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5171 April, 1967 ST 2

Journal of the

STRUCTURAL DIVISION

Proceedings of the American Society of Civil Engineers

# WOOD—A RELIABLE ENGINEERING MATERIAL[a]

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## INTRODUCTION

To be reliable, structural materials must be made and sold with integrity and used with full knowledge of their properties. Wood is no exception. It must be selected and graded for strength, with quality maintained throughout its manufacture, distribution, and use. It must also be fully understood by the designer, relying on scientific knowledge of its properties and recognizing the interplay between properties and uses.

## TECHNICAL DATA ON WOOD

Standard strength tests of clear wood are the keystone of the arch of its structural use. The tests include those to determine bending strength and stiffness, compression and tension both parallel and perpendicular to grain, shear parallel to grain, and other properties; they are made by standard American Society for Testing and Materials (ASTM) methods.[2] The methods include sampling techniques, and these are now being revised and improved.

By the old sampling method, a limited number of trees was chosen, relying on one person's judgment that they were representative. Many samples were tested from each tree; to illustrate, 7,063 standard strength tests were made on material from 15 western hemlock trees. Only stands that were thought to be available or potentially available were sampled. A modern technique con-

Note. - Discussion open until September 1, 1967. Separate discussions should be submitted for the individual papers in this symposium. To extend the closing date one month, a written request must be filed with the Executiv3e Secretary, ASCE. This paper is part of the copyrighted Journal of the Structural Division, Proceedings of the American Society of Civil Engineers, Vol. 93, No. ST2, April, 1967. Manuscript was submitted for review for possible publication on June 8, 1966.

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[2] "Standard Methods of Testing Small Clear Specimens of Timber," D143-52, ASTM, Philadelphia, PA., 1961.

siders a tree of marketable size anywhere as potentially available, and selects at random many small areas in which one specific gravity test is made on every tree. An additional sampling of a few trees is used to show the relation of the strength properties to the specific gravity, and that relation is then applied to the full range of specific gravities found in the larger sample. This is called double sampling, and is exemplified by a recent wood density survey that sampled 9,133 Douglas fir trees and 1,040 of western hemlock. The variability in the relation of strength to specific gravity is recognized. Both the average value and the variability of the strength properties are estimated.

Data by species from standard strength sampling are published by the United States Forest Service and are the basis for the structural design of lumber, plywood, glued-laminated members, and round timbers. A list has also been prepared by ASTM,[3] which gives an average value and a measure of variability in each species. The measure of variability most used is the 5% exclusion value, so that 95% of the individual values equal or exceed this level. The 5% exclusion level, when considered in relation to the average value, tells something of the whole range of values from highest to lowest.

Materials subcommittees of the ASTM Committee on Wood take these clear-wood strength test values and apply suitable factors to convert them to safe working stresses for structural design. The principal factors, after variability, are duration of load, moisture content, and safety, but many minor factors are also considered. As the factor of safety is essential to any reliable structural material, it warrants further consideration here.

It has long been recognized that the true factor of safety depends on the use as well as the strength of a material. A structural member that has less than its expected strength, and never receives its expected load, may have as much factor of safety as the extra-strong member that is overloaded. This dual nature of the factor of safety has been recognized by structural engineers for many years, and has been considered by Freudenthal[4] and others. Wood[5] considered both strength and use, and made a further analysis into 13 factors appropriate to wood members. Each factor was considered as a frequency distribution and was expressed in such a way that the frequency distributions could be combined mathematically to show the distribution of the factor of safety.

The safety requirement in a single joist or rafter is different from that in a principal column, the failure of which could cause collapse of a building and human injury. Expression of the factor of safety as a frequency distribution permits consideration of it in relation to the probability of failure; that probability may be tolerated at a higher level in a joist than in a principal column. Thus, in load-sharing members, such as joists with 16-in. spacings, design stresses will be higher than in principal structural members.

