RESEARCH CHALLENGES FOR STRUCTURAL USE OF SMALL-DIAMETER ROUND TIMBERS

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ABSTRACT

Forest managers have identified forest stands overstocked with small-diameter trees as a critical forest health issue. Overstocked stands are subject to attack by insects and disease and, as a result of the heavy fuel load, risk total destruction by fire. Prescribed burning is an economic tool for suppressing the growth of brush and tree seedlings, but its use is often restricted for environmental reasons. Forests that contain a heavy fuel load extending into the canopy must be thinned to reduce the fuel load before prescribed burning can be used to avoid future loss caused by fire, insects, and disease. One way to help recover the cost of mechanical thinning is to promote value-added structural uses of the small-diameter round timber to be removed. Although the cost of mechanical removal thinning can be partially justified on the basis of time and money saved by preventing future resource destruction, savings based on conjecture and probability of occurrence are difficult to quantify. Value-added uses of this material can provide immediate return in the form of increased revenue for thinnings and rural economic development. This paper is an overview of the options for round timber structural applications and contains recommendations for research needed to promote acceptance of engineered applications.

Significant portions of our national forest lands are in a precarious condition. Many of these forested ecosystems are overstocked with small-diameter trees and have deteriorated to a point where their resiliency and ability to meet current and future demand for forest products have been compromised. Immediate management concerns are the alteration of these forest systems so that they become more resilient to problems such as drought, pest epidemics, and extensive and unusually hot wildfires (48, 49).

The cost of mechanical thinning, along with ecological concerns for the use of prescribed burning, inhibits good management practice in terms of forest resistance to fire. Even when prescribed burning is considered to be the most appropriate treatment, overstocked stands must first be mechanically thinned to reduce the risk of extreme heat that could damage larger trees. By increasing the market value for the removed material, these costs may be recoverable. Currently, the average value of small-diameter timber is in the range of $26 to $60/green ton. Uses include firewood ($26 to $40/green ton), chips ($26 to $30/green ton), fence posts ($140/green ton), lumber ($140 to $160/green ton), and small poles ($200/green ton). Round timber poles have the greatest value on a unit weight basis. This is due in part because, as the end product, round timber poles require less processing per unit. The problem is that the market for poles is small and variable. The contrast between the value of small poles and that of other small-diameter timber applications suggests that an initial effort to optimize economic return should focus on expanding markets for full log sections that require minimal processing.

OBJECTIVES

Information useful in developing and coordinating research focused on expanding structural-use markets for small-diameter timber is given in this paper. Conventional round timber applications, small-diameter timber attributes, and limitations that will influence acceptance for structural applications and their sensitivity to silviculture are

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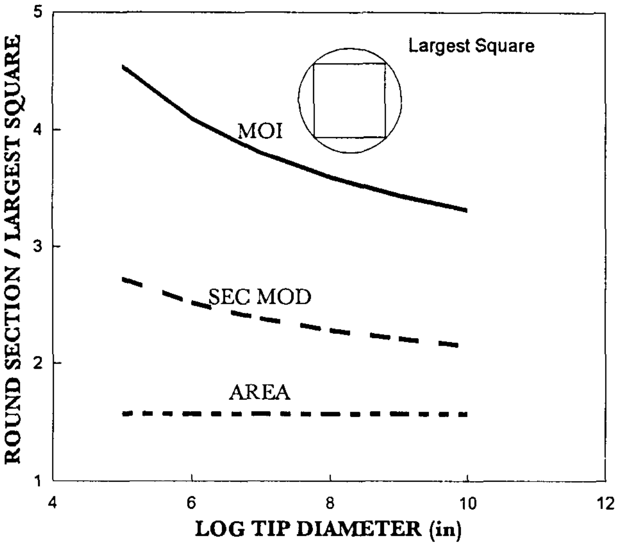

Figure 1. – Effective section property ratios for beams of small-diameter timber compared with the largest sawn timber section they would yield. A 3.1 m (8-ft.) span and 1 percent taper were assumed.

discussed. Recommendations are given for research that could significantly impact the development and acceptance of value-added products from a resource that currently has limited appeal for structural applications.

OVERVIEW

The concept of using round timbers as structural elements may be perceived as old or unrefined technology. There is little doubt that the first wood structural components were used in their natural round/tapered form. In nature, trees evolved to carry load as cantilever/columns. Strength and stiffness vary within the tree, roughly in proportion to the distribution of gravity- and wind-imposed forces. In addition to the change in strength properties along the height of the tree, strength and stiffness of the wood tend to increase from the assumed centroidal axis (pith) to the surface, as do the bending forces in any beam element. The fact that wood fibers on the tree surface are naturally oriented parallel to the direction of principal stress also serves to enhance bending strength. When trees are sawn into lumber, the inherent efficiencies of fiber placement and orientation are compromised in return for the convenience associated with standard dimensions, light weight, and versatility in the construction of structural assemblies. Although it may seem primitive to use wood in the round form, in many ways it represents an efficient use of the material.

