[a]Lognormal distribution assumed for strength properties: normal distribution assumed for stiffness and moisture content.
[b]Letters in parentheses refer to glulam beam combinations from Figure 10.1.
[c]For 24F-1.8E glulam beams, load was applied perpendicular to wide face of laminations; for 2 by 4/2 by 6 glulam beams, load was applied parallel to wide face of laminations.
[d]Adjusted MOR equals 5th percentile divided by $C_v = (5.125/W)^{0.1}\ (21/L)^{0.1}\ (12/d)^{0.1}$ and by 2.1.

Phases I and II: 24F-1.8E Glulam Beams

During testing, beams emitted fiber fracture sounds before reaching ultimate failure load. Some beams were observed with localized compressive wrinkling between the load points prior to ultimate failure on the tension side. Most failures were attributed to finger-joints, and other beams failed because of a combination of finger-joint and other intrinsic strength-controlling characteristics. In Phase I, shallow wood failures were observed at the gluelines of the failed beams. Examination of the gluelines suggested this related to a probable inadequacy in clamping pressure. These types of glueline failures were not observed in the failed beams of Phase II. Therefore, the modifications to the manufacturing process (discussed earlier) appeared to be successful. Results of 24F-1.8E beam strength and stiffness test evaluations are summarized in Table 10.5. All calculations of glulam beam MOR include the dead weight of the beams.

Phases I and II: Finger-Jointed Lumber

Tensile strength, MC, and specific gravity results for the finger-jointed special tension lamination specimens are given in Table 10.6.

Phase III: 2 by 4/2 by 6 Combination Glulam Beams

For bending tests of the 2 by 4/2 by 6 glulam beams, the majority of failures involved a strength-reducing characteristic, such as knots, slope of grain, or grain deviation. The use of the edge-to-edge laminations did not appear to affect the bending strength results. Summary results from the flexural testing are presented in Table 10.5.

For the horizontal shear tests of the 2 by 4/2 by 6 glulam beams, the first audible sound of failure was emitted at ultimate load; then the load-carrying capacity was observed to decrease. Because no catastrophic failure was observed during this loading sequence, cross sections of each of the 12 beams were cut at the location of failure, and the propagation of horizontal shear failure was observed. Summary test results for beam horizontal shear and the ASTM D143 shear-block are given in Table 10.7.

Analysis of Results

The analysis conducted in this section assumes the lognormal distribution for strength property characterization, recommended by ASTM D3737. Analysis of glulam MOE, MC, and specific gravity were conducted assuming the normal distribution.

Design Strength and Stiffness Comparison

Phases I and II: 24F-1.8E Glulam Beams

The design bending strength values of the 24F-1.8E glulam beams were calculated and are reported in Table 10.5. Note that the design bending strength levels calculated for each combination from Phases I and II far exceed the targeted 2,400 lb/in^2. More importantly, the results for all combinations between the lowest and highest calculated

Table 10.6—Results of finger-jointed red maple tension lamination material (specimens with failure involving end joint)[a]

	Phase I			Phase II
Property	2 by 4	2 by 6	2 by 8	2 by 6
Sample size	19	26	18	15
Average moisture content (%)	8.6	8.6	7.8	13.1
Average specific gravity[b]	0.57	0.57	0.56	0.55
Average tensile strength (lb/in^2)	8,470	8,720	8,010	6,490
COV tensile strength (%)	27.6	21.1	16.2	27.0

[a]Moisture content is based on ovendrying methods; strength calculations assume a lognormal distribution.
[b]Based on volume at time of test and ovendry weight.

Table 10.7—Results of shear strength (τ) for Phase III[a]

	Average MC (%)	Average τ	COV of τ	$\tau_{0.05}$ at 75% tolerance	$(\tau_{adjusted})^b$
2 by 4/2 by 6 glulam beams	—	1,730	7.4	1,490	—
ASTM D 143 block shear specimens					
Unconditioned	8.7	1,940	11.8	1,490	364
Conditioned to 12% EMC	12.7	1,830	8.5	1,540	384

[a]EMC is equilibrium moisture content; COV is coefficient of variation; MC is moisture content based on ovendrying method. All shear calculations assume a lognormal distribution.
[b]$(\tau_{adjusted}) = \tau_{0.05}$ divided by 4.1 per ASTM D 3737 for block shear values.

design bending strengths were approximately 5%. This provides strong evidence that the E-rating process can ensure that the properties of the laminating lumber are adequate, regardless of the lumber resource.

For glulam beam bending stiffness, average MOE values are reported in Table 10.5. Note that in both studies, average glulam beam MOE values met or exceeded the targeted 1.8×10^6 lb/in^2 beam stiffness. In addition, as is typical with the use of E-rated lumber in glulam manufacture, the variability of beam MOE was quite low, as shown by the coefficient of variation in beam MOE reported in Table 10.5.

Phases I and II: Finger-Jointed Lumber

For structural finger-joints, the ANSI A190.1 (ANSI 1992) standard requires that the 5th percentiles of finger-joint tensile strength (at 75% tolerance) meet a strength level that is 1.67 times the targeted design bending strength of the glulam beams. For the 2,400 lb/in^2 glulam combinations, the finger-joints were required to meet a 5th percentile tensile strength of approximately 4,010 lb/in^2. Table 10.6 summarizes the finger-joint test results. For the finger-joints tested in Phase I, the 2 by 6 and 2 by 8 finger-joints exceeded the targeted strength level, whereas the 2 by 4 finger-joints were approximately 2% short of meeting the targeted level.

In Phase II, however, the 2 by 6 finger-joints fell short of the targeted strength level by approximately 15%. Taking into consideration that the Phase II beams had nearly identical design bending strength performance as the Phase I beams, and that the sample of finger-joints reported in Table 10.6 is heavily weighted toward the maximum allowable strength-reducing characteristics, all evidence indicates that the finger-joints used for beam manufacture in Phase II were adequate for the 2,400 lb/in^2 design bending strength.

Phase III: 2 by 4/2 by 6 Glulam Beams

The results in Table 10.5 show that the calculated design bending strength for the 2 by 4/2 by 6 glulam beam combination was 2,360 lb/in^2, which greatly exceeds the published design bending stress for No. 2 red maple of 1,450 lb/in^2 (AITC 1996).

From Table 10.7, the calculated 5th percentile (at 75% tolerance) of horizontal shear strength for the 2 by 4/2 by 6 glulam beams was 1,490 lb/in^2. Methods for determining horizontal shear design values from glulam beam test results are not established. For small, clear test specimens, design values for horizontal shear strength are determined by dividing the calculated 5th percentile horizontal shear strength of ASTM D143 shear block specimens by a factor of 4.1, which accounts for a combined effect of duration of load, stress concentration, and safety. Given that published design horizontal shear strength for No. 2 red maple glulam with multiple-piece laminations and having four or more laminations is 65 lb/in^2, the results observed in Table 10.7 would greatly exceed published values, even with a factor of 4.1.

For bending stiffness, the AITC 119 standard publishes the same value for orientations loaded with respect to the *y*-*y* and *x*-*x* beam axes (see Fig. 10.1 for orientations). For No. 2 red maple glulam, the published MOE is 1.3×10^6 lb/in^2, which is very conservative compared with the 1.87×10^6 lb/in^2 experimental value observed in the *y*-*y* orientation and the 1.86×10^6 lb/in^2 value observed in the *x*-*x* orientation (Table 10.5).

Predicted Strength and Stiffness Comparison

In this section, ASTM analysis procedures were used to predict the performance of the glulam test results using the available lumber properties information.

Phases I and II: Bending Strength of 24F-1.8E

Actual MOE data from Table 10.3 and actual knot property data from Table 10.4 were used to predict the performance of the 24F-1.8E glulam combinations using ASTM D3737 procedures. Knot property information from Phase I was used for the 2.0-1/3 and 1.8-1/3 grades in both Phases I and II. Minimum strength ratios were used as originally planned (Table 10.1). For bending stress indices, a value of 3,250 lb/in^2 for E-rated lumber having an average MOE of 2.0×10^6 lb/in^2 (2.0E) was originally used (Table 10.1) for development of the 24F-1.8E glulam combinations. This value is currently in the ASTM D3737 standard, which is based on a linear interpolation between a bending stress index value of 3,000 lb/in^2 for 1.9E lumber to a bending stress index of 3,500 lb/in^2 for 2.1E lumber. In Phase I, an analysis was conducted to determine appropriate bending stress index levels for 2.0E red maple lumber. Based on the analysis of 42 red maple glulam beams, a bending stress index of 3,500 lb/in^2 was found to be applicable for 2.0E red maple lumber. Thus, we concluded that the bending stress indices specified in the D3737 standard for E-rated grades of lumber, which are based on softwood data from past research, are conservative when applied to red maple. Based on the findings of Phase I, a bending stress index of 3,500 lb/in^2 was used for 2.0E red maple lumber, and a bending stress index of 3,000 lb/in^2 was used for 1.8E red maple lumber in the following analysis.

In Phase I, the predicted design bending strength values for the combinations shown in Figure 10.1a–c were 3,080 lb/in^2, 3,180 lb/in^2, and 3,230 lb/in^2, respectively. These values were within 2%, 0%, and 3% of the actual calculated design bending strength values reported in Table 10.5. For the combination in Phase II, the predicted design bending strength was 2,800 lb/in^2, which was within 14% of the actual calculated design bending strength.

A comparison between the 2.0-1/6 knot properties from Phase II ($\bar{x}$ = 1.5% and $\bar{x} + h$ = 34.8%) and those from Phase I ($\bar{x}$ = 0.1% and $\bar{x} + h$ = 13.6%) shows a significant difference, especially with the $\bar{x} + h$ values. The knot properties reported in Phase I for the 2.0-1/6 grade resemble the properties of the Phase I tension lamination grade ($\bar{x}$ = 0.5% and $\bar{x} + h$ = 15.0%). When the same combination was analyzed using the tension lamination knot properties instead of the 2.0-1/6 knot properties from this study, the maximum calculated design bending strength was 3,080 lb/in^2, which is within 3% of the actual design bending strength.

One possible explanation for the difference in calculated knot sizes of the 2.0-1/6 grade between Phases I and II is that the resource of cant-sawn lumber in Phase II may have different knot characteristics (such as pith-associated wood, spike knots) than lumber sawn from full-size logs (Phase I). Analysis of knot sizes on two types of timber resources may have resulted in vastly different calculated knot properties for Phases I and II. Consequently, this would affect the predicted design bending strength values using standard ASTM D3737 procedures, albeit D3737 predictions of design bending strength values for the glulam beams made with E-rated red maple lumber were very conservative for the targeted 2,400 lb/in^2 level.