The concept of plastic design recognizes the redistribution of stresses of a structural frame as a result of plastic adjustment under loads. Because wood has plastic as well as elastic properties, the effect of plastic adjustments can be taken into account in structures of wood as well as in those of steel or

[3] "Tentative Methods for Establishing Clear Wood Strength Values," D2555-66T, ASTM, Philadelphia, Pa., 1966.

[4] Freudenthal, A.M., "Safety, Reliability, and Structural Design." Transactions, ASCE, Part II, Vol. 127, 1962, pp. 304-319.

[5] Wood, L. W., "Factor of Safety in Design of Timber Structures," Transactions, ASCE, Part I, Vol. 125, 1960, pp. 1033-1045.

concrete. The science is new, but is developing rapidly, aided by the use of high-speed computing equipment. It permits better understanding of wood structures, and thus increased confidence in them.

Technical data other than those on strength contribute to the reliability of structural wood. Wood can change in moisture content—and thereby in its dimensions—with moisture changes in its environment. Through environmental studies, shrinkage studies, and surveys of moisture content of wood in use, the structural effects from changes of dimension can be predicted or overcome.

Electrical properties, heat transmission, thermal expansion, and other physical properties of wood are known. These are generally different across the grain than with the grain, but both have been determined. The resistance of wood to fire has been calculated theoretically and observed experimentally. Because wood is a poor conductor of heat, heavy structural members have longer duration in fire than do metal members designed for the same loads; surface deterioration in fire is carried only slowly to the interior of the member.

## STRUCTURAL GRADING OF WOOD

Wood is a natural product with natural variability, and it must be selected or graded for strength. Strength grading of wood or wood products is a science in itself, and is the subject of ASTM standards and recommended practices.[6,7] Grading for strength by visual inspection takes into account both the clear wood and the strength-reducing characteristics. The strength of the clear wood is known from its species, but in some species is known also from indicators of density, such as rate of growth and proportion of summerwood in each annual ring. The strength-reducing characteristics include knots, cross grain, splits, and others. Effects of these are known from strength tests of structural timbers and of clear wood cut from those timbers. The effects are expressed numerically in the "strength ratio" of timber strength to clear-wood strength.

No two knots of the same size are exactly alike in their effect on strength, and strength ratios from visual inspection of lumber tend toward the conservative side. Further, any strength grade includes a range of characteristics, from the worst permitted in the grade, to those that barely exclude the piece from the next higher grade. The working stress for structural design is based on the worst permitted in the grade. Thus, there is in any visually determined grade an excess of strength in most of the pieces. To reduce this excess, and thus to use structural lumber more efficiently, researchers have looked for more precise methods of grading that are nondestructive and rapid enough to be applied to every piece. Machine grading is one of the results of this search.

Machine grading of lumber is practiced commercially in the United States and Australia, and experimentally in Canada, England, and elsewhere. All of the present machines operate on the principle of the relation of bending strength to the stiffness in flatwise flexure. The piece of lumber is passed between machine rolls that bend it flatwise and sense the deflection and the force to give a measure of its stiffness. Strength is correlated with stiffness through laboratory test. The laboratory correlation is not perfect (correlation coefficients of about 0.7). but is at least as efficient as conventional visual

[8] "Tentative Methods for Establishing Structural Grades of Lumber," D245-64 T, ASTM, Philadelphia, Pa., 1964.

[7] "Tentative Recommended Practice for Determing Design Stresses for Load-Sharing Lumber Members," D2018-62 T, ASTM, Philadelphia, Pa., 1962.

grading. The grading by machine is supplemented by visual grading at the ends of the pieces, and elsewhere in some instances.

Certification requirements on lumber grading machines call for bending tests in a qualified laboratory of 20 pieces of each species and grade produced. The average modulus of elasticity must equal or exceed the rated value, and 19 of the 20 pieces must show an ultimate strength of two times the rated value or higher. The copyrighted machine grade stamp cannot be used until these requirements are met.