SMALL-DIAMETER TIMBER

The term "small-diameter timber" used throughout this paper refers to round wood stems, ranging in diameter from 100 to 225 mm (4 to 9 in.) and having physical properties acceptable for structural applications. To be used as structural elements, these timbers must meet minimum requirements for straightness, knot size, grain angle, and the size and occurrence of defects.

Small-diameter timbers represent a more efficient use of material than sawn lumber in that they have a greater load capacity than the largest prismatic timber that could be sawn from them. This is due in part to the section geometry and in part to the tree physiology. The size of the largest sawn timber is dictated by the diameter at the small end. Axial capacity is directly related to cross-sectional area; bending moment capacity is a function of a section property called section modulus (SM); resistance to bending deflection is directly related to a property called moment of inertia (MOI). A round section's area, SM, and MOI will be 1.57, 1.66, and 2.35, respectively, times the properties of the largest inscribed square. Given that the round log has a taper, and the prismatic member that would be cut from it will have dimensions dictated by the small end, the effective section properties of a beam or column element are actually greater than the ratio of round to the largest inscribed square.

Figure 1 shows ratios of effective section properties for tapered compared with prismatic beams from the same log. These properties were calculated on the basis of the bending strength and stiffness for 2.4-m (8-ft.-) span beams loaded to the same level of stress or deflection. For this comparison, the small-diameter beams were assumed to have a diameter taper of 0.25 mm/mm (0.01 in./in.) and tip diameters ranging from 102 to 254 mm (4 to 10 in.) The effective SM ratio is equal to the ratio of loads that will give equivalent maximum stress in the round versus square section from a given log. The effective MO1 ratio is the ratio of loads to give equivalent maximum deflections. From **Figure 1,** we can conclude that the small-diameter timber has 2 to 3 times the moment capacity, 3 to 4.5 times the allowable load for a given deflection limit, and 1.57 times the axial load capacity of the sawn timber.

In addition to advantages derived from geometry, round timber has strength advantages derived from grain orientation. A comparison of round timber strength data (58) to dimension lumber strength data (26) shows that strength variability for round timbers is about one-half to two-thirds that of lumber. This is due to the surface continuity of the wood fibers. In lumber, the fibers around knots are cut and discontinuous, leading to stress concentrations and fracture initiation. In small-diameter timber, fibers flow continuously around knots on the surface. Taking the lower variability into account, design load capacity of the small-diameter timbers could be more than 5 times that of the largest prismatic timber that could be sawn from them.

Finally, fiber continuity on the surface also gives a product that is more user friendly in that it is less likely to produce splinters than the grain orientation common to sawn lumber. This is especially advantageous for applications such as playground equipment.

BARRIERS TO STRUCTURAL APPLICATIONS

Barriers to expanded structural use of small-diameter timber fall into categories of economics, forest management, engineered design, and construction. Economic barriers include the perception by small business entrepreneurs that small-diameter timber market value does not exceed the cost of harvesting, processing, and transporting. Innovative methods of adapting this resource to existing markets as well as an exploration of new markets are needed. Forest management barriers include the cost of thinning small-diameter timber in the absence of subcontracted harvest and the limited ability to identify high quality structural small-diameter timber. Engineered design requires improved information for material and connection properties as well as improvements to standards to guide the derivation of design stresses for small-diameter timber and its connections. Finally, and perhaps most important, are the barriers to acceptance as a structural component. Contractors need information to show how round and tapered logs can be easily applied to a structure, and building code officials need construction standards to provide guidance for inspecting pole-frame structural assemblies.

ECONOMIC ISSUES

A primary consideration for the use of small-diameter timber in any application is the feasibility of harvesting, processing, and marketing. On the basis of a 30-year review of published forest industry literature, Barbour et al. (9) summarized industry concerns related to supply, quality, harvesting, and processing of small-diameter timber. They concluded that the forest products industry's marketing philosophy must change from product orientation to marketing orientation and that there is a need for extensive business training of forestry students in order to adapt to the changing forest resource. Barbour et al. pointed to many innovative ideas that have been shown to be technically feasible but were not successfully marketed due to a resistance to continually modify or improve product lines.

