

STRENGTH PROPERTIES OF PLANTATION-GROWN CONIFEROUS WOODS

A. Richard Olson

Nicholas V. Poletika

Henry W. Hicock

CONNECTICUT AGRICULTURAL
EXPERIMENT STATION
NEW HAVEN



Bulletin 511 — December, 1947

Strength Properties of Plantation-Grown Coniferous Woods

A. RICHARD OLSON, NICHOLAS V. POLETIKA AND HENRY W. HICOCK¹

INTRODUCTION

During the past half century many thousands of acres in New England and New York have been planted to coniferous trees. Many of these plantings are now old enough to produce some merchantable material in the form of thinnings. A survey of the literature indicated that, although a large number of tests had been made to determine the strength properties of woods grown under natural forest conditions (7), very little data were available on woods grown in forest plantations. This bulletin offers such data, based on tests made here since 1939. Information on the strength properties of plantation-grown woods will be increasingly useful as more of these young stands reach an age where improvement cuttings are necessary.

Damage by the hurricane of 1938 was extensive in all forest types in central and eastern Connecticut and was particularly severe in coniferous stands, both natural and planted, aged 25 years or more. Salvage operations afforded opportunity to collect sufficient material from plantation-grown stands for a series of standard strength tests. Under a plan drawn up in cooperation with Dean George A. Garratt of the Yale School of Forestry, the trees were selected and the samples prepared in the manner described below.

The Station's Experimental Forest Plantations at Rainbow were chosen as the chief source of material because (a) they included a number of planted species, both native and exotic; (b) their history since establishment was well recorded; (c) site conditions were quite uniform throughout the planted area.

The wood of seven species, Austrian pine, jack pine, red or Norway pine, Scotch pine, eastern white pine, Norway spruce and European larch, was used in the tests. All came from the Rainbow Plantations except the European larch which was from the Nipmuck State Forest in Union.

The Rainbow Plantations are located on a tract of 110 acres in the towns of Windsor and East Granby. They include some 70 experimental blocks, planted between 1902 and 1930. The material for testing came from stands

¹ Mr. Olson is research technician, Forestry Department; Mr. Poletika is research aide in forestry, and Mr. Hicock is chief forester, all of the Connecticut Agricultural Experiment Station.

The authors wish to extend their thanks to the following persons:

Dean George A. Garratt and Professors Hess and Wangaard of the faculty of the School of Forestry, Yale University, for advice and assistance in conducting the tests and in preparing the manuscript, and for use of the necessary laboratory and other apparatus.

Dr. J. Hugo Kraemer for assistance in making the strength tests.

Messrs. A. A. Wehrle and C. A. Johnson, Jr., for making the strength tests and other determinations for white pine and Norway spruce. Their data have been incorporated into this report.

Dr. C. I. Bliss of this Station for assistance in organizing the statistical computations and in preparing those sections of the report dealing with statistical analysis.

planted prior to 1910. The plantings were established as tests of species, spacings and mixtures on a flat glacial outwash plain which, at the time of planting, had been abandoned for agricultural use and was occupied principally by poverty grass (*Andropogon*). Growth during the early life of the stands was quite slow but improved to some extent with time. It is probable that the density of the wood produced was somewhat greater than that from trees planted on more fertile soils.

Most of the stands sampled had been thinned between 1920 and 1936 and a great many trees had been pruned. A detailed description of the several blocks will be found in Bulletin 464 of this Station, "The Rainbow Forest Plantations, 1942".

Comparatively little is known about the conditions under which the European larch was grown. The stand was probably established prior to 1912. The soils of the area are upland tills of the Brookfield or similar series and are of comparatively low fertility, although superior to those of the Rainbow Tract.

The original plan called for the selection of 25 trees of each species but it was impossible to secure the full complement of trees in all cases. Table 1 gives the D.B.H. (diameter breast high), total height, age and number of trees for the several species finally selected.