The correlation of bending strength with flatwise stiffness is shown by extensive tests, but a similar correlation of strength values in compression or tension parallel to grain is supported mostly by inductive reasoning. Design values in these two properties are therefore at a lower level than those in bending strength. Tests of tension and compression parallel on machine-graded lumber are under way. Compression-perpendicular and shear strength values are unrelated to flatwise stiffness; where values for these are needed, they are obtained by conventional grading methods.

## STRUCTURAL DESIGN WITH WOOD

The design of wood structures follows established and well-known engineering principles. Wood, however, has certain specialized structural properties that must be kept in mind if a sound design for a reliable structure is to be made.

Wood is a fibrous material having much greater strength and stiffness parallel to the grain than it does across the grain. For example, there are two compression design values, and the one with the grain is several times the value of that across the grain. In plywood or other cross-laminated products the properties parallel and perpendicular to the face grain are more nearly equalized.

With the grain, wood has good strength for its weight. The ratio of stiffness to strength, however, is lower than in some other structural materials. This means that structural designs are controlled by considerations of stiffness or lateral stability more often in wood than in other materials. This is well recognized by timber engineers, and adequate design rules based on stiffness as well as strength are available.[8]

Mechanical fasteners such as nails, bolts, or toothed plates are much used in wood structures. They offer advantages of easy application and good strength and durability. Most of these fasteners, however, have the property of taking on a limited amount of slip or deformation before they will pick up their full load. In some of the more complex structures, this slip must be taken into account in calculating member stresses. However, a mechanical joint in wood is comparable to a plastic hinge in steel in that it may give improved member stress distributions when fully loaded. Allowable working loads for mechanical fastenings take into account rigidity as well as strength, being often controlled by the allowable slip under load.

Glued joints have a rigidity equaling or exceeding that of wood itself. Structural adhesives of proved strength and durability are available for use in designs where the slip of a mechanical fastening is undesirable. Where wood

[8] "National Design Specification for Stress-Grade Lumber and its Fastenings," National Lumber Manufacturers Association, Washington, D. C., 1962.

members enter a rigid glued joint at different angles, subsequent moisture change in the members can set up shrinkage or swelling stresses with undesirable effects. Research is now being directed toward development of glued joints with a controlled degree of rigidity to reduce such shrinkage stresses, which still provide the required strength and freedom from slip.[9] With any jointing system, it is desirable to have the wood at time of fabrication as near as possible to the moisture content that it will reach in service, thus minimizing later dimensional changes.

The design of frames with rigid joints or with a combination of rigid and pinned joints is facilitated by modern methods made possible by high-speed computers. These methods are being applied to wood roof trusses[10] and, experimentally, to frames utilizing wood poles.[11]

## TECHNICAL STANDARDS FOR WOOD

Structural reliability of wood also depends on standard sizes and grades having strength ratings that are technically sound. Standard sizes of stress-rated lumber related to realistic moisture contents are in proposed revisions to American Lumber Standards[12] that are now under consideration. Recognition of this relation makes for a better understanding of and confidence in structural lumber.

Plywood types and sizes and standards for glued-laminated structural members are established by several commercial standards that are widely known and accepted. These standards are prepared under the sponsorship of the United States Department of Commerce and represent a consensus of practice among producers, distributors, and users of the product.

Grade standards are defined in publications of the manufacturing industry or its grading agencies. These include, among others, the Western Wood Products Association, the Southern Pine Association, the American Plywood Association, and the American Institute of Timber Construction. Industry cooperates with users and with members of ASTM in formulating the principles by which wood products grades are established. The cooperation is voluntary, and the manufacturing industry has final responsibility for the published grades.

Most wood structural materials (but not all) are produced under these standards. Users will protect themselves by insisting on evidence of compliance with a recognized standard in the materials they buy. Such evidence may be a grade stamp on each piece, or a certificate of inspection from the recognized grading agency.