Marketing is an important aspect that contributes to the feasibility of utilizing small-diameter timber. For structural applications, the acceptance of round wood will require a major adjustment to conventional thinking among design engineers, building contractors, architects, and others. Promoters may emphasize greater design stresses, better fire resistance, and lower raw material costs, but these applications will require the development of new tools, new connections, and new construction techniques. Therefore, marketers must be keenly aware of the advantages of using small-diameter timber if they are going to convince potential users of the advantages of using non-standard, tapered round wood in place of conventional light-frame dimension lumber.

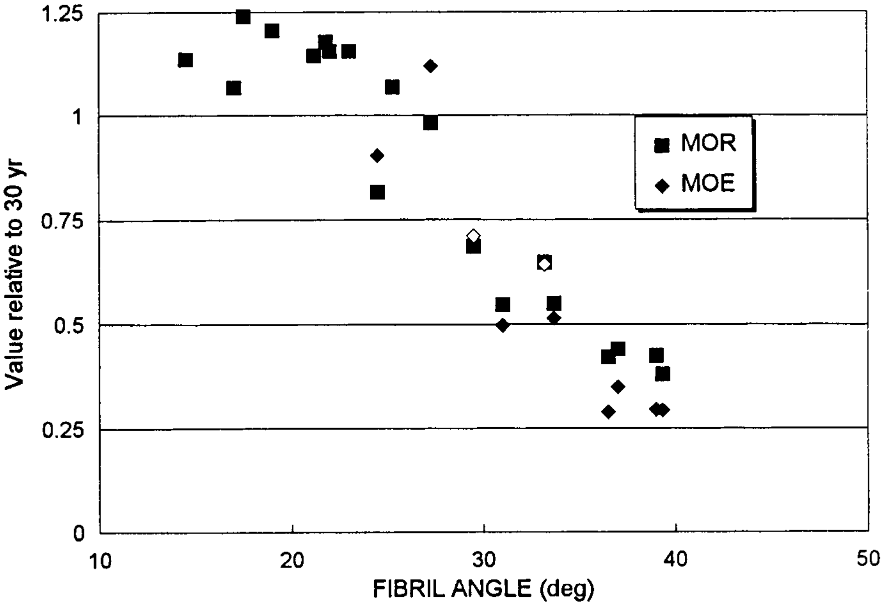

Figure 2. – Effect of fibril angle on strength and modulus of elasticity (10).

TECHNICAL ISSUES

Technical issues that must be resolved deal with how to select and use small-diameter timber for engineered applications. Research needed to address these issues covers a broad range of topics including silviculture, engineering properties, stress grading, connections, processing, and design standards.

Silviculture. – Silviculture covers the care and cultivation of forests. Many studies have been conducted to evaluate silvicultural effects on tree physiology (13, 16, 17, 19, 25, 33, 34, 38, 39, 43, 44, 51, 52). Although the majority of these studies were prompted by a need to develop guidelines for the management of tree plantations for maximum fiber production, they offer insight into the environment conditions conducive to preferred properties for engineered applications as well (10, 13, 17, 20, 41, 50).

As a result of the number of variables involved and the complex nature of their interaction, it is difficult to draw general conclusions, but it is apparent that properties of importance for engineered applications are strongly influenced by silviculture. Properties such as specific gravity (10,11,38,40,52), taper (25, 34,39), crownwood portion (i.e., wood laid down when the stem is within the active crown of the tree) (13,17), and the occurrence of reaction wood (19) are highly correlated to wood strength and stiffness.

Specific gravity, the parameter most often cited as an intrinsic measure of wood strength and stiffness, is not dependent on growth rate (17, 19, 38, 52) but is affected by crownwood, latewood portion (that portion of the annual ring produced late in the growing season after the spring rush of auxin production has subsided) (13, 40), and reaction wood. These parameters are, in turn, affected by latitude, crown vigor, nutrients, moisture, and competition. Trees having growth suppressed by competition and showing little summerwood development are likely to have low specific gravity relative to trees in the same region that do not have to compete for water and nutrients. Greater than average specific gravity that has been observed for trees from suppressed stands (44) may be an indication of an effect of low crown vigor, as discussed by Megraw (38). His observation was that low crown vigor is commensurate with slow height growth, faster earlywood-latewood transition, therefore greater specific gravity.

Taper varies with species and growing conditions. It is generally lowest for trees grown in tight stands and having small crown height (39, 43, 51, 52).