TABLE 1. DESCRIPTION OF MATERIAL

Species	Number of trees	Average age from seed, years	Average d.b.h., inches	Average height, feet
European larch	23	30 ¹	11.4	47
Austrian pine	9	33	7.7	34
Jack pine	13	31	7.5	39
Red pine	9	40	7.6	44
Scotch pine	14	35	8.7	44
Eastern white pine	25	36	9.2	44
Norway spruce	12	34	8.0	41

Approximate

TESTING PROCEDURE AND ANALYSIS OF RESULTS

SELECTION OF TREES

Since it was desirable that the trees furnish as many testing samples as possible, those with the largest diameters breast high were chosen. For the most part these were dominants. Only healthy trees were taken and no trees showing hurricane damage to the trunks were used.

Two definite sections of each tree were selected for the test bolts as follows: (a) a section of the bole, four feet long, extending from $\frac{1}{2}$ foot to $4\frac{1}{2}$ feet above ground; (b) a section of the bole, four feet long, extending

from 8 to 12 feet above ground. Each bolt was marked with a symbol which indicated the species, the tree number and the position of the bolt relative to the ground.

The bolts were cut during the winter of 1938-9. In May, 1939, they were ripped into planks $2\frac{1}{4}$ inches thick on a portable sawmill. After sawing, the planks were peeled and carefully piled under cover for air seasoning. Later they were resawed into $2\frac{1}{4}$ inch "squares", planed to a nominal 2×2 inch cross section in a four-sided planer and shaped for the several tests described below. Toughness samples, sawed to $\frac{5}{8} \times \frac{5}{8} \times 10$ inches, were selected from any clear wood not used in other tests.

In order to produce test pieces with a minimum of cross grain, special care was taken in sawing the planks and squares. If a bolt produced only one plank capable of yielding two squares, sawing at the mill was done by making two cuts parallel to the pith and discarding the slabs. When the plank was resawed on a table saw to form $2\frac{1}{4}$ inch squares, the cuts were made parallel to the bark on each side and the wedge-shaped center piece was discarded. On larger bolts the first cut on the sawmill was made parallel to the bark on one side to remove a slab. This was followed by one or more cuts parallel to the first, removing planks $2\frac{1}{4}$ inches thick. When the pith was reached, the bolt was turned 180° on the carriage and a similar procedure followed for the opposite side. The wedge-shaped center of the bolt was discarded. Resawing of these planks on a table saw was performed in a manner similar to that described above for bolts of smaller diameter.

METHODS USED AND DETERMINATIONS MADE

The method of testing used followed, in general, the American Society for Testing Materials Designation D 143-27, "Standard Methods of Testing Small Clear Specimens of Timber" (1), except for the determination of toughness. For this test the procedure developed by the United States Forest Products Laboratory (3) was used.

The standard formulae adopted by the Forest Products Laboratory (7) were used to calculate unit stresses from the test data. These formulae and their significance are discussed in subsequent sections.

Tests to determine strength in static bending, compression parallel and perpendicular to the grain, hardness, shear, cleavage and tension perpendicular to the grain were made on an Olsen 30,000 pound universal testing machine. Toughness tests were made on a Forest Products Laboratory toughness-testing machine (3).

The number of tests of each property varied with the species. This was due to the difference in the number of trees used and to the fact that the yield of satisfactory material varied with the species and with the individual tree. In all, 4,356 samples were tested. Table 2 shows the distribution of trees and samples among the properties tested.

TABLE 2. NUMBER OF TREES USED AND NUMBER OF TESTS PERFORMED

Species	Kind of Test															
	Static bending		Compression parallel to grain		Compression perpendicular to grain		Hardness		Shear parallel to grain		Cleavage		Tension perpendicular to grain		Toughness	
	Number		Number		Number		Number		Number		Number		Number		Number	
	Trees	Tests	Trees	Tests	Trees	Tests	Trees	Tests	Trees	Tests	Trees	Tests	Trees	Tests	Trees	Tests
European larch	23	122	23	141	22	60	22	60	24	147	21	98	20	124	23	592
Austrian pine	9	22	8	26	9	30	9	30	13	74	10	44	9	32	11	149
Jack pine	13	31	6	19	9	30	9	30	11	45	10	34	8	30	11	119
Red pine	9	28	11	34	11	40	11	40	12	40	10	35	12	36	8	84
Scotch pine	14	54	20	76	23	73	23	73	19	65	21	76	20	80	19	231
Eastern white pine	25	164	25	137	25	188	25	97	24	108	25	154	—	—	—	—
Norway spruce	12	54	12	49	12	56	12	50	12	61	12	54	10	40	—	—