Phases I and II: 24F-1.8E Bending Stiffness

For glulam stiffness, actual lumber MOE values from individual beam maps were used in a transformed section analysis to predict each individual glulam beam. The calculated glulam MOE values were then reduced by a factor of 0.95 to account for shear deformation effects. The transformed section method of analysis and the 0.95 factor are specified in the ASTM D3737 standard for calculating horizontally laminated glulam beam MOE. Analysis of the Phase I beams resulted in predicted average glulam MOE values that fell within 2% of the actual values for each of the three combinations. Analysis of the Phase II beams resulted in a predicted average glulam beam MOE of 1.85×10^6 lb/in^2. This compares well with the actual average glulam beam MOE of 1.77×10^6 lb/in^2 (less than 5% difference in the average). For both studies, the differences between the actual and predicted results can be attributed to variations in the regression relationship between dynamic and static MOE, used to determine lumber MOE values.

Phase III: 2 by 4/2 by 6 Bending Strength

The 2 by 4/2 by 6 glulam beams were evaluated for loads applied parallel to the wide face of the laminations (*y*-*y* beam axis). The ASTM D3737 standard specifies procedures for determining the design bending strength of vertically laminated glulam beams (F_{by}). The procedures are based on the characteristics of the single-ply laminations using the allowable edge- and center-knot sizes and allowable slope of grain for the particular grade of lumber. For No. 2 red maple vertically laminated glulam, D3737 analyses predicted a design bending strength of 1,310 lb/in^2. This prediction was based on the controlling strength ratio for slope of grain. If the analysis were based solely on the calculated strength ratios for the allowable knot sizes (overriding the slope-of-grain strength ratio), the predicted design bending strength would be 1,550 lb/in^2.

Published design bending stress for vertically laminated glulam beams (F_{by}) made from No. 2 red maple lumber is 1,450 lb/in^2 (AITC 1996). All predicted and published F_{by} values are very conservative when compared with the calculated design bending strength of 2,360 lb/in^2 given in Table 10.5.

Phase III: 2 by 4/2 by 6 Bending Stiffness

For stiffness of the 2 by 4/2 by 6 glulam beam combination, ASTM D3737 procedures were used to determine the glulam MOE of the members tested in both the horizontally (MOE_x) and vertically (MOE_y) laminated orientations. The analysis resulted in a predicted average glulam beam MOE_x of 1.74×10^6 lb/in^2, which is approximately 7% less than the observed value of 1.86×10^6 lb/in^2. Predicted glulam MOE_y was 1.75×10^6 lb/in^2, which was also approximately 7% less than the observed value of 1.87×10^6 lb/in^2. As was the case with the 24F-1.8E glulam beams, differences between actual and predicted glulam MOE were attributed to variation in the regression relationship between dynamic and static MOE.

Phase III: 2 by 4/2 by 6 Horizontal Shear Strength

Procedures are also given in ASTM D3737 for determining design horizontal shear stresses for vertically laminated glulam timber. Based on these procedures, vertically laminated glulam timber manufactured with 2 by 4/2 by 6 laminations of No. 2 red maple lumber have a calculated design horizontal shear stress of 111 lb/in^2.

This value is similar to the design horizontal shear stress of 65 lb/in^2 published in the AITC 119 standard. However, both the predicted and published values are very conservative when compared with the actual values given in Table 10.7.

In addition to establishing design horizontal shear values for the full-size glulam beams with ASTM D3737 procedures, a different approach to determining horizontal shear strength of glulam timber was studied. Soltis and Rammer (1994) established a method of predicting the horizontal shear strength of full-size glulam timber based on the tests of ASTM D143 shear-block specimens. Results from the ASTM shear-block tests are shown in Table 10.7. For shear-block specimens conditioned to 12% equilibrium MC, the average shear strength of 1,830 lb/in^2 is almost identical to the average shear strength of 1,850 lb/in^2 published in the Wood Handbook (FPL 2010) for red maple.

Soltis and Rammer (1994) developed a relationship between average results of ASTM shear-block tests and full-size horizontal shear tests of glulam timber, represented by

$$\tau = (1.3 C_f \tau_{\mathrm{ASTM}})/A^{1/5} \tag{1}$$

where τ is average glulam horizontal shear strength (lb/in^2); $C_f = 2$, a stress concentration factor for an ASTM shear-block notch; τ_{ASTM} is average shear strength from ASTM D143 test (lb/in^2), and A is shear area of glulam beam (in^2).

Substituting the average ASTM shear-block values (unconditioned specimens) in Table 10.7 and the shear area of the 2 by 4/2 by 6 glulam beams into Equation (1) resulted in an estimated average glulam horizontal shear strength of 1,660 lb/in^2. This predicted result is within 4% of the actual average horizontal shear strength of 1,730 lb/in^2 reported in Table 10.7. Thus, it appears that the ASTM D143 shear-block approach developed by Soltis and Rammer (1994) provides more accurate predictions of glulam horizontal shear stresses than the current ASTM D3737 procedures.

Conclusions

The results of studies by Manbeck et al. (1993) and Janowiak et al. (1995) showed that it is technically feasible to manufacture structural glulam timber using red maple lumber. Specific points observed in this paper include the following:

- Structural glued-laminated (glulam) timber beams manufactured with E-rated red maple lumber in the outer zones and either No. 2 or No. 3 lumber in the core met or exceeded the target design bending stress of 2,400 lb/in^2 and MOE of 1.8×10^6 lb/in^2. Thus, it appears that the E-rating process ensures the required strength and stiffness performance of the laminating lumber, regardless of the lumber resource.
- Structural glulam timber beams manufactured with laminations made from No. 2 red maple 2 by 4's and 2 by 6's are technically feasible. Test results indicate that target design stresses were exceeded for vertically laminated bending strength (F_{by}), MOE in both the horizontally and vertically laminated orientations (MOE_x and MOE_y), and horizontal shear strength in the vertically laminated orientation (F_{vy}).
- The ASTM D3737 procedures developed for softwood species accurately predict beam stiffness and provide conservative bending and horizontal shear strength estimates for glulam beams made with red maple lumber.
- Using results from ASTM D143, shear-block tests accurately predicted the horizontal shear strength of red maple glulam timber made from 2 by 4/2 by 6 laminations.
- The results of this red maple glulam research were incorporated into the AITC 119 hardwood glulam standard (AITC 1996) as the 24F-E4 combination.

Literature Cited

AITC. 1992. Inspection manual. AITC 200-92. Vancouver, WA: American Institute of Timber Construction.

AITC. 1996. Standard specifications for hardwood glued-laminated timber. AITC 119-96. Vancouver, WA: American Institute of Timber Construction.

ANSI. 1992. American national standard for wood products—structural glued laminated timber. ANSI/AITC A190.1. Vancouver, WA: American National Standards Institute.

ASTM. 1993. Standard method for establishing stresses for structural glued-laminated timber (glulam). ASTM D3737-93. Standard methods of static tests of timbers in structural sizes. ASTM D198-84. Standard methods of testing small, clear specimens of timbers. ASTM D143-83. Philadelphia, PA: American Society for Testing and Materials.

FPL. 2010. Wood handbook—wood as an engineering material. General Technical Report FPL–GTR–190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 508 p.

Freas, A.D.; Selbo, M.L. 1954. Fabrication and design of glued-laminated wood structural members. Tech. Bulletin 1069. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Green, D.W.; McDonald, K.A. 1993. Investigation of the mechanical properties of red oak 2 by 4's. Wood and Fiber Science. 25(1): 35–45.

Janowiak, J.J.; Manbeck, H.B.; Wolcott, M.P.; Davalos, J.F. 1992. Preliminary refinement of hardwood stress values. Final Rep. Project SS-047. Harrisburg, PA: Pennsylvania Department of Transportation, Office of Special Studies.

Janowiak, J.J.; Manbeck, H.B.; Hernandez, R.; Moody, R.C.; Blankenhorn, P.R.; Labosky, P. 1995. Efficient utilization of red maple lumber in glued-laminated timber beams. Research Paper FPL–RP–541. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Johnson, J.W. 1978. Edge-gluing Douglas-fir lumber to improve strength properties. Forest Products Journal. 28(11): 37–43.

Manbeck, H.B.; Janowiak, J.J.; Blankenhorn, P.R.; Labosky, P.; Moody, R.C.; Hernandez, R. 1993. Performance of red maple glulam timber beams. Research Paper FPL–RP–519. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

McAlister, R.H. 1973. Edge-glued dimension lumber from low-grade southern pine. Forest Products Journal. 24(7): 17–22.

McDonald, K.A.; Green, D.W.; Dwyer, J.; Whipple, J.W. 1993. Red maple stress-graded 2 by 4 dimension lumber from factory-grade logs. Forest Products Journal. 43(11/ 12): 13–18.

McDonald, K.A.; Hassler, C.C.; Hawkins, J.E.; Pahl, T.L. 1996. Hardwood dimension lumber from log heart cants. Forest Products Journal. 46(6): 55–62.

Metriguard. 1993. Precision testing equipment for wood. Catalog 201. Pullman, WA: Metriguard, Inc.

Moody, R.C.; Hernandez, R.; Davalos, J.F.; Sonti S.S. 1993. Yellow-poplar timber beam performance. Research Paper FPL–RP–520. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

NELMA. 1991. Grading rules for northeastern lumber. Cumberland Center, ME: Northeastern Lumber Manufacturers Association.

NHLA. 1992. Grading rules for hardwood lumber. Memphis, TN: National Hardwood Lumber Association.

Shedlauskas, J.P.; Manbeck, H.B.; Janowiak, J.J.; Hernandez, R.; Moody, R.C.; Labosky, P.; Blankenhorn; P.R. 1994. Efficient use of red oak for glue-laminated beams. ASAE Paper 94-4575. American Society of Agricultural Engineers, Transactions. 39(1): 201–209.

Soltis, L.A.; Rammer, D.R. 1994. Shear strength of unchecked glued-laminated beams. Forest Products Journal. 44(1): 51–57.

Chapter 11

Hardwoods for Timber Bridges

A National Program Emphasis by the USDA Forest Service

James P. Wacker, Research General Engineer
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

Ed Cesa, Program Coordinator (retired)
USDA Forest Service, National Wood in Transportation Center, Morgantown, West Virginia

Hardwood timbers have been used extensively as track ties, or sleepers, in the U.S. railroad industry for over a hundred years. However, the structural use of hardwood timbers for highway bridges was a new idea proposed in the 1980s as a solution to two issues: an overabundance of secondary grade hardwoods and an aging highway bridge inventory with many needs for replacement options. In 1988, a special supplement (AFPA 1988) to the 1986 edition of the National Design Specification (NDS) introduced structural design values for numerous hardwood species and provided the technical stimulus for two national programs aimed at improving the utilization of timber as a structural material for highway bridges.

In 1989, the National Timber Bridge Initiative (Crist 1990) was created by Congressional legislation with the primary goal of enhancing forest-based economies in rural communities of the United States. A national Wood in Transportation (WIT) program evolved from these efforts and was administered by the USDA Forest Service (FS) from a new information center located in Morgantown, West Virginia. The FS established three main emphasis areas: research, demonstration structures, and technology transfer. One of the primary goals of the WIT program was to foster the utilization of locally available and underutilized wood species for wood transportation structures. These WIT structures primarily include highway bridges, pedestrian and trail bridges, and portable bridges. In many regions of the United States, underutilized wood species are identified as secondary (structural) grade hardwoods. Traditionally, timber bridges were constructed primarily with Douglas-fir and Southern Pine because of their comparatively high mechanical properties and good availability. Therefore, research was needed to overcome many technical obstacles associated with efficiently utilizing hardwood species for timber bridge applications.