Crownwood is normally characterized as having lower stiffness and strength and greater longitudinal shrinkage with change in moisture content than mature wood. These properties are normally attributed to microscopic fibrils that form the layered walls of individual wood fibers (13, 16). **Figure 2** shows the relationship between the strength and stiffness of wood fibers and the angle between the fibril and fiber axes. As the active crown moves higher on the tree, wood fibers in the lower stem tend to get longer and the fibril angle decreases from 45° to 50° to 10° and the wood density increases. This transition occurs over 7 to 20 years (17, 41, 50). Bendtsen and Senft (10) measured the change in strength and stiffness with age, attributing this to the transition from crownwood to mature wood **(Fig. 3).** This transition varies with species as well as growing conditions (10, 17). In general, a slow grown tree of a given diameter will have a lower crownwood portion than a fast grown tree of the same diameter, giving credence to the idea that suppressed growth small-diameter timber will give superior performance to fast grown small-diameter timber.

Reaction wood also affects strength. It is normally assumed to occur in response to loads that push the tree out of vertical alignment, but has been noted to occur in response to thinning (19) without the influence of directional loading. The fiber properties of reaction wood are similar to those of crownwood.

As a result of the numerous complex interactions, it is impractical to develop general rules for managing forests for specific engineering properties. On a regional level, however, it may be possible to identify the combination of exposure conditions that lead to the best small-diameter timber properties for a given species. Observed interactions between species and silviculture suggest that the promotion of value-added uses for small-diameter timber would benefit from a combination of silviculture and genetics research aimed at developing or selecting strains specially adapted to climate, elevation, and latitude for a given site.

Engineering properties. – Among the issues of greatest concern for engineering applications of small-diameter timber are the variability and predictability of strength and stiffness of the timber and the load capacity and failure modes of available connections. Poles have traditionally been used in structural applications where they are loaded as cantilever beams or as combined cantilever beam columns. In utility structures and pole barn applications, loads are applied along the vertical surface either in the form of a transverse wind or a gravity load hung on the surface using some form of shear connection. Pole design loads are rarely controlled by axial load capacity, and there is little information available to provide a basis for the efficient design of round timber structural elements in applications other than as traditional bending elements. To expand round-timber structural markets, there is a need to expand the database for round timber strength and stiffness and focus research on the development of economically feasible connections to transfer axial loads and bending moment.

Design standards and specifications for round timbers concentrate heavily on members used in cantilever-beam bending and column applications (1, 3, 5, 6). Four industries have had significant influence on the development of design standards and specifications for round timbers. The electric utility industry has been the driving force behind most activity involving full-sized pole tests (37, 58). Their concern is primarily bending strength and long-term durability of poles used in distribution and transmission line applications. The timber pile industry has influenced the development of design standards for round timber in column applications (3, 5). Timber pile design standards incorporate small, clear test data for wood to derive axial, shear, and compression perpendicular-to-the-grain design stresses. The pole-frame building industry has influenced the design of poles used in utility building construction (6). Their interest is in using poles in cantilever/column applications as framing members for pole buildings. Finally, the log home industry played a key role in writing the design standard (2) for log buildings. These logs are used primarily as beam elements, and the standard is modeled after the American Society for Testing and Materials (ASTM) standard governing derivation of design values for lumber (4).

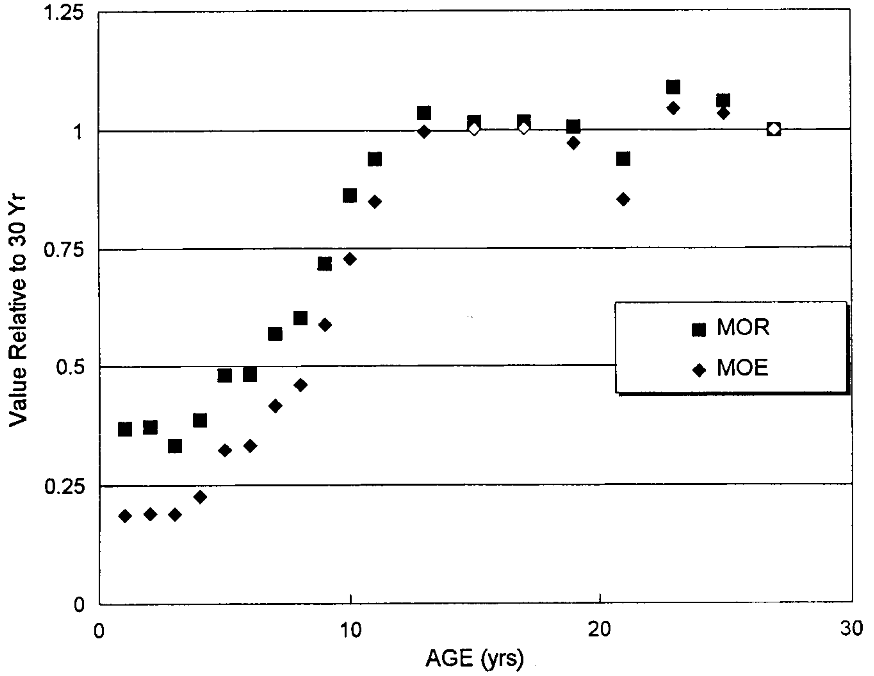

Figure 3. – Change in mechanical properties with tree age (10).