In addition to the strength tests, the following determinations were made :

Specific gravity and number of rings per inch were determined for all samples used in tests of static bending, compression parallel to the grain and compression perpendicular to the grain. Specific gravity was obtained on the basis of oven-dry weight and oven-dry volume.

Weight per cubic foot was calculated from specific gravity data and adjusted to a moisture content of 12 per cent.

Moisture content at the time of test was determined on all samples tested in static bending, compression parallel and perpendicular to the grain, shear, cleavage and tension perpendicular to the grain. Moisture content of these samples ranged from 8.1 to 15.8 per cent. Corresponding strength values were later adjusted to 12 per cent moisture content according to methods described on pages 51-57, U.S.D.A., Technical Bulletin 479 (7).

Moisture content at the time of test was determined on about 10 per cent of the toughness samples. These ranged from 9 to 20 per cent moisture content.

CULLING OF SAMPLES AND UNSATISFACTORY DATA

One of the more difficult problems in any study involving mechanical testing is the control of the quality of the tested material. Indiscriminate testing of all available material from a given tree does not determine the strength of small, clear wood specimens, since the presence of defects in a test piece may significantly change the value of the results obtained. The culling procedure described below was followed to secure data as representative as possible from the material at hand. All samples with obvious defects such as knots, checks, shakes, wane, pronounced compression wood and marked decay were discarded without testing. Incipient decay, mild compression wood and cross grain may also affect the results, although they may not be detected in the specimen itself before testing. Data from specimens which exhibited these defects during the test were eliminated as described below.

Incipient Decay

Since low strength, accompanied by brash failure, is often indicative of the presence of incipient decay, all specimens showing these properties were closely examined for incipient decay and, if the latter was found, the data were discarded.

Compression Wood

Compression wood, sometimes called "hard grain", "pressure wood" and "Rotholz", is an abnormal type of wood which is formed on the lower side of branches and the underside of leaning stems of coniferous trees. Pronounced compression wood can be readily detected by the presence of abnormal annual rings. The width of the summer wood in the annual ring is usually greater, the transition from spring wood to summer wood not as pronounced and the general appearance duller than normal wood. The

density of compression wood is usually considerably higher than that of normal wood (8). While pronounced compression wood can be easily eliminated before testing, mild forms of compression wood are more difficult to recognize. Fortunately, mild forms exert relatively little influence on the properties of the timber.

The effect of compression wood on the strength of structural timbers varies with the type of stress. Timbers containing compression wood may be stronger in static bending (8), but are usually definitely weaker in toughness than normal wood. If such abnormal strengths are due to compression wood, the failure is usually brash. Test specimens showing abnormal strength values and brash failure were carefully examined for compression wood. If the latter was found, the data were discarded.

Cross Grain

Another defect which is often somewhat difficult to detect but which exerts a pronounced influence on the strength of wood is cross grain. Toughness and modulus of rupture are the properties most severely affected by this defect. Compressive strength is least affected. When wood is tested, cross grain can be detected by the manner in which the piece fails. Data from all tests in which cross grain affected the failure of the piece were discarded.

All data from samples, not eliminated as described above, were used in the preparation of the several tables appearing in this report.

COMPILATION OF DATA

Tests made at the A level ($\frac{1}{2}$ foot to $4\frac{1}{2}$ feet above ground) and at the B level (8 to 12 feet above ground) were recorded separately. A preliminary tabulation, based on averages of the values obtained at the two levels, showed that the levels differed in strength and that this difference was not consistent among the several properties and species tested.