In 1991, the Federal Highway Administration (FHWA) established a parallel national program for WIT-related research and demonstration projects (Duwadi and Wood 1996). However, few demonstration hardwood bridges were built as part of the FHWA efforts because program emphasis was for conventional bridge designs and using traditional softwood species.

This paper describes the joint efforts of the FS and the FHWA to administer national programs including research, demonstration bridges, and technology transfer components. Summary information on a number of FS–WIT demonstration bridges constructed with hardwoods is also provided.

Research Summary

The foundation of the WIT program was various research efforts related to wood transportation structures. The FS has traditionally constructed more than half of their forest road bridges using timber, and the Forest Products Laboratory (FPL), primary FS research facility for wood and paper products, has a long history of studying new timber bridge structural systems in the laboratory and conventional timber bridge systems in the field. In the wake of the establishment of two national programs emphasizing wood for transportation structures, FPL and the FHWA Turner–Fairbanks Highway Research Center joined resources in 1991 to conduct a joint national wood transportation structures research program, which has been maintained to the present. Six research categories, established by Congressional legislation, were the basic framework for establishing research priorities within an initial needs assessment study (Wipf et al. 1993). Efforts are currently underway to update the initial needs assessment to lay out research priorities further into the future. Table 11.1 summarizes past studies that were identified as higher priority areas and are related to the development of hardwood timber bridge technologies.

Table 11.1—Examples of FPL/FHWA research studies related to hardwoods for timber transportation structures

Research category[a]	Study description	New for engineers
I. Design	Develop glulam technologies	Glulam options
	Develop standard bridge plans	Bridge design aides
II. Lumber properties	Grade and yield studies	Design values for mechanical grades
III. Preservatives	Efficacy of wood preservatives	Treatment specifications
V. Inspection & rehabilitation	Field inspection guidelines	Inspection guidance manual

[a]For area IV—Alternative transportation system structures, there were no hardwood-related studies; for Area VI—Technology and Information Transfer, see following section in this paper for more details.

Another report (Ritter and Duwadi 1998) includes a comprehensive summary of various FPL–FHWA WIT joint research projects and accomplishments. The outcome of these hardwood-related research projects is the elimination of major technical barriers to the application and use of hardwood species for highway bridges and other transportation structures. This work has resulted in the construction of numerous demonstration bridge projects throughout the country.

Demonstration Project Summary

A key component of the WIT program is the construction of demonstration structures, which provide real-world examples to potential users of the capabilities of timber as a structural material for bridges and other transportation structures. The NWITIC administers the WIT demonstration structure process by convening an annual review and selection panel that determines which project applications are offered cost-sharing (50 percent) grants to cover associated materials, design, and construction costs within budgetary constraints.

Between 1989 and 2004, approximately 140 demonstration hardwood bridges were constructed in 17 states (Table 11.2). Four states—West Virginia, Pennsylvania, Iowa, and New York—have constructed substantial numbers of demonstration hardwood bridges. The most demonstration hardwood bridges (60 vehicular) were constructed in West Virginia. West Virginia University (WVU) collaborated with the West Virginia Division of Highways to design and construct several red oak, mixed oak, and yellow poplar demonstration bridges. Most of the bridges constructed in West Virginia are summarized in a two-volume set of fact sheets by Dickson (1995). The main bridge superstructure types emphasized in West Virginia were the stress-laminated deck (Figure 11.1), stress-laminated T-section, and stress-laminated box-section. Much development work was conducted by WVU on the longer span stress-laminated superstructure types, the T-beam and box-beam sections, which utilize hardwood lumber flange sections in conjunction with softwood glulam beams as the web members.

Table 11.2—Summary of USDA Forest Service WIT-funded hardwood demonstration bridge projects in various states

State	No. bridges	Wood species
WV	60	Red oak/yellow poplar
PA	17	Red oak/red maple
IA	14	Cottonwood
NY	13	Red maple/mixed hardwood
MI	5	Red maple/red oak
ND	5	Cottonwood
OH	5	Red oak
KS	3	Mixed oak
MD	3	Red oak
OK	3	Cottonwood
VA	3	Hickory/white oak
IN	2	Red oak
RI	2	Red oak
VT	2	Red maple
AR	1	Red oak
MA	1	Red oak
MO	1	Mixed oak

Figure 11.1—Glade Creek Mill stress-laminated deck bridge located in West Virginia's Babcock State Park. Deck has red oak laminations.

Figure 11.2—A three-pin arch bridge located in Pennsylvania's Trough Creek State Park. Deck panels are red maple.

Figure 11.3—Christian Hollow stress-laminated box-beam timber bridge located in Steuben County, New York. Deck flange laminations are mixed hardwoods.

In Pennsylvania, the Department of Transportation (PennDOT) constructed 17 vehicular and 1 pedestrian demonstration hardwood bridges, primarily with red oak and red maple (Figure 11.2). PennDOT cooperatively worked with the Pennsylvania State University to develop red maple and red oak hardwood species for bridge applications, including the adaptation of glulam beam technologies. This collaboration also resulted in hardwood glulam bridge design standards being developed and adopted by PennDOT (Manbeck et al. 1994).

In Iowa, several counties worked with the Iowa Department of Transportation and constructed 14 vehicular demonstration hardwood bridges using low-valued cottonwood species. The main bridge superstructure types emphasized in Iowa were the stress-laminated deck (Ritter et al. 1995) and transverse glulam decks on steel beam girders.

In New York, 13 vehicular demonstration hardwood bridges were constructed by various county highway departments using a variety of hardwood species (Figure 11.3). Several other states constructed fewer than 5 demonstration hardwood bridges.

A key component in those states that have succeeded in constructing significant numbers of hardwood demonstration bridges (West Virginia, Pennsylvania, and Iowa) appears to be the support of their state transportation departments, including the adoption of standardized plans for hardwood timber bridges.

Technology Transfer Summary

The backbone of the WIT program is technology transfer. Technical information on underutilized wood species for bridges, retaining walls, piers, noise barriers, and other structures must be made available to potential user groups to successfully increase the utilization of timber as structural material in transportation structures. The National Wood in Transportation Information Center (NWITIC), formerly known as the Timber Bridge Information Resource Center, disseminates and distributes information on all aspects of wood in transportation structures from its Morgantown, West Virginia, location. Their program website (www.fs.fed.us/na/wit) includes an abundance of information, including more than 300 publications and a searchable database of 400 funded projects. Since federal funding for the National Wood in Transportation Program ended in federal fiscal year 2004, the Forest Service transferred the WIT database of information to a new National Center for Wood Transportation Structures (NCWTS) and website (www.woodcenter.org). The NCWTS was established in 2007 through a partnership among the FHWA, Forest Products Laboratory, National Park Service, and Iowa State University. It is currently maintained by Iowa State University.

NWITIC also organized various conferences and workshops as an effective means of transferring information to targeted user groups. Several conferences and workshops included significant information related to hardwood timber bridge technologies. The following provides a brief summary of literature related to hardwood timber transportation structures technology transfer efforts.

In 1992, the *National Hardwood Timber Bridge Conference* was held in State College, Pennsylvania. Although a formal conference proceeding was not produced from this conference, one resulting publication describes the material design considerations for hardwood glulam bridges (Manbeck and Shaffer 1994).

In 1994, the *Engineered Wood for Transportation Structures National Workshop* was held in Morgantown, West Virginia (CFC 1996). During the two-day workshop, participants were organized into 10 discussion groups on various topics, including hardwood bridge materials, and were asked focus on key issues facing bridge designers and builders.

In 1996, the *National Conference on Wood Transportation Structures* was held in Madison, Wisconsin, and the conference proceeding is available (Ritter et al. 1996).

During this two-day conference, more than 10 technical papers were presented covering various topics related to the application of hardwoods for timber bridges.

In 1997, a conference entitled *"Eastern Hardwoods, Resources, Technologies, and Markets"* was held at Harrisburg, Pennsylvania. A paper presented by Cesa and Kasey (1997) summarizes the WIT program's history, mission, and organizational structure and provides specific examples of how the WIT program is addressing the needs of the hardwood industry.

A group of hardwood timber bridges, originally constructed during the period 1991–1993 in Pennsylvania, is summarized by Wacker et al. (2004). This paper summarizes the long-term field performance of seven stress-laminated deck bridges over a 4-year period beginning August 1997 and ending July 2001. Results should be available soon from field evaluations conducted in 2019 at many of these same Pennsylvania hardwood timber bridges after more than 25 years of service.

In 2013, the Second International Conference on Timber Bridges was held in Las Vegas, Nevada. Several papers highlighted covered timber bridge projects utilizing hardwood materials for bridges (conference information at www.woodcenter.org/past-conferences/).

Concluding Remarks

Recent research and development work for structural hardwood species has eliminated the major technical barriers to their application and use for highway bridges and other transportation structures. To date, nearly 140 demonstration hardwood bridges have been built in 17 states. A key component in those states that have constructed significant numbers of hardwood demonstration bridges appears to be the support of their state transportation departments, including the adoption of standardized plans for hardwood timber bridges.

Acknowledgments

Thanks to Chris Grant and Jeff Bejune, formerly of the National Wood in Transportation Information Center staff, for assistance with compiling data on demonstration bridges.

Literature Cited

AFPA. 1988. Design values for wood construction—a supplement to the 1986 National Design Specification. Washington, DC: American Forest and Paper Association (formerly National Forest Products Association). 40 p.

CFC. 1996. Engineered wood for transportation structures workshop record. CFC Report 96-232. Morgantown, WV: West Virginia University, Constructed Facilities Center.

Cesa, E.; Kasey, R. 1997. Wood in Transportation program: technology transfer in the hardwood industry. In: Proceedings of the conference on eastern hardwoods, resources, technologies, and markets; April 21–23, 1997; Harrisburg, PA. Madison, WI: Forest Products Society.

Crist, J.B. 1990. The National Timber Bridge Initiative. Wood Design Focus. 1(3): 11–12.

Dickson, B. 1995. Modern timber bridges of West Virginia: Volumes I and II. Morgantown, WV: West Virginia University, Constructed Facilities Center.

Duwadi, S.R.; Wood, R.C. 1996. The Federal Highway Administration Timber Bridge Program. In: Ritter, M.A.; Duwadi, S.R.; Lee, P.D.H., eds. National conference on wood transportation structures; 1996 October 23–25; Madison, WI. Gen. Tech. Rep. FPL–GTR–94. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 333–339. (www.fpl.fs.fed.us/documnts/PDF1996/Duwad96a.pdf)

Manbeck, H.B.; Shaffer, K. 1994. Materials for and design of hardwood glulam bridges. NA-TP-09-94. Morgantown, WV: U.S. Department of Agriculture, Forest Service, Northeastern Area, State and Private Forestry, National Wood in Transportation Information Center. 57 p.