Design standards for poles were initiated in 1933 by the American Standards Association (ASA), with the adoption of a standard published by Bell Telephone (18). This was the precursor to today's American National Standards Institute (ANSI) standard for wood poles (1). It was not until steel and concrete became accepted as piling materials that the timber industry began thinking about design standards for timber piles. The current standard for derivation of design stresses for timber piling (5) was not adopted until 1970. The history of this evolution is summarized by Wolfe (56).

Among the first nationally recognized standards for grading round timbers were "Specifications for Round Timber Piles" published by ASTM in 1915 and Wood Pole Specifications and Dimensions published by the ASA in 1924. These were minimum quality specifications that form the basis for today's ASTM (3) and ANSI (1) standards used to rate acceptability of poles and piles. Round timber design load capacity varies only with size classification. Unlike conventional sawn timber, which is classified according to visual/mechanical attributes into appearance or stress grades, there is only one stress grade for poles or piles (1, 3, 5).

Stress grading. – The single stress-grade approach is preferred for round timbers, partially due to the ways in which round timbers are used and partially because of their relatively low sensitivity to variations in visual quality attributes. Pole and pile applications were originally more dependent on shape and size than on strength. Early demand for distribution poles was simply to get utility lines up in the air, out of the way. Wood poles offered an inexpensive and reliable solution. Prior to 1940, timber piles were used as a means of stabilizing soil and little concern was given to the individual pile loads. By the time concern did develop for individual round timber design values, size classes were well developed as the basis for specifying both poles and piles. Few data were available to suggest that strength variability within a species-size class was large enough to warrant further separation by stress grades.

The ASTM standard D 3957-80 "Establishing Stress Grades for Structural Members in Log Buildings" advocates the use of within-species, quality-based strength classification for round/shaped timbers used as wall logs (2). The committee that developed this standard modeled it after standards developed for the derivation of visually graded lumber design stresses (4) and design stresses for round timber piles (5). Although intended for grading sawn or shaped timbers, this work lays a foundation for establishing visual stress grades for logs. The National Association of Home Builders-Log Home Council established their log grading rules on the basis of this ASTM standard (14). However, there has been no published assessment of the efficacy of this or a similar visual-quality stress classification applied to round timbers.

Although there is likely to be a long-term advantage to adopting more rigorous stress grading methods for round timber structural members, this will not be a high priority research topic for small-diameter timbers until they become more widely accepted as structural elements. In the near term, it seems plausible to simply apply the convention of setting minimum specifications calibrated to structural use as primary (e.g., beam, pole, column, chord) or secondary (e.g., web, strut, brace) structural elements.

Specification enhancement. – Conventional material specifications for poles (1) and piles (3) could be adopted for small-diameter timber with few modifications. Variables that should be considered in tightening these specifications include roundness, percentage of crownwood, ring count, percentage of summerwood, and spiral grain. The "out of round" ratios (maximum diameter/minimum diameter) currently specified for poles could result in considerable under-design if timbers selected for circumference (C) (1) are designed assuming a round section (diameter = C/π). In the case of poles, these errors are offset by conservatism inherent in the size classification system. The lower axial strength and stiffness of crownwood must also be considered in evaluating the net section properties of a small-diameter timber. Although it is not easy to detect by visual inspection, data relating crownwood to years of growth could be used to limit the crownwood portion of a small-diameter timber. Ring count and percentage of summerwood provide information related to density that in turn is related to wood strength. Finally, spiral grain can lead to problems with drying in service as well as greater strength variability. The piling specification (3) is more stringent than that for poles, restricting spiral grain to 180° in 6.1 m (20 ft.). This same restriction should be applied to small-diameter timber to be used in structural applications.

Nondestructive evaluation (NDE). – If and when rigorous engineered designs for small-diameter timber structural systems are developed, NDE may play an important role in the selection of small-diameter timber structural elements. The term NDE generally refers to techniques used to estimate the strength and stiffness of a material, component, or assembly with no detrimental effect on strength. NDE methods include visual inspection but normally refer to techniques that include a measured response to an external excitation. This could be something as simple as a measured bending deflection or as complex as measurement of infrared emissions resulting from applied stress (42). From the standpoint of a practical and cost-effective application, visual inspection coupled with some measure of response to a mechanical or electromagnetic energy disturbance appear to hold the most promise for predicting strength and stiffness of small-diameter timber (54).