An examination of the entire body of data indicated that it was not feasible to subject it all to statistical analysis. The distribution of the samples among species, trees and levels was not uniform. Moreover, a number of factors were not evaluated. Probably the most important of these was the variable density of the wood within the individual test specimens.

However, the values for stress at proportional limit, modulus of rupture and modulus of elasticity, obtained from static bending tests on red pine, were analyzed statistically. The results showed that the difference at the A and B levels was significant for the properties analyzed. Based on this analysis, a modified method was developed for computing the tree averages from the data taken at the A and B levels. The results for the several species, which are presented in Table 3 were obtained by using this modified method. They are not appreciably different from those obtained from a straight average of all samples from the two levels tested. They do, how-

ever, compensate to some extent for uneven distribution of the samples and it is believed that they portray quite accurately the strength properties of the several species tested.

STRENGTH AND RELATED PROPERTIES

Table 3 summarizes the results of the strength tests conducted on seven plantation-grown coniferous species and presents corresponding values for similar tests performed on forest-grown material. Data for the indigenous forest-grown woods were taken from Table 1, U.S.D.A. Technical Bulletin 479 (7); jack and red pine were grown in Wisconsin, eastern white pine in Wisconsin, Minnesota and New Hampshire. Data for Norway spruce were taken from a Swedish publication (10) and for European larch and Scotch pine from an English publication (2).

Species (Column 1)

The scientific names of tree species are according to Rehder (9). The common names are those in use in the northeastern United States.

Species tested:

- European larch—*Larix decidua* Mill.
- Norway spruce—*Picea excelsa* Link.
- Jack pine—*Pinus banksiana* Lamb.
- Austrian pine—*Pinus nigra* Arnold.
- Red pine—*Pinus resinosa* Ait.
- Eastern white pine—*Pinus strobus* L.
- Scotch pine—*Pinus sylvestris* L.

Additional species mentioned in the text:

- Eastern hemlock—*Tsuga canadensis* Carr.
- Douglas fir—*Pseudotsuga taxifolia* Britt.

Specific Gravity (Column 2)

Specific gravity is a measure of the density of a material, expressed as the ratio of the weight of the material to that of an equal volume of water (7). The values presented are based on oven-dry weight and oven-dry volume. Specific gravity is a fairly reliable indication of the strength of wood. A subsequent section of this report discusses this relationship in greater detail.

Rings Per Inch (Column 3)

The number of rings per inch is an indication of the rate of growth of a tree. A great deal of attention has been devoted by many investigators to the effect of rate of growth upon the quality of the wood produced. In conifers extremes in rate of growth usually produce weak wood and the strongest wood of a species is associated with a moderate growth rate. However, clear-cut relationships between strength and the number of annual rings per inch have not been generally established.

Weight Per Cubic Foot (Column 4)

The weight of wood per cubic foot was first calculated for each test specimen from specific gravity by multiplying the latter by 62.4 (the weight of a cubic foot of water). This gave the weight per cubic foot of wood in an oven-dry condition. Since the moisture content of air dry wood in northeastern United States averages about 12 per cent, the weight of wood at this moisture content is of more value to the potential user than the oven dry weight. Using the oven dry weight as a basis, the weight per cubic foot was calculated for a moisture content of 12 per cent according to a formula developed by the United States Forest Products Laboratory (7) which assumes that, if the weight of wood per cubic foot at any moisture content below the fiber saturation point (25-30 per cent moisture content) is known, an increase (or decrease) of 1 per cent in moisture content will be accompanied by an increase (or decrease) of $\frac{1}{2}$ per cent in weight per cubic foot.

Static Bending

The term static bending signifies the gradual imposition of an external force (load) to a beam to produce deflection and, ultimately, failure. The formulae and statements presented below apply only to solid wood beams, rectangular in cross section, which are supported at the ends and loaded at the center.