Manbeck, H.B.; Janowiak, J.J.; Blankenhorn, P.R.; Labosky, P. 1994. Development of hardwood glulam timber bridge standards. In: Proceedings of the 1994 ASCE Structures Congress; April 24–27; Atlanta, GA. Reston, VA: American Society of Civil Engineers. p. 1304–1309.

NA. 2001. The National Wood in Transportation CD-ROM: Information on modern timber bridges in the United States, 1988-2001. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, State and Private Forestry, Northeastern Area Office.

Ritter, M.A.; Wacker, J.P.; Tice, E.D. 1995. Design, construction, and evaluation of timber bridge constructed of cottonwood lumber. In: Proceedings of 4th International bridge engineering conference; 1995 August 28–30; San Francisco, CA. Washington, DC: National Academy Press; Vol. 2: 358–370. (www.fpl.fs.fed.us/documnts/pdf1995/ritte95d.pdf)

Ritter, M.A.; Duwadi, S.M. 1998. Research accomplishments for wood transportation structures based on a national research needs assessment. Gen. Tech. Rep. FPL–GTR–105. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 30 p. (www.fpl.fs.fed.us/documnts/fplgtr/fplgtr105.pdf)

Ritter, M.A.; Duwadi, S.R.; Lee, P.D.H., eds. 1996. Proceedings of national conference on wood transportation structures. Gen. Tech. Rep. FPL–GTR–94. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 494 p. (www.fs.fed.us/na/wit/WITPages/witconproc.html)

Wacker, J.P.; Calil, C., Jr.; Hislop, L.E.; Hilbrich Lee, P.D.; Kainz, J.A. 2004. Long-term performance monitoring of hardwood timber bridges in Pennsylvania. Research Paper FPL–RP–612. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 56 p.

Wipf, T.J.; Ritter, M.A.; Duwadi, S.R.; Moody, R.C. 1993. Development of six-year research needs assessment for timber transportation structures. Gen. Tech. Rep. FPL–GTR–74. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 44 p. (www.fpl.fs.fed.us/documnts/fplgtr/fplgtr74.pdf)

Chapter 12

Hardwoods for Engineered Specialty Products

C. Adam Senalik, Research General Engineer
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

Lon A. Yeary, Graduate Research Assistant
Mississippi State University, Mississippi

Robert J. Ross, Supervisory Research General Engineer
John R. Erickson, Former Director (deceased)
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

Thomas M. Maloney, Director, Wood Materials and Engineering Laboratory (deceased)
Washington State University, Pullman, Washington

John W. Forsman, Assistant Research Scientist (retired)
College of Forest Resources and Environmental Science, Michigan Technological University, Houghton, Michigan

The abundance of underutilized hardwoods creates an opportunity to construct a variety of engineering materials and specialty wood products. This chapter gathers information from several studies that focus on products made from hardwood. Brashaw et al. (2012) give contact information for trade associations that represent manufacturers of several hardwood products.

Aircraft Propellers

Since its founding in 1910, the USDA Forest Service, Forest Products Laboratory (FPL), and the U.S. Department of Defense (DoD) have worked cooperatively on a wide range of topics, all with a focus on ways of improving materials used in support of the DoD's mission to protect the United States and its allies. The use of wood in aircraft became a focal point of FPL research and development efforts in 1917 (Risbrudt and others 2007). Research was conducted on the design and use of wood in every aspect of the design of aircraft, including propellers.

Early FPL research focused on developing appropriate technologies for the manufacture of wood propellers. Wood has a unique combination of physical and mechanical properties that make it well suited for use as propellers: it is light, is strong parallel to the fiber axis, has excellent vibration response and damping, and is relatively easy to machine into a variety of shapes. FPL identified the primary tree species for use as wood propellers as mahogany (Central American, African, and Philippine), yellow poplar, hard (sugar) maple, yellow birch, red gum, and white oak. Lumber drying technologies and adhesive systems were developed. FPL research revealed that quartersawn lumber was best suited for propeller manufacture; however, gluing quartersawn lumber to other cuts of lumber could result in poor quality joints, which would adversely affect propeller performance.

FPL developed manufacturing guidelines to ensure optimal performance of wood propellers. The guidelines included the following recommendations:

- Only woods of similar density should be laminated into a propeller.
- The wood should remain at the same relative humidity throughout the manufacture of the propeller.
- Only wood of the same species should be used in an individual propeller.
- The use of animal-protein-based adhesives, which was widespread in the wood products industry in the early 1900s, was not recommended for wood propeller construction.

These recommendations helped to ensure that anticipated wood shrinkage and expansion for in-service propellers would be as uniform as possible. If nonuniform shrinkage or expansion occurred, then stress cracks could develop, which would adversely affect propeller performance.

Wood propellers are still utilized in a variety of aircraft: small civilian passenger aircraft, cargo planes, and remotely piloted military aircraft (drones). Two examples of the use of wood propellers in drones are shown in Figure 12.1. The Shadow 2000 is a reconnaissance drone that uses laminated hard maple propellers. It carries cameras and other optical equipment for gathering critical information for military operations in a variety of environments. The Tiger Shark is made entirely from wood. The design of its fuselage, wings, and propeller are all based on early FPL research. It weighs 260 lb, has a wingspan of 22 ft, and is capable of carrying

Figure 12.1—Two reconnaissance drones that use laminated hard (sugar) maple propellers. (a) Shadow 2000 (source: United States Marine Corps). (b) Tiger Shark (source: NASA).

50 lb of equipment. It can remain on a mission for over 10 h, and has an operating range of approximately 50 miles.

Today, most wood propellers are made from hard maple, a relatively high-strength wood that is widely available in the upper Midwest region of the United States. Minimizing wood shrinkage is a priority for many wood products and particularly for engineered products manufactured to small tolerances, such as propellers. In 2007, a supplier of wooden propellers to the DoD contacted FPL with a question regarding shrinkage of their product during storage in the Middle East. Specifically, the wood propellers used on surveillance drones in Iraq and Afghanistan were undergoing excessive in-service shrinkage, which resulted in misalignment of the hub bolt holes. The misalignment made proper installation problematic and resulted in subsequent performance issues.

In an FPL study by Bergman and Ross (2008), the extent and location of wood shrinkage of the hubs in response to high temperature and low relative humidity conditions encountered prior to installation and in-service were quantified. Seven wood propellers were supplied to FPL for experimental evaluation by Sensenich Wood Propellers (Plant City, Florida, USA). Each propeller was machined from a 16-ply sugar maple (*Acer saccharum*) veneer blank manufactured by Burkel, Inc. (Oconto Falls, Wisconsin, USA). Moisture content (MC) of the blanks varied from

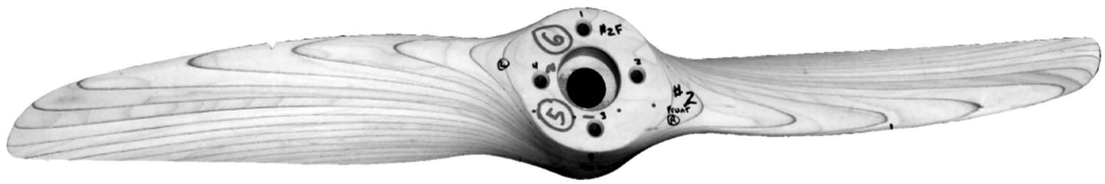


Figure 12.2—Wood propeller provided to the Forest Products Laboratory for evaluation.

approximately 5% to 7%. Wood propellers 29 in. (73.7 cm) tip-to-tip were machined from the blanks by Sensenich. MC of the finished propellers was approximately 9% to 10%. These wood propellers were not coated with a finish (Fig. 12.2).

To evaluate the extent of shrinkage in response to moisture changes, the propellers were dried from 11% to 3% moisture content in a controlled environment of 150 °F (65 °C) for three days. Two of the propellers were encased in polyethylene bags. Results showed 5 to 20 times more shrinkage for the thickness of the propeller hub and the hub face perpendicular to the propeller blades (across the grain) compared with the hub face parallel to the blades (along the grain). Two hubs that were coated with aluminum oxide paint showed dimensional changes similar to those observed for uncoated hubs. For the two wood propellers encased in polyethylene bags, moisture loss was slowed during the course of the experiment by roughly 46%. This indicated that wrapping the wood propellers prior to shipping would slow moisture desorption, thereby minimizing shrinkage during short-term storage.

The following recommendations were made to address performance problems from shrinkage of wood propellers stored in high-temperature environments:

- Maintain the MC of the wood propeller at 6% during the entire manufacturing process, including both veneer blanks and wood propellers, to limit the effect of in-service shrinkage. This MC is less than the median of 6.9% equilibrium moisture content that the propellers would be exposed to during summer and winter months in Baghdad, Iraq. A lower MC than the median would be prudent because of the uncertain length of time the wood propeller may be stored in a high-temperature environment prior to installation.
- Vacuum pack both the veneer blank and the finished wood propeller in an airtight polyethylene bag for transport and storage. Encasing the propeller would limit shrinkage during short-term storage in a high-temperature environment.
- Remove the propellers from dry storage and unwrap at least two to four weeks prior to installation.

Laminated Tool Handles

Traditionally, handles for working tools such as axes, hammers, and mauls have been made from straight-grained sugar maple or white ash lumber. The combination of strength, flexibility, and shock absorption make these woods well suited for tool handles. Tool handles constructed of these woods are strong, durable, and reduce the impact shock pulse transferred from the point of impact to the wielder.

The supply of sugar maple and white ash lumber in the sizes and of the required quality necessary for use as tool handles is dwindling and becoming more costly. Erickson and Forsman (1998) examined the feasibility of constructing tool handles from laminated blanks composed of small-dimensioned white ash lumber, which is more abundant and less costly. Six different variations of solid wood or wood laminates were mechanically tested to determine stiffness and strength. Clear, straight-grained specimens were prepared from lumber and tested in flexure. The specimens were loaded either on tangential or radial planes, with respect to growth ring orientation. Laminated materials, composed of two or three layers, were fabricated and tested with the glue line either parallel or perpendicular to load. The glue line of the laminates was parallel to the tangential face of the wood. Tables 12.1 and 12.2 summarize results obtained from the testing of clear wood and laminated specimens fabricated from white ash lumber. Modulus of elasticity (MOE) and modulus of rupture (MOR) values were reported. Mean MOR and MOE values obtained from the laminates closely matched those obtained from solid specimens, and the standard deviations of MOR and MOE of the laminate specimen groups were smaller than those of the solid specimens. The results indicate that tool handles manufactured from laminated blanks would likely perform similarly to those manufactured from solid blanks.

Blockboard

Blockboard is an engineered composite product composed of narrow boards, blocks, or strips of wood side by side forming a panel that is crossbanded on both sides with veneer (FAO 1966). It has been manufactured worldwide and is an accepted alternative to other types of composites (medium density fiberboard and industrial particleboard) for high value applications.