Among the more popular forms of NDE methods being studied for application to wood, the speed of flight of a mechanical "stress" wave has received the most attention (27). This is the simplest to induce and measure. Results can be highly variable, however, especially when applied to logs. Wood response to stress waves has been an active research topic for more than 30 years. Burmester (15) was among the first to study relationships between sound velocity and mechanical properties of wood. Timoshenko (47) is among the most widely referenced authors on the topic of wave theory in elastic media. During the past 15 years, increasing attention has been focused on the use of stress wave measurements as a means of estimating wood strength. Various techniques have been used to assess wood quality and strength by initiating a mechanical wave pulse and measuring its speed (12). The literature provides strong support for this technique as a determinant of wood quality and moisture content (31). As a result of moisture gradients, knots, and varying cross-sectional properties from butt to tip, however, the use of axial wave speed alone, as a predictor of log strength, is likely to be subjective. A longitudinal wave speed measurement, used in combination with an evaluation of other wave characteristics, such as the dominant natural frequencies, energy dissipation, and/or wave attenuation, may provide a means of reliably grading logs that have already been visually graded (8).

Other approaches to wood NDE are also being investigated. A technique labeled ultrasonic (27) makes use of an ultrasonic pulse signal such as that generated using a piezoelectric transducer. Time of flight, natural frequency, and wave attenuation are the major parameters to be correlated to strength and stiffness. Microwaves, which are electromagnetic rather than mechanical, have been used with some success to determine specific gravity and moisture content. These high frequency energy waves dissipate in the form of heat too rapidly in wood to be used in log stress grading.

Connections. — As with all wood structures, connections are likely to present the greatest challenge for structural use of small-diameter timber. The evolution of wood structures during the past 150 years has concentrated heavily on the use of sawn lumber with parallel flat surfaces and standard dimensions. A major reason for the switch to lightweight sawn lumber in the early to middle 19th century was the development of the mass-produced nail. Mortise and tenon joints used with heavy timber were labor intensive, and the tenon required sufficient dimension to transfer loads between the structural elements. Although natural evolution of conventional practice has drawn attention away from round timber connections, tools and materials that have been developed may show benefit for round timber as well as for dimension lumber.

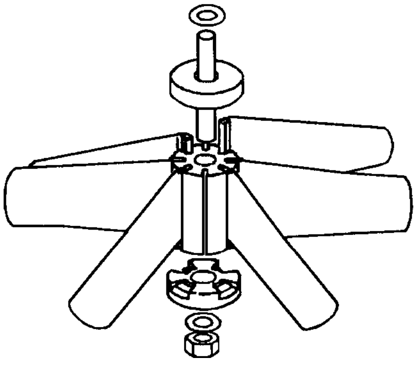

Figure 4. – Space-frame node connection will accept up to 8 members and provides a connection point for cladding.

Lukindo (35) provides a summary of several techniques that have been proposed and used for connecting round timbers. Some techniques make use of a “Flitch-plate” connection, which is composed of a steel plate placed diametrically through the timber with a dowel connector passing through the wood/metal section to transfer shear loads from the log to the metal plate. Other techniques include steel clamps fastened around the perimeter dowel-nuts, such as those commonly used in furniture (21), and form-fit nail plates.

Huybers (28) conducted one of the more rigorous studies to develop a connection for small-diameter round timber. He developed a steel-wire-laced connection to deal with problems associated with in-place drying of round sections. His connection made use of a flitch plate, held in place by hollow pins, to transfer axial and bending loads. To limit effects caused by splitting, Huybers developed a tool for applying a wire lacing that is wrapped around the log and through the hollow pins. This connection detail allows green timbers to be used with limited degradation in joint capacity as a result of in-place drying.

In addition to the potential problems associated with force transfer between round members, there is the problem of fastening cladding to round, tapered, small-diameter timber. Designers of steel space frame structures often fasten cladding to the node point connectors **(Fig. 4).** This is one way to avoid problems associated with cladding attached to tapered, round structural elements. The problem of taper on a vertical wall pole could be resolved in a similar manner using threaded metal studs that can be cantilevered from the pole surface to compensate for taper. With a diameter taper of 2 percent and the pole set plume, the cantilever length may be as much as 38 mm (1.5 in.) on a 3.6-m (12-ft.) elevation change. The metal stud would have the shape of a hollow cylinder with a course screw-type thread on the outside and a course bolt thread on the inside. Using a plume line to set depth, these studs could be spaced to correspond with wood battens and driven to the desired depth using a power drill. Battens fastened to the studs would then provide support for panelized cladding.