Stress at Proportional Limit (Column 5)

Several properties are obtained from static bending tests. The first is stress at proportional limit. If a load-deflection curve is plotted, it will be found that the relationship between load and deflection is linear up to a certain point, beyond which deflection increases at a faster rate than the load applied. This point of departure from linearity is known as the proportional limit. If loading is continued beyond the proportional limit, the beam will not recover its original shape and will exhibit a certain amount of permanent set or deformation after the load is removed. The unit stress at the proportional limit is obtained from the formula:

$$S_{PL} = \frac{3 \times P' \times L}{2 \times b \times d^2}$$

Where:

- S_{PL} = stress at proportional limit, pounds per square inch
- P' = load at proportional limit, pounds
- L = span, inches
- b = breadth, inches
- d = depth, inches

Modulus of Rupture (Column 6)

The term modulus of rupture is used to express the maximum strength of a beam at failure. It is a measure of a beam's ability to support a load for a short period of time. Modulus of rupture is a computed rather than a true stress but it is widely accepted as a basis for calculating working stresses. Comparisons of the bending strength of different kinds of wood are generally based upon values for modulus of rupture. The following formula is used in calculating modulus of rupture:

$$R = \frac{3 \times P \times L}{2 \times b \times d^2}$$

Where:

- R = modulus of rupture, pounds per square inch
- P = maximum load, pounds
- L = span, inches
- b = breadth, inches
- d = depth, inches

Modulus of Elasticity (Column 7)

The term modulus of elasticity is an expression of the stiffness of a beam. A beam of a species with a modulus of elasticity of 1,000,000 pounds per square inch will deflect only one-half as much under the same load as a similar beam of another species characterized by a modulus of elasticity of 500,000 pounds per square inch. Values for modulus of elasticity are obtained from the following formula:

$$E = \frac{P' \times L^3}{4 \times b \times d^3 \times y}$$

Where:

- E = modulus of elasticity, pounds per square inch
- P' = load at proportional limit, pounds
- L = span, inches
- b = breadth, inches
- d = depth, inches
- y = deflection, inches

If the modulus of elasticity of the wood is known, the above formula may be used to compute the deflection corresponding to any load below the proportional limit.

While the values for modulus of elasticity in Table 3 were determined from static bending tests, they may be used as an approximation of the modulus of elasticity in compression and tension parallel to the grain. This assumption is valid because both tensile and compressive stresses are encountered during the bending of a beam.

Compression Parallel to the Grain (Short Columns)

Compression parallel to the grain, sometimes called endwise compression, is a measure of the ability of wood to resist the effect of two axial forces directed toward each other and acting parallel to the grain on a short column. The values for stress at proportional limit and maximum crushing strength given in Table 3 are applicable only to columns in which the ratio of length to least cross-sectional dimension does not exceed 11 to 1. Above this ratio, bending is introduced and the formulae, from which these values were obtained, do not apply.

Stress at Proportional Limit (Column 8)

Stress at proportional limit in compression parallel to the grain is a stress beyond which the load increments and deformation (shortening) increments are no longer proportional. Loads above the proportional limit cause permanent deformation of a column. In practice, the use of stress at proportional limit in design is not extensive. In computing stress at proportional limit the following formula is used:

$$S_{PL} = \frac{P'}{A}$$

Where:

- S_{PL} = stress at proportional limit, pounds per square inch
- P' = load at proportional limit, pounds
- A = area under direct stress, square inches

Maximum Crushing Strength (Column 9)

Maximum crushing strength is the term applied to the greatest stress which a short column can withstand under a slowly applied load of short duration. It is computed from the following formula:

$$S_c = \frac{P}{A}$$

Where:

- S_c = maximum crushing strength, pounds per square inch
- P = maximum load, pounds
- A = area under direct stress, square inches

Maximum crushing strength is extensively used to determine safe working stresses in compression parallel to grain.