Table 12.1—Modulus of elasticity (MOE) for clear and laminated white ash specimens

Layup	Load direction	Number of specimens	MOE ($\times 10^6$ lb/in^2)			
			Minimum	Maximum	Mean	Std. dev.
Solid	Loaded on radial face	60	0.88	2.40	1.69	0.387
Solid	Loaded on tangential face	60	0.91	2.59	1.70	0.407
Two-ply	Glueline parallel to load	29	1.36	2.28	1.79	0.193
Two-ply	Glueline perpendicular to load	29	1.12	2.28	1.76	0.228
Three-ply	Glueline parallel to load	29	1.28	2.20	1.69	0.249
Three-ply	Glueline perpendicular to load	29	1.22	2.20	1.68	0.280

Table 12.2—Modulus of rupture (MOR) for clear and laminated white ash specimens

Layup	Load direction	Number of specimens	MOR ($\times 10^3$ lb/in^2)			
			Minimum	Maximum	Mean	Std. dev.
Solid	Loaded on radial face	60	8.91	22.35	15.19	3.013
Solid	Loaded on tangential face	60	9.72	22.52	15.15	3.050
Two-ply	Glueline parallel to load	29	13.11	20.86	16.09	1.575
Two-ply	Glueline perpendicular to load	29	8.51	19.89	15.50	2.617
Three-ply	Glueline parallel to load	29	11.50	18.16	14.54	1.662
Three-ply	Glueline perpendicular to load	29	11.34	18.59	15.10	1.770

Table 12.3—Summary of research investigating species and adhesive systems in blockboard manufacture

Reference	Species		Adhesive used
	Face laminations	Core laminations	
Bowyer (1979)	Elm	Aspen	Phenolic
Bowyer and Stokke (1982)	White elm	Aspen	Resorcinol
Maloney et al. (1993)	Alder, maple, yew, lodgepole pine	Alder, white fir, hemlock, lodgepole pine	Polyvinyl acetate, urea formaldehyde
SITR (1967)	Birch	Pine	N/A

The construction of blockboard products varies considerably, based on the available resource and desired characteristics of the final product. Some blockboard produced with thin veneer faces is made with thin veneer crossbands placed just below the outer veneer faces. Referred to as a “5-ply layup,” this type of construction is very stable dimensionally and allows for the use of very thin, high-quality face veneers.

Blockboard can be produced without edge gluing the core strip, but most modern manufacturing systems do edge glue core material. Blockboard can also be produced by using lumber strips instead of veneer for the face layers.

Considerable research and development activities have been conducted to examine various layup patterns and the suitability of different types of raw materials for the manufacture of blockboard (Bowyer 1979; Bowyer and Stokke 1982; Maloney and others 1993; SITR 1967). Table 12.3 summarizes various species and adhesive systems used in these studies. A wide range of hardwood species (alder, aspen, birch, elm, maple, and yew) have been used successfully to produce blockboard in laboratory investigations.

Cross-Laminated Timber (CLT)

Cross-laminated timber (CLT) is described in U.S. editions of the CLT Handbook (Karacabeyli and Douglas 2013). CLT panels are composed of three or more layers of lumber boards fixed together with differing grain orientations. The panels provide an alternative to some building applications that currently use concrete, masonry, or steel. Often the panels contain an odd number of layers with the grain angle alternating by 90° between consecutive layers. The outer layers are oriented in the direction of gravity loads or major spans. The wide faces of the lumber boards abut between layers and the layers are connected by glue, nails, or dowels. When glue is used, the narrow face of the boards abutting within a layer may also be glued. Figure 12.3 shows a diagram of a three-layer CLT panel.

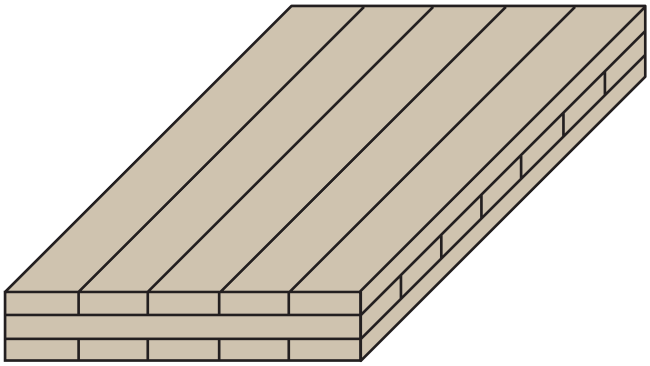


Figure 12.3—Three-layer CLT panel.

Slavid (2013) noted that softwoods have dominated CLT panel construction because of density, stiffness, and strength requirements. In recent years, greater attention has been paid to the use of hardwoods in CLT panels. The overlapping layup construction of CLT reduces the deleterious effect of individual knots on the overall panel strength, opening up the potential use of lower grades timber in CLT construction without loss of quality or strength.

Stauder (2013) provided an overview of CLT and briefly discussed the benefits of using undervalued hardwood in CLT panels. Hardwood as a base material for CLT construction is becoming more widely investigated. Hardwoods may allow CLT panels to be constructed with higher bending stiffness and greater shear resistance without increasing the overall dimensions, and in some cases reducing the thickness of the panels. CLT panels could have vertically oriented layers made of softwoods for compressive strength and transverse layers of hardwoods to take advantage of superior rolling shear and bending stiffness. Finger jointing can be used to overcome potential feedstock dimension limitations, and low-grade wood can be used in CLT. As demand for low-grade wood increases, the potential to use undervalued hardwoods becomes more viable.

Krackler et al. (2011) discussed results of a Swiss National Forest Inventory in which it was shown that hardwood volumes had increased by 10.4% while softwood volumes had decreased. It was noted that hardwood processing after harvest was more complicated than softwood processing. Hardwood yields were nearly half the useful stem woods of softwoods, and almost 60% of the hardwood harvest was used for energy purposes immediately following harvesting. This was despite the fact that Swiss mills were underutilizing their machines and could process an additional 8,500 m^3 of hardwood yearly. Krackler et al. (2011) identified several possible production areas where the use of hardwoods could be increased. Only one company in Switzerland was found to be offering solid hardwood panels. Solid wood construction was one area that was dominated by softwood, but the inclusion of hardwood could yield higher strength or smaller dimensioned panels. With respect to glue laminated products, Krackler et al. (2011) identified hardwood species with the most promising potential for use as beech, ash, and oak. Combined beams of softwoods and beech and beams composed of pure beech wood were found to perform to acceptable levels. The presence of red heartwood in the beech wood was found to have no negative effects on bonding.

Callegari et al. (2010) described a project of constructing CLT panels made of chestnut (*Castanea sativa* Mill.) and poplar wood (*Popolus x euroamericana*), using the industrial framework then available locally in the area of Piedmont, Italy. The focus of the project was increasing the value of the construction timber supply chain in Piedmont, Italy. Two industrial partners were identified: a sawmill that worked with chestnut wood and a plywood company capable of producing the panels. The project confirmed the feasibility of producing reduced sized CLT panels using equipment available in the plywood sector. A notable problem with the process was the presence of shakes. Prior to panel construction, shakes were not evident and within allowable tolerance. After board production, excessively large shakes could develop during the panel conditioning phase.

Brandner (2013) described the use of hardwood in CLT as demonstrated in Brucknerstrasse, Graz, Austria. A three-story building was constructed of CLT panels composed of silver birch (*Betula pendula*). Several other hardwoods were identified as possible candidates for use in CLT due to their physical characteristics, availability, and economic viability including poplar (*Populus* spp.) and ash (*Fraxinus excelsior*). The use of hardwoods in CLT may allow for additional optimization of CLT properties by utilizing hardwoods in transverse layers and exploiting the higher rolling shear of such species or using species with high bending strength as outer CLT layers.

Ehrhart et al. (2015) examined the rolling shear properties of several European hardwood species for use in CLT. The performance of hardwood species birch (*Betula pendula* Roth), beech (*Fagus sylvatica* L.), poplar (*Populus* spp.) and ash (*Fraxinus excelsior* L.) were compared with those of softwood species Norway spruce (*Picea abies* (L.) Karst.) and pine (*Pinus sylvestris* L.). When all species were examined together, a strong correlation was found between both density and rolling shear modulus and also density and rolling shear strength. With respect to the rolling shear properties, poplar was comparable to both softwood species, birch slightly exceeded both softwoods, and ash and beech had property values between two to three times those of either Norway spruce or pine. The findings indicated that beech, ash, birch, and poplar all had great potential for use in CLT.

Beagley et al. (2014) examined the use of yellow-poplar (or tulipwood) (*Liriodendron tulipifera*) for potential use in CLT panels. Yellow-poplar has a specific gravity that meets the current CLT requirements (APA 2012). In this study, six five-layer CLT panels were constructed using yellow-poplar. Preliminary results from nondestructive tests of CLT panels constructed of yellow-poplar indicate met requirements for bending and shear stiffness as dictated by ANSI/APA PRG 320-2012 Standard for Performance-Rated Cross-Laminated Timber (APA 2012). The research showed that yellow-poplar had great potential as a feed material for CLT construction. Slavid (2013) explained that yellow-poplar is a hardwood of particular interest for CLT construction because it has mechanical properties close to many softwoods, grows tall and straight, and has fewer knots than many other hardwoods. Yellow-poplar is one of the fastest drying hardwoods as well, meaning that less time is required to kiln dry it than other wood types. It is also abundant in the United States and relatively low cost. Stauder (2013) noted that yellow poplar was likely to be among the first hardwoods accepted for CLT construction, and research has been conducted on use of yellow poplar in CLT (Mohamedzadeh and Hindman 2015).

Vetsch (2015) constructed CLT panels from aspen (*Populus tremuloides*), which is a locally abundant and underutilized wood in Minnesota. Panels were constructed using locally acquired aspen wood. The panels were tested in accordance with ASTM D198-09 Standard Test Methods of Static Tests of Lumber in Structural Sizes and ANSI/APA PRG 320-2012 (APA 2012). The maximum loads from the aspen panels exceeded those required in the standards; however, the modulus of elasticity (MOE) and modulus of rupture (MOR) fell below standard levels. It was noted by Vetsch that during failure testing, complete delamination occurred between some panel layers; at some point during the testing, there was no bonding between adjacent layers. As tested, the sample performance was close to meeting standard levels. It was theorized that improved panel manufacturing would prevent delamination during testing and the resulting panels would exceed standard requirements. The preliminary study showed that aspen had potential to be used in CLT panels, but additional testing was needed due to the delamination and small sample size before a conclusion could be drawn.

Kramer (2014) and Kramer et al. (2014) demonstrated the viability of using plantation-grown, low-density hybrid poplar (or Pacific albus) in performance-rated CLT panels. The shear and bending performance of the panels used in the study was evaluated against ANSI/APA PRG-320-2012 (APA 2012). The available supply of hybrid poplar in the Pacific Northwest has increased due to a decrease in its use by the pulp and paper industry. Panels constructed of hybrid poplar will likely meet or exceed bending and shear strength requirements, but the panels did not meet stiffness (MOE) requirements. Hybrid poplar could be used in conjunction with higher density wood species to create panels with greater property efficiency that fully comply with standard requirements.