Processing. – Although small-diameter timber can be used as beam or column elements in the raw form, many of the high-valued engineering applications will require some degree of processing to provide reliable, long-term performance. At the very minimum, most structural applications will require peeling. Applications involving connections applied to machined surfaces will most likely require drying to service conditions. For more unique applications, there could be some desire to steam bend. Methods must be developed to facilitate small-diameter timber processing at a cost that will not exceed the value of the final product.

Drying of small-diameter timbers could represent the greatest challenge to value-added structural applications. Round wood does not dry as quickly as sawn lumber, and high temperatures used to accelerate drying could cause mechanical as well as physical degrade. Wood strength is sensitive to high temperature for extended periods. This sensitivity varies with species and needs to be considered when deriving design stresses. Physical degrade associated with drying involves surface checking. As round timber dries, the outer (mature) wood is likely to dry faster and exhibit more tangential shrinkage than the inner (crown) wood. As a result, small splits, known as drying checks, appear on the surface. Splits are normally more of an appearance or maintenance problem than a structural problem. Although difficult to avoid, splits can be controlled to some extent by the use of a sawkerf cut parallel to the length of the timber. As the wood shrinks, the sawkerf is pulled open, relieving tangential stresses elsewhere on the surface of the log.

Wood shrinkage as a result of drying may also cause problems with the end-joint configuration. Huybers (28) addressed these problems by using a wire banding to confine the wood in the area of the joint. His wire-wrapped, flitch-plate joint improved the interaction between the steel plate and the wood, despite the tendency for the wood to split with drying. More work needs to be done in this area to provide guidelines for joint fabrication in either the green or dry condition to avoid the negative influence of drying on joint strength and stiffness.

Steam bending is an area that may have limited appeal for unique architectural effects. Ito et al. (30) experimented with the use of saturated steam to compress wood to form building components. There is also information available on the steam bending of wood (23, 32, 45). Steam bending is rarely used with members as large as a 200-mm-(8-in.-) diameter round timber. However, for the large radius bends contemplated for structural applications (3 to 9 m; 10 to 30 ft.), it may be a viable method of producing uniformly curved ribs for a domed or arched building.

Design standards. – In 1933, the American Standards Association (ASA) adopted the standard for ultimate fiber stresses in wood poles, which were originally published by Bell Telephone (18). This standard was based on tests of full-sized poles. In 1935, the USDA published Technical Bulletin 479 (36), which tabulated strength and related properties of U.S. timber species based on standard tests of small, clear, green specimens. In 1941, the ASA standard and Bulletin 479 were used as the basis for deriving design stresses for commercial pole species (7). At the same time, the American Association of State Highway Officials assigned allowable bearing stresses for three primary species of timber piles (southern yellow pine, Douglas-fir, and oak).

The next major revision of pole and pile design stresses occurred 30 years later. In the middle to late 1950s tests were conducted under the guidance of ASTM committee on wood, culminating in the ASTM Wood Pole report (58). This effort provided a substantial improvement to the database for strength of full-size poles. In 1965, Wood (57) summarized the results of the pole test program and recommendations for the derivation of wood pole design stresses. The ASA committee, which later became the ANSI committee on wood, adopted fiber stress values for wood poles partially on the basis of results presented by Wood (57) and partially on the basis of established precedents.

About the same time, ASTM adopted standard derivations of design stresses for wood piles (5, 24, 46, 53). This standard derivation was similar to that used for stress grade lumber, but without quality gradations. Additional data developed within the past 20 years (22, 37) has expanded the knowledge of pole strength, but there is still resistance to adopting a strength-based grading system for large round timbers because of the perceived problems associated with revising established market practices.

Wolfe et al. (55) recently completed a pilot study to determine the applicability of conventional round timber design specifications and guidelines (ANSI, ASTM, ASAE) that were established and verified on the basis of mature tree stems. This study indicated that for small-diameter timber harvested from Douglas-fir, white fir, and ponderosa pine stands in southwest Oregon, the current design guidelines are appropriate for bending strength and stiffness but may be slightly non-conservative in axial compression. When loaded in bending, stress is assumed to be distributed in a manner giving the greatest stress at the extreme fibers in the plane of the bending moment. In this case, the conventional design assumption is close to what actually happens. When loaded in axial compression, however, the conventional design assumption is that load is uniformly distributed over the cross-sectional area. This is a non-conservative assumption in that the inner fibers are less stiff than the outer fibers. If the cross section is uniformly strained (i.e., deflects uniformly), the stress is distributed in proportion to fiber stiffness. If the crownwood portion of a cross section has 1/10 the stiffness of the mature wood portion and occupies 50 percent of the cross section, the mature wood portion will be stressed at a level 5% greater than estimated using total load divided by gross cross-sectional area. A more accurate axial stress model could be developed to account for stress distribution as a function of the material modulus of elasticity distribution.