Compression Perpendicular to the Grain

Fiber Stress at Proportional Limit (Column 10)

By compression perpendicular to the grain is meant the ability of a piece of wood to withstand a crushing force at right angles to the grain. As the load increases, the wood mass continues to compress and a greater resistance to the load is developed. For this reason fiber stress at proportional limit is the only value determined. It is a measure of the maximum stress that can be sustained without the development of permanent set. The stress is calculated by the formula:

$$S_{PL} = \frac{P'}{A}$$

Where:

- S_{PL} = stress at proportional limit, pounds per square inch
- P' = load at proportional limit, pounds
- A = area of specimen under load, square inches

Hardness (Columns 11 and 12)

Hardness is the ability of wood to resist indentation and abrasion. It is measured as the load required to embed a 0.444 inch steel ball to $\frac{1}{2}$ its diameter in the wood. The value thus obtained may be used for comparing the hardness of different woods but not in design. Two types of hardness are determined, end and side hardness. In all cases end hardness is greater than side hardness.

Shear Parallel to the Grain — Maximum Shearing Strength (Column 13)

Shear parallel to the grain is a measure of the resistance offered to two forces applied to the ends of a short block in such a manner as to cause one part of the block to slide along the grain and break apart from another part adjacent to it. While the values obtained by this method of testing do not represent true shearing strength, they are of importance in design. Maximum shearing strength is expressed in pounds required to shear one square inch of area and is calculated from the formula:

$$S_s = \frac{P}{A}$$

Where:

- S_s = maximum shearing strength, pounds per square inch
- P = maximum load, pounds
- A = area under shear, square inches

Wood is relatively low in shearing strength parallel to the grain and this property is often the limiting factor in the use of wood in construction.

Cleavage — Load to Cause Splitting (Column 14)

Cleavage is a measure of the force required to cause splitting in one inch of width of a standard specimen and is computed from the following formula:

$$S_{CL} = \frac{P}{b}$$

Where:

S_{CL} = load to cause splitting, pounds per inch of width

P = maximum load, pounds

b = breadth subjected to cleavage, inches

The cleavage figures in Table 3 cannot be used in designing wood members because the values are applicable only to the size of specimen tested. They do, however, permit comparison among species.

Tension Perpendicular to the Grain — Maximum Tensile Strength (Column 15)

Tension perpendicular to the grain is a measure of the maximum force which a wood member can withstand when it is pulled apart across the grain. Only the maximum tensile strength is measured. Its value is obtained from the following formula:

$$S_{TP} = \frac{P}{A}$$

Where:

S_{TP} = maximum tensile strength perpendicular to grain,
pounds per square inch

P = maximum load, pounds

A = area stressed in tension, square inches

The figures in Table 3 may be used to compare species and to estimate the splitting action of fasteners. Since wood is weak in tension perpendicular to the grain, this property often becomes one of the more important limiting factors in construction.

Toughness — Work in Inch Pounds (Column 16)

Toughness as applied to wood means its ability to resist shock when it is employed for tool handles, athletic equipment and similar uses. High toughness values characterize wood that is capable of withstanding impact. When failure occurs in tough woods it is gradual rather than abrupt. It is

not possible to apply the toughness values in Table 3 directly in design because they express the amount of energy used to fracture a specimen of a given size and would not apply to timbers of other dimensions. They do serve well for comparison of species.

OTHER TESTS OF PLANTATION-GROWN WOOD

Very little mechanical testing has been performed in the United States on the wood of planted conifers because most American plantations have not yet reached merchantability. Five separate studies of the wood of plantation-grown conifers have been made at the Yale School of Forestry. Tracey (11) and Wehrle (12) investigated the properties of the wood of white pine; Kraemer (6) and Jones (5), that of red pine; and Johnson (4), that of Norway spruce. The data obtained by Wehrle and Johnson have been incorporated into this report. For purposes of comparison the results obtained by Tracey for white pine and by Kraemer for red pine are presented below in Tables 4 and 5.