There is great potential for the use of undervalued hardwoods in CLT panels. Although much of the research in the area of using hardwoods to construct CLT panels relatively new, the initial findings are favorable. It may be possible to construct CLT panels capable of meeting performance standards using hardwoods in part or in whole. Yellow-poplar has several characteristics that make it a strong candidate as a sole building material for CLT construction. Other hardwoods may have greater potential when used in in conjunction with softwoods to exploit superior rolling shear and bending strength of the hardwoods with the high compressive stiffness of softwoods. Regardless of use, CLT panels represent a potential new market for undervalued hardwood.

Literature Cited

APA. 2012. Standard for performance-rated cross-laminated timber. ANSI/APA PRG 320-2012 Tacoma, WA: APA–The Engineered Wood Association.

Beagley, K.S.M; Loferski, J.R.; Hindman, D.P.; Bouldin, J.C. 2014. Investigation of hardwood cross-laminated timber design. Proc., World Conference on Timber Engineering: Renaissance of Timber Construction, Aug. 10–14, 2014.

Bergman, R.; Ross, R.J. 2008. Evaluating shrinkage of wood propellers in a high-temperature environment. Research Note FPL–RN–0309. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 7 p.

Bowyer, J.L. 1979. Faceglued blockboard from low grade northern hardwoods. Wood and Fiber Science. 11(3): 184–196.

Bowyer, J.L; Stokke, D. 1982. The effect of core block length on strength of face glued block board. Wood and Fiber Science. 14(1): 60–69.

Brandner, R. 2013. Production and technology of cross laminated timber (CLT): a state-of-the-art report. In: COST Action FP1004, Focus STS–European Conference on Cross-Laminated Timber (CLT): 2–36.

Brashaw, B.K.; Ross, R.J.; Wang, W.; Wiemann, M.C. 2012. Wood utilization options for urban trees infested by invasive species. Madison, WI: Forest Products Society. 82 p.

Callegari, G.; Cremonini, C.; Rocco, V.M.; Spinelli, A.; Zanuttini, R. 2010. The production of hardwood X-Lam panels to valorize the forest-wood chain in Piemonte (Italy). In: Proceedings of the World Conference on Timber Engineering.

Ehrhart, T.; Brandner, R.; Schickhofer, G.; Frangi, A. 2015. Rolling shear properties of some European timber species with focus on cross laminated timber (CLT): test configuration and parameter study. Doctoral dissertation, Andrea Frangi.

Erickson, J.; Forsman, J. 1998. Evaluate the potential of laminating 5/4 + lumber to replace and equal the performance and quality of 9/4 + straight grained white ash and sugar maple for tool handles. Institute of Wood Research. Houghton MI: Michigan Technological University. 22 p.

FAO. 1966. Plywood and other wood-based panels. Report of an international consultation on plywood and other wood-based panel products. Rome, Italy: Food and Agricultural Organization of the United Nations. July 8–19, 1963.

Karacabeyli, E.; Douglas, B., eds. 2013. CLT handbook: cross-laminated timber: U.S. edition. Special publication, ISSN 1925-0495; SP-529E. Pointe-Claire, QC, Canada: FP Innovations and Binational Softwood Lumber Council.

Krackler, V.; Keunecke, D.; Niemz, P.; Hurst, A. 2011. Possible fields of hardwood application. Wood Research. 56(1): 125–136.

Kramer, A. 2014. Cross-laminated timber engineering: improvement and application. M.S. thesis. Corvallis, OR: Oregon State Univ.

Kramer, A.; Barbosa, A.; Sinha, A. 2014. Viability of hybrid poplar in ANSI approved cross-laminated timber applications. Journal of Materials in Civil Engineering. 26(7): 10.

Maloney, T.M.; Ross, R.J.; Lentz, M.T.; Allwine, R. 1993. Developing high-value blockboard made of alder and other Pacific Northwest hardwoods. Pullman, WA: Washington State University, Wood Materials and Engineering Laboratory, College of Engineering and Architecture. 81 p.

Mohamedzadeh, M.; Hindman, D. 2015. Mechanical performance of yellow-poplar cross laminated timber. Report No. CE/VPI-ST-15-13. Blacksburg, VA: Virginia Polytechnic Institute and State University. 34 p.

Risbrudt, C.D.; Ross, R.J.; Blankenburg, J.J.; Nelson, C.A. 2007. Forest Products Laboratory—supporting the nation's armed forces with valuable wood research for 90 years. Forest Products Journal. 57(1–2): 7–14.

Slavid, R. 2013. Endless Stair – A towering Escher-like structure made from American tulipwood CLT for the London Design Festival 2013. https://www.americanhardwood.org/sites/default/files/publications/download/2017-04/AHEC%20The%20Endless%20Stair_pages.pdf (accessed February 24, 2020)

SITR. 1967. Strength properties of Finnish blockboard and laminboards I. Report Series 1, No. 40. Helsinki, Finland: State Institute for Technical Research.

Stauder, C. 2013. Cross-laminated timber—an analysis of the Austrian industry and ideas for fostering its development in America. Austrian Marshall Plan Foundation, September.

Vetsch, N. 2015. A performance evaluation of cross-laminated timber manufactured with aspen. University of Minnesota Digital Conservancy, http://hdl.handle.net/11299/172229.

Chapter 13

Cellulose Nanomaterials and Their Products from Hardwoods

Ronald C. Sabo, Research Materials Engineer
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin

Cellulose nanomaterials are an emerging class of materials with unique properties that offer promising outlets for undervalued hardwood species. As wood is broken down into nanometer-scale fibers and particles, the resulting materials begin to exhibit unique and interesting properties, including remarkable strength, liquid crystal behavior, transparency when cast as a film, low thermal expansion, high capacity to absorb water, and piezoelectric and electroactive behavior. Potential applications for cellulose nanomaterials include food additives (Turbak et al. 1982, medical and pharmaceutical applications (Innami and Fukui 1987), paper and paperboard additives (Klemm et al. 2011), automotive parts (Kiziltas et al. 2013), substrates for flexible electronics (Sabo et al. 2012, Seo et al. 2015), paints and coatings (Syverud 2011), aerogels (Javadi et al. 2013), and barrier packaging (Lavoine, et al. 2012), among numerous others. Therefore, cellulose nanomaterials may well provide new high-value markets for undervalued and underutilized hardwood species. An overview of these materials, their properties, and potential products is provided here, with an emphasis on undervalued hardwood sources.

Cellulose Nanomaterials

Cellulose nanomaterials, a class of lignocellulosic materials with dimensions below about 100 nm, are typically classified as either cellulose nanocrystals (CNCs) or cellulose nanofibrils (CNFs). CNCs are discrete, rod-shaped cellulose particles with nanometer-scale diameters typically having lengths of hundreds or thousands of nanometers. Typically, CNCs have high crystallinity and are most commonly produced by sulfuric or hydrochloric acid hydrolysis of wood pulp. CNFs usually consist of more network-type structures instead of discrete particles. A countless number of methods are available to produce CNFs, although they almost entirely consist of some combination of chemical or biological pretreatment with mechanical processing to liberate individual or bundles of cellulose microfibrils. A wide range of morphologies and material properties can be attained by processing wood into cellulose nanomaterials, and the application of these materials varies widely with various processing courses.

Cellulose Nanocrystals

CNCs are typically produced by acid hydrolysis of native cellulose using hydrochloric, sulfuric, or phosphoric acid. Cellulose nanocrystals prepared by sulfuric acid hydrolysis have charged surfaces, whereas those prepared using hydrochloric acid are not charged (Azizi Samir et al. 2005). CNCs with charged surfaces can form stable aqueous suspensions, so CNCs are usually produced using sulfuric acid. The yield of CNCs from natural plant fibers is found to be about 30% (Bondeson et al. 2006). Wood-derived CNCs typically have diameters of several nanometers and lengths of hundreds on nanometers (Fig. 13.1).

CNCs have some interesting properties, including exceptional mechanical properties and the ability to self-assemble. Tensile strength and elastic modulus of CNCs are reported to be about 8 GPa and 100–200 GPa, respectively, so they are often targeted as a reinforcement for polymeric materials (Moon et al. 2011). The self-assembly of CNCs in water results in optical activity, which means that they change the orientation of polarized light and behave as liquid crystals (Beck-Candanedo et al. 2005). When dried as a film, this self-assembly can be controlled, resulting in colored films whose colors have the potential to be

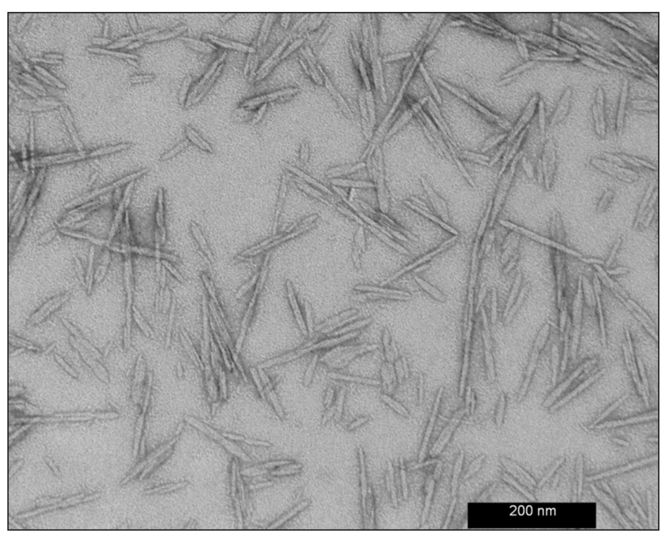


Figure 13.1—Cellulose nanocrystals from Eucalyptus.

manipulated (Cranston and Gray 2006). Because of these interesting properties, CNCs have potential for applications as polymer reinforcements and for use in sensors and security papers.

Cellulose Nanofibrils

CNFs are typically produced from wood pulp that has been chemically or enzymatically treated followed by some type of mechanical refining (Lavoine et al. 2012; Qing et al. 2013; Siró and Plackett 2010). Mechanical treatments to produce CNFs can include disk refining, stone grinding, homogenizing, microfluidizing, cryogenic crushing, and ultrasonic processing. Chemical pretreatments of wood often include some type of chemical pulping, such as sulfite or Kraft pulping, and examples in the literature commonly involve CNFs produced from bleached pulps. Additional chemical or enzymatic treatments, or both, are then applied to these pulps. One prominent chemical treatment is an oxidation treatment involving 2,2,6,6-tetramethylpiperidinyl-1-oxyl (TEMPO)-mediated oxidation of cellulose (Saito et al. 2007, 2009). This TEMPO process dramatically reduces the energy required to produce CNFs and yields uniform nanofibers with diameters around 10 nm and lengths up to micrometers. Other pretreatments, such as endoglucanase hydrolysis, have also been widely demonstrated (Qing et al. 2013; Siró and Plackett 2010). Such enzymatic pretreatments reduce the amount of energy required to produce CNFs but not as effectively as TEMPO-mediated oxidation, and the resulting CNFs are typically not as uniform or long. Figures 13.2 and 13.3 show typical scanning electron micrographs of CNFs created by both of these treatments. Depending on the pretreatment reaction conditions, energy input, and other processing considerations, the morphologies and properties of CNFs can vary quite dramatically.