Structural systems. – Round timber structural systems are not a new idea. Poles have been used for many structural applications, including wall logs, posts, beams, and trusses. However, many of these applications involve custom design that is heavily reliant on the expertise of an individual designer. Research needs to focus on providing the tools to facilitate small-diameter timber design and use in construction by providing standard design guidelines for a variety of structural applications. Examples of more highly engineered small-diameter timber structural systems might include trussed or space-frames roof systems, bent-pole arched or dome systems, round timber rafter roofs, raised pile foundations, and playground structures.

Encouraging acceptance of round timber structural components means more than simply developing a round wood connection or providing an accurate means of assigning design stresses. It will involve changing conventional thinking about how buildings are designed and constructed. This can best be accomplished by:

- Developing construction details that compensate for the use of round and tapered sections in non-standard sizes;
- Ensuring that new methods are compatible with existing commodity markets, while exploiting advantages over light-frame dimension lumber: lengths exceeding 9.1 m (30 ft.), lower strength and stiffness variability, heavy sections that are more resistant to fire, and rustic appeal;
- Demonstrating the versatility of long round timber members by incorporating steam bending into the design of arched or domed structures;
- Providing designs focused on improving building efficiency by reducing the system redundancy inherent in most wood-frame residential and light-commercial buildings or by incorporating aerodynamic concepts to improve resistance to wind loading.

Commercial finite element or structural analysis programs are at an advanced stage to easily incorporate round wood in the analysis of trusses and space frames, given the proper material and connection properties. Work that has been done on modeling light-frame, repetitive-member-building systems could be adapted to less redundant pole frame buildings with shear diaphragms (29). Existing system-modeling capabilities can be used to develop designs that would be compatible with existing commodity markets, yet optimize the use of materials for a variety of building system applications.

CONCLUSIONS

The form and structure of small-diameter timber suggest that they could be used as structural elements with a minimal processing cost. A review of the literature suggests that a coordinated effort involving research in forest management, wood science and technology, engineering, and economics could provide the information necessary to successfully harvest, process, and sell small- diameter timber as structural elements for use in a variety of applications ranging from rafters to elements in trussed space-frame systems.

To promote structural uses of small-diameter timber, guidelines must first be developed to address the concerns of small businesses and consumers. These guidelines should cover material selection and processing, development of design values for wood elements and connections, systems design and construction, and resource and marketing considerations.

Economic guidelines would involve a survey of the resource availability to ensure a sustainable supply of raw material, assurance of a viable market to support harvest, processing, and shipping costs and methods of gaining public acceptance for structural systems that may be perceived as unrefined.

Selection guidelines require knowledge of desirable wood quality and associated silvicultural issues. These may involve the selection and management of stands to produce high quality thinnings as well as standard specifications for assigning harvested timbers to a structural use classification.

Processing guidelines require knowledge of treatment, conditioning, and machining of wood in various species. Connection details may be especially sensitive to shrinkage and drying checks that result from drying. In addition, a processing guideline may include information on processes such as steam bending to modify the form of the small-diameter timber.

Development of design values involves the accumulation of a database of strength and stiffness for members and connections. The guideline would provide options for deriving design values using standard test procedures or interpreting available test results.

System design and construction would focus on techniques to exploit the strength values and minimize the drawbacks of using tapered, round timbers in structural applications.

RECOMMENDATIONS

The need for economic incentives to promote ecosystem management, coupled with the potential for value-added structural application of small-diameter timber, appears to warrant research support. An initial program should focus on the following:

- Characterization of small-diameter timber material properties;
- Support for engineered design of round timber connections;
- Forest management methods to promote low taper and high specific gravity in mature wood;
- Market surveys to determine what incentives are required to encourage design engineers, architects, and building contractors to consider using small-diameter timber.

If results of this coordinated effort continue to support the feasibility of round timber structural applications, a second phase should focus on techniques to demonstrate the benefits of small-diameter timber structural elements. Suggested projects include the following:

- Development of guidelines for designing and constructing arched or dome framing members;
- Design and construction of a small-diameter timber space frame structure;
- Test and evaluation of proof-loaded, small-diameter timber engineered components comprising the structural element as well as the end connections.

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