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[9] Krueger, Gordon P., "Ultimate Strength Design of Reinforced Timber Frames with Semirigid Joints," thesis presented to the University of Wisconsin, at Madison, Wis., in 1964, in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

[10] Suddarth, S. K., "Determination of Member Stresses in Wood Trusses with Rigid Joints," Research Bulletin No. 714, Wood Research Lab., Purdue University, Lafayette, Ind., 1961.

[11] Parker, J. E., "A Study of Wind Stresses in Three Typical Pole Building Frames," Research Note FPL-049, Forest Products Lab., U. S. Forest Service, Madison, Wis., 1964.

[12] "American Lumber Standards for Softwood Lumber," Simplified Practice Recommendation 16-53, U. S. Dept. of Commerce, Washington, D. C., 1953.

Structural design standards for wood have been in existence for many years. Several universities and colleges offer courses in timber engineering, and textbooks are available. The published books reflect, for the most part, conventional design methods, but modern techniques are being taught at advanced schools.

Good construction with wood was formerly the responsibility of craftsmen, most of whom had a personal pride in their work. Today many of those craftsmen are gone. However, organized industry recognizes the importance of construction standards, and the American Institute of Timber Construction has prepared a "Timber Construction Manual ."[13] A similar manual has been available in Canada since 1961, prepared under the sponsorship of the Canadian Institute of Timber Construction.[14]

## USE OF WOOD

Structural reliability of wood also depends on the way in which it is used. Wood for use in contact with the ground should be treated. Interior-type plywood is entirely satisfactory for many uses, but will deteriorate under exterior exposure. Any wood product should be protected from rain that may cause water stain or fungus attack during transportation and fabrication. A wood joist that has been carefully graded for strength can lose most of that strength from indiscriminate cutting to install plumbing or heating ducts. These points emphasize the fact that the user of a structure, and the designer and builder who represent him, have-a responsibility to be aware of the kinds or grades of wood available to obtain those that may reasonably be expected to give good service, and to exercise care in using them, so that the expected service will be realized.

Confidence in the reliability of structural wood can be increased by understanding its properties and applying the safeguards that are available for its use. Their recognition and use, from the forest to the final user, will go far to help wood achieve its fullest potential as a reliable structural material.

## CONCLUSIONS

1. New techniques assure even greater reliability of the basic strength and variability data for each structural species of wood and thus provide an excellent foundation for the development of structural criteria.
2. Visual grading techniques and rules based thereon have established sound engineering working stresses. New nondestructive testing procedures can, however, provide for improved structural wood use by grading each piece in accordance with its inherent characteristics.
3. Structural design with wood, to be efficient, must recognize its unique structural properties.
4. The reliability of wood as a structural material may be assured by development of sound technical data, quality controlled manufacture, and intelligent use.

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[13] "Timber Construction Manual," Amer. Inst. of Timber Const., John Wiley & Sons, New York, N. Y., 1966.

[14] "Timber Construction—A Manual for Architects and Engineers." Canadian Ist. of Timber Construction, Ottawa, Ont., Canada, 1963 (Revised).

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KEYWORDS: grading; standards; structural engineering; timber (structural); wood strength

ABSTRACT: The reliability of wood as an engineering material depends on sound information and enlightened usage. Efficient structural design must recognize wood's unique structural properties and use them correctly. The way in which results of standard tests on wood are transformed into safe working stresses for structural design is summarized, and the factor of safety is considered. Reference is made to the structural grading of wood, emphasizing the importance of variability, and how this is accounted for in both visual and machining grading. In designing with wood, the designer needs to know about such inherent properties as strength with or across the grain, and about the place of fastenings. Structural reliability of wood depends on sound construction standards and discriminating use.

REFERENCE: Wood, Lyman W., Wood—AReliable Engineering Material," Journal of the Structural Division, ASCE, Vol. 93, No. ST2, Proc. Paper 5171, April, 1967, pp. 57-62.