When elementary fibrils and fibril bundles are liberated from the wood cell wall, the material begins to take on characteristics distinct from coarse wood fibers. For example, CNF suspensions have high viscosities and are shear thinning. A TEMPO-oxidized CNF suspension with about 2% solids will be viscous enough to not flow under the force of gravity, making CNFs candidates for rheology modifiers and colloidal stabilizers. Films made from CNFs are typically highly transparent (Fig. 13.4) and are thus being considered in applications requiring transparency (such as food packaging and electronic displays). These films also exhibit good mechanical properties, especially tensile properties; randomly oriented CNF films are routinely reported as having tensile strengths of 200 MPa or more and moduli of 10-20 GPa (Qing et al. 2013; Saito et al. 2009; Siró and Plackett 2010). Thermal expansion of CNF films has also been measured to be low, with coefficient of thermal expansion values commonly reported as lower than 20 ppm/K and as low as 3 ppm/K, which is lower than most polymers (Iwamoto et al. 2007; Nakagaito et al. 2010).

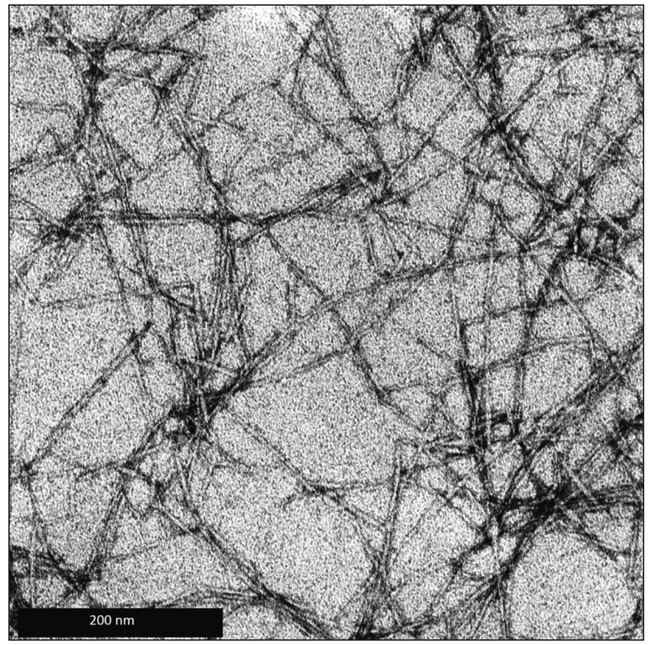


Figure 13.2—Cellulose nanofibrils from TEMPO-mediated oxidation of yellow poplar.

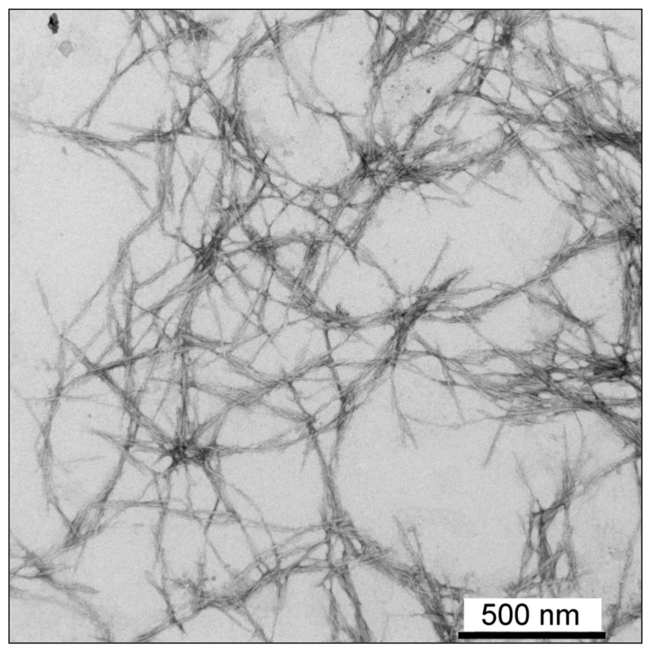


Figure 13.3—Cellulose nanofibrils produced by enzymatic and mechanical treatment of Eucalyptus.

Cellulose nanofiber films have also been demonstrated to act as good barriers to oxygen and other gases, especially at low humidity (Fukuzumi et al. 2009; Lavoine et al. 2012). The rheological, mechanical, optical, barrier, and thermal properties of CNFs make them a unique biobased material with numerous potential applications.

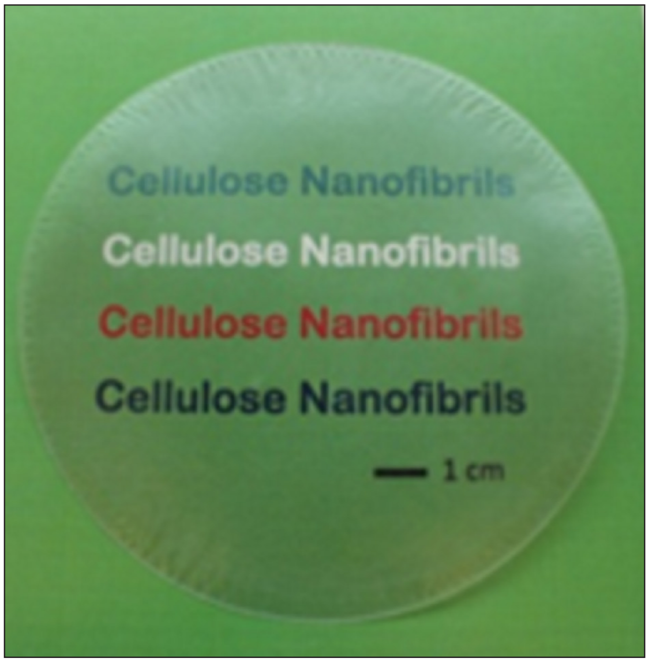


Figure 13.4—Cellulose nanofibril film from hardwood pulp.

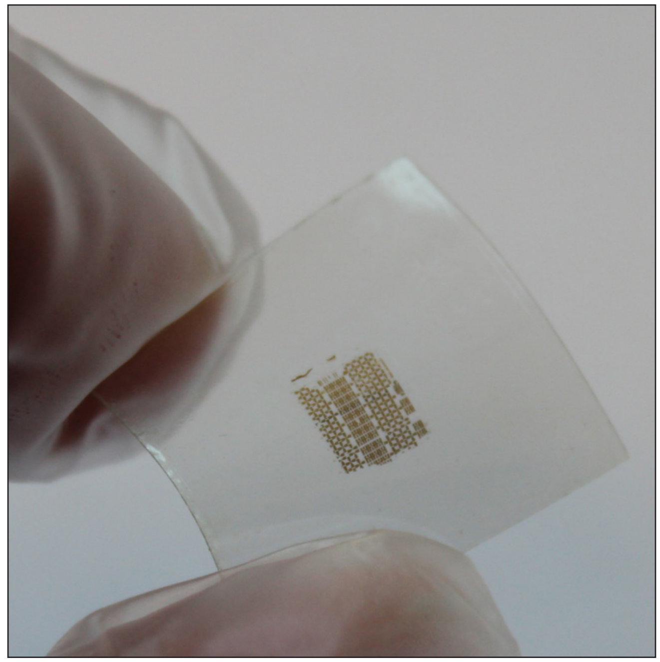


Figure 13.5—Electronic circuit on flexible cellulose nanofibril substrate from hardwoods.

Preparing Cellulose Nanomaterials from Hardwoods

Cellulose nanomaterials can be produced from virtually any lignocellulosic plant, and the limited comparisons among various species indicate that CNCs and CNFs from hardwoods are comparable to those from other species. For example, Fukuzumi et al. (2009) compared the differences of CNFs produced by TEMPO-mediated oxidation of bleached Kraft hardwood and softwood pulps (of unnamed species), and they found nearly identical mechanical properties of films made from both species (Fukuzumi et al. 2009). The hardwood films exhibited somewhat lower transparency than the softwood films, a phenomenon attributed to the hardwood xylan content, which is affected by pulping and other pretreatment processes. Although there may be slight differences in the morphologies and properties of cellulose nanomaterials from bleached pulp derived from various wood species, these differences are minor compared with differences due to manufacturing variabilities and differences between wood and nonwoody sources. For example, differences between chemical and enzymatic pretreatments on CNF properties are far greater than differences between wood species. Therefore, although the effects of varying constituent components of different wood species for producing cellulose nanomaterials has not been thoroughly studied, undervalued hardwood species are expected to yield high-quality cellulose nanomaterials based on numerous examples of these hardwoods being used to create CNCs and CNFs.

There are numerous examples of using hardwoods as a source material for both CNCs and CNFs. In one example, CNFs were produced from southern hardwood pulp containing gum, maple, oak, eucalyptus, poplar, or beech or a mixture (Stelte and Sanadi 2009). Processes for producing cellulose nanomaterials from hardwoods as a bioenergy co-product have also been described (Song et al. 2014; Zhu et al. 2011). Zhu et al. (2011) produced CNFs from bleached Kraft Eucalyptus pulp fibers using a combination of enzymatic hydrolysis and mechanical treatments, and they separated the sugar streams to create ethanol. Song et al. (2014) later performed similar experiments using northern maple hardwood. Poplar has also been used to produce both CNCs (Yang et al. 2014) and CNFs (Chen et al. 2013; Hassanzadeh et al., 2017). Birch is another hardwood that was used to produce cellulose nanomaterials (Vartiainen et al. 2011). Clearly, a wide variety of hardwood species can be used to produce cellulose nanomaterials.

Applications and Products

A number of applications containing cellulose nanomaterials derived from hardwoods have been demonstrated. Researchers at the University of Wisconsin and the USDA Forest Service, Forest Products Laboratory, demonstrated that cellulose nanofibril films from Eucalyptus can be used as substrates for high-speed flexible electronics (Fig. 13.5) (Sabo et al. 2012; Seo et al. 2015). These substrates were demonstrated to be biodegradable, offering possible solutions for growing electronic waste issues. Another example of using cellulose nanomaterials to improve the environmental impact of electronics includes recyclable solar cells that were constructed on substrates made of CNCs from hardwoods (Zhou et al. 2014). Modified cellulose nanofibril aerogels from Eucalyptus were demonstrated to be excellent candidates for cleaning oil spills because they preferentially absorbed oils and other organic liquids in quantities up to nearly 100 times their own weight (Zheng et al. 2014). CNCs and CNFs have also been demonstrated to facilitate void structure in foamed polymers to yield plastic parts with better strength-to-weight properties, which has enormous potential, for example, to reduce the weight of interior automotive parts and thus improve fuel efficiency (Peng et al. 2016; Srithep et al. 2012). CNCs from Eucalyptus were found to be a potential reinforcement in concrete and to result in increased hydration (Cao et al. 2015). Coatings made from CNCs have also been demonstrated to improve abrasion resistance, potentially offering more durable paints and coatings. Cellulose nanomaterials from hardwoods clearly have a wide range of applications and products, and those applications continue to expand.

Many demonstrated applications of cellulose nanomaterials derived from sources other than hardwoods can also be extended to CNCs and CNFs derived from hardwoods, so some of these applications merit discussion in this context. CNFs can potentially be used in food applications as thickeners and to improve consistency and texture of foods (Turbak et al. 1982). CNFs have been demonstrated to improve the properties of paper and to facilitate the addition of inexpensive fillers (Phipps et al. 2015; Taipale et al. 2010). A variety of cellulose nanomaterials have been demonstrated to act as barriers to moisture and oxygen and to improve the barrier properties of polymers, so both CNCs and CNFs from hardwoods have the potential to be incorporated into packaging materials (Lavoine et al. 2012). CNFs have also been shown to act as a stabilizing agent for paints and other colloidal systems (Syverud 2011). The number of potential and demonstrated applications for cellulose nanomaterials is quite substantial and continues to grow. As the field matures, more of these applications are expected to become commercialized.

Outlook

Research and development of cellulose nanomaterials and their use in products is rapidly growing, and numerous efforts to advance commercialization are underway. Many see these biobased materials as potentially revolutionary for their unique properties, and market projections for cellulose nanomaterials are in the tens of millions of tons per year (Cowie et al. 2014; Shatkin et al. 2014). Cellulose nanomaterials are currently being produced at numerous demonstration- and pilot-scale facilities, many of which are operating at a scale on the order of a ton per day (Walker 2012). Cellulose nanomaterials are beginning to be incorporated into products, but manufacturers are reluctant to advertise the use of nanomaterials because of regulatory and public perception uncertainties. As the economics and health and safety impacts are better understood, the production and adoption of cellulose nanomaterials is expected to dramatically rise, and these materials have the potential to improve the value of hardwoods and offer partial solutions to forest management issues.

Literature Cited

Azizi Samir, M.A.S.; Alloin, F.; Dufresne, A. 2005. Review of recent research into cellulosic whiskers, their properties and their application in nanocomposite field. Biomacromolecules. 6(2): 612–626.

Beck-Candanedo, S.; Roman, M.; Gray, D.G. 2005. Effect of reaction conditions on the properties and behavior of wood cellulose nanocrystal suspensions. Biomacromolecules. 6(2): 1048–1054.

Bondeson, D.; Mathew, A.; Oksman, K. 2006. Optimization of the isolation of nanocrystals from microcrystalline cellulose by acid hydrolysis. Cellulose. 13(2): 171–180.

Cao, Y.; Zavaterri, P.; Youngblood, J.; Moon, R.; Weiss, J. 2015. The influence of cellulose nanocrystal additions on the performance of cement paste. Cement and Concrete Composites. 56: 73–83.

Chen, P.; Yu, H.; Liu, Y.; Chen, W.; Wang, X.; Ouyang, M. 2013. Concentration effects on the isolation and dynamic rheological behavior of cellulose nanofibers via ultrasonic processing. Cellulose. 20(1): 149–157.

Cowie, J.; Bilek, E.M.; Wegner, T.H.; Shatkin, J.A. 2014. Market projections of cellulose nanomaterial-enabled products—Part 2: Volume estimates. TAPPI Journal. 13(6): 57–69.

Cranston, E.D.; Gray, D.G. 2006. Morphological and optical characterization of polyelectrolyte multilayers incorporating nanocrystalline cellulose. Biomacromolecules. 7(9): 2522–2530.

Fukuzumi, H.; Saito, T.; Iwata, T.; Kumamoto, Y.; Isogai, A. 2009. Transparent and high gas barrier films of cellulose nanofibers prepared by TEMPO-mediated oxidation. Biomacromolecules. 10(1): 162–165.

Hassanzadeh, M.; Sabo, R.; Rudie, A.; Reiner, R.; Gleisner, R.; Oporto, G.S. 2017. Nanofibrillated cellulose from Appalachian hardwoods logging residues as template for antimicrobial copper. Journal of Nanomaterials. 2017: 2102987.

Innami, S.; Fukui, Y. 1987. United States Patent No. 4,659,388.

Iwamoto, S.; Nakagaito, A.N.; Yano, H. 2007. Nano-fibrillation of pulp fibers for the processing of transparent nanocomposites. Applied Physics A: Materials Science & Processing. 89(2): 461–466.

Javadi, A.; Zheng, Q.F.; Payen, F.; Altin, Y.; Cai, Z.Y.; Sabo, R.; [and others]. 2013. Polyvinyl alcohol-cellulose nanofibrils-graphene oxide hybrid organic aerogels. ACS Applied Materials & Interfaces. 5(13): 5969–5975.

Kiziltas, A.; Han, Y.; Gardner, D.J. 2013. Carrier systems for cellulose nanofibrils in hydrophobic polymer composites for the automotive applications. Paper presented at the 13th Annual Society of Plastic Engineers Automotive Composites Conference Exhibition.

Klemm, D.; Kramer, F.; Moritz, S.; Lindström, T.; Ankerfors, M.; Gray, D.; [and others]. 2011. Nanocelluloses: a new family of nature-based materials. Angewandte Chemie International Edition. 50(24): 5438–5466.

Lavoine, N.; Desloges, I.; Dufresne, A.; Bras, J. 2012. Microfibrillated cellulose—its barrier properties and applications in cellulosic materials: a review. Carbohydrate Polymers. 90(2): 735–764.

Moon, R.J.; Martini, A.; Nairn, J.; Simonsen, J.; Youngblood, J. 2011. Cellulose nanomaterials review: structure, properties and nanocomposites. Chemical Society Reviews. 40(7): 3941–3994.

Nakagaito, A.N.; Nogi, M.; Yano, H. 2010. Displays from transparent films of natural nanofibers. [10.1557/mrs2010.654]. MRS Bulletin. 35(03): 214–218.

Peng, J.; Walsh, P.; Sabo, R.; Turng, L.-S.; Clemons, C. 2016. Water-assisted compounding of cellulose nanocrystals into polyamide 6 for use as a nucleating agent for microcellular foaming. Polymer. 84(10): 158–166.

Phipps, J.; Svending, P.; Skuse, D. 2015. Development, scale-up and production of mineral/ microfibrillated cellulose composite materials for paper and board applications. Paper presented at the 2015 International Conference on Nanotechnology for Renewable Nanomaterials.

Qing, Y.; Sabo, R.; Zhu, J.Y.; Agarwal, U.; Cai, Z.; Wu, Y. 2013. A comparative study of cellulose nanofibrils disintegrated via multiple processing approaches. Carbohydrate Polymers. 97(1): 226–234.

Sabo, R.; Seo, J.-H.; Ma, Z. 2012. Cellulose nanofiber composite substrates for flexible electronics. Paper presented at the 2012 TAPPI International Conference on Nanotechnology for Renewable Materials, Montreal, Quebec, Canada.

Saito, T.; Hirota, M.; Tamura, N.; Kimura, S.; Fukuzumi, H.; Heux, L.; [and others]. 2009. Individualization of nano-sized plant cellulose fibrils by direct surface carboxylation using TEMPO catalyst under neutral conditions. Biomacromolecules. 10(7): 1992–1996.

Saito, T.; Kimura, S.; Nishiyama, Y.; Isogai, A. 2007. Cellulose nanofibers prepared by TEMPO-mediated oxidation of native cellulose. Biomacromolecules. 8(8): 2485–2491.

Seo, J.-H.; Chang, T.-H.; Lee, J.; Sabo, R.; Zhou, W.; Cai, Z.; [and others]. 2015. Microwave flexible transistors on cellulose nanofibrillated fiber substrates. Applied Physics Letters. 106(26): 262101.

Shatkin, J.A.; Wegner, T.H.; Bilek, E.M.; Cowie, J. 2014. Market projections of cellulose nanomaterial-enabled products—Part 1: applications. TAPPI Journal. 13(5): 9–16.

Siró, I.; Plackett, D. 2010. Microfibrillated cellulose and new nanocomposite materials: a review. Cellulose. 17(3): 459–494.

Song, Q.; Winter, W.T.; Bujanovic, B.M.; Amidon, T.E. 2014. Nanofibrillated cellulose (nfc): a high-value co-product that improves the economics of cellulosic ethanol production. Energies. 7(2): 607–618.

Srithep, Y.; Turng, L.-S.; Sabo, R.; Clemons, C. 2012. Nanofibrillated cellulose (NFC) reinforced polyvinyl alcohol (PVOH) nanocomposites: properties, solubility of carbon dioxide, and foaming. Cellulose. 19(4): 1209–1223.

Stelte, W.; Sanadi, A.R. 2009. Preparation and characterization of cellulose nanofibers from two commercial hardwood and softwood pulps. Industrial & Engineering Chemistry Research. 48(24): 11211–11219.

Syverud, K. 2011. A novel application of cellulose nanofibrils for improving the water resistance of commercial paints. Paper presented at the Eleventh International Conference on Wood and Biofiber Plastic Composites.

Taipale, T.; Österberg, M.; Nykänen, A.; Ruokolainen, J.; Laine, J. 2010. Effect of microfibrillated cellulose and fines on the drainage of kraft pulp suspension and paper strength. Cellulose. 17(5): 1005–1020.

Turbak, A.F.; Snyder, F.W.; Sandberg, K.R. 1982. United States Patent No. 4,341,807.

Vartiainen, J.; Pöhler, T.; Sirola, K.; Pylkkänen, L.; Alenius, H.; Hokkinen, J.; [and others]. 2011. Health and environmental safety aspects of friction grinding and spray drying of microfibrillated cellulose. Cellulose. 18(3): 775–786.

Walker, C. 2012. Thinking small is leading to big changes. Paper360°. January/February: 8–13.

Yang, J.; Zhao, J.-J.; Han, C.-R.; Duan, J.-F.; Xu, F.; Sun, R.-C. 2014. Tough nanocomposite hydrogels from cellulose nanocrystals/poly(acrylamide) clusters: influence of the charge density, aspect ratio and surface coating with PEG. Cellulose. 21(1): 541–551.

Zheng, Q.F.; Cai, Z.Y.; Gong, S.Q. 2014. Green synthesis of polyvinyl alcohol (PVA)-cellulose nanofibril (CNF) hybrid aerogels and their use as superabsorbents. Journal of Materials Chemistry A. 2(9): 3110–3118.

Zhou, Y.; Khan, T.M.; Liu, J.-C.; Fuentes-Hernandez, C.; Shim, J.W.; Najafabadi, E.; [and others]. 2014. Efficient recyclable organic solar cells on cellulose nanocrystal substrates with a conducting polymer top electrode deposited by film-transfer lamination. Organic Electronics. 15(3): 661–666.

Zhu, J.Y.; Sabo, R.; Luo, X. 2011. Integrated production of nano-fibrillated cellulose and cellulosic biofuel (ethanol) by enzymatic fractionation of wood fibers. Green Chemistry. 13(5): 1339–1344.