TABLE 4. COMPARISON OF STRENGTH VALUES FROM THIS INVESTIGATION WITH THOSE OBTAINED BY TRACEY(11) ON PLANTATION-GROWN WHITE PINE

	Our Values	Tracey Values
Specific Gravity	.319	.302
Number of Rings per Inch	5.8	3.6
Static Bending		
Fiber Stress at Proportional Limit, p.s.i.	4080	4153
Modulus of Rupture, p.s.i.	6790	5912
Modulus of Elasticity, 1000 p.s.i.	955	752
Compression Parallel to Grain		
Fiber Stress at Proportional Limit, p.s.i.	2620	2598
Maximum Crushing Strength, p.s.i.	3610	3325
Compression Perpendicular to Grain		
Fiber Stress at Proportional Limit, p.s.i.	440	478
Average Age of Trees, years	36	27

TABLE 5. COMPARISON OF STRENGTH VALUES FROM THIS INVESTIGATION WITH THOSE OBTAINED BY KRAEMER(6) ON PLANTATION-GROWN RED PINE

	Our Values	Kraemer Values
Specific Gravity	.39	.36
Number of Rings per Inch	7.1	6.6
Static Bending		
Fiber Stress at Proportional Limit, p.s.i.	4200	4477
Modulus of Rupture, p.s.i.	8500	7974
Modulus of Elasticity, 1000 p.s.i.	1100	1069
Compression Parallel to Grain		
Maximum Crushing Strength, p.s.i.	3880	3680
Average Age of Trees, years	40	31

Although the material tested by Tracey and Kraemer came from better sites, their results compare very closely for all properties with the results obtained in this investigation. This indicates that the material used to obtain the latter was representative of the wood of immature plantation-grown trees.

European literature describes the results of strength tests of wood of European larch, Scotch pine and Norway spruce in plantations but the incompleteness of the data makes it inadvisable to present them for comparison here.

PLANTATION-GROWN COMPARED WITH FOREST-GROWN MATERIAL

In order to make valid comparisons of the strength and other properties of the woods tested with wood from forest-grown trees of the same species, it was essential to use only data which had been obtained under standardized procedures. Domestic data were available for eastern white pine, jack pine and red pine (7). Data for Scotch pine and European larch were taken from work done in England (2) and those for Norway spruce from work done in Sweden (10). Both of these countries have adopted testing procedures similar to those set up by the American Society for Testing Materials. The age of the trees from which the test specimens were secured permitted the assumption that the trees were forest-grown. The small amount of data available on Austrian pine was not used because it was obtained under methods of testing not comparable with current practice and complete information was not available on age of the trees and on specific gravity and moisture content of the wood.

Table 3 summarizes comparative information on six of the seven species tested. It may be seen from this table that, with few exceptions, the strength of forest-grown material is higher than that of plantation-grown woods.

The greatest difference in strength, based on modulus of rupture, was found in red pine, followed in decreasing order by European larch, Norway spruce, Scotch pine, white pine and jack pine. With the exception of jack pine, the forest-grown material was higher in specific gravity and exhibited a slower growth rate. These differences account, at least in part, for its

greater strength. In plantations the spacing and, consequently, the rate of diameter growth, can be partially regulated by proper thinning. It is reasonable, therefore, to predict that, as the plantations mature, the quality of wood will improve. There seems to be no reason to suppose that plantation-grown trees, under forest management, cannot produce wood of high quality.

ANALYSIS OF VARIABILITY

The variation in strength of the individual pieces from the species average is important to the potential user of wood. The basic information should enable him to compute the percentage of material falling within desired strength limits. This can be determined most readily from the estimated standard deviation. Assuming that the observations follow a normal distribution and are large in number, 68 per cent of the values will fall within the range of one standard deviation above and below the mean, 95 per cent within the range of two standard deviations, and 99 per cent within the range of three standard deviations. If, for example, the mean obtained for one strength property of a given species is 5,000 pounds per square inch and the standard deviation is calculated to be 1,000 p.s.i., then, in large series, 68 per cent of all observations will have strength values between 4,000 p.s.i. and 6,000 p.s.i.

The standard deviations in Table 6 represent a statistical analysis of the static bending and specific gravity data for the seven species under test. Variation in other strength properties may be expected to correspond generally to that shown for static bending. As given in Table 6 the standard deviation is an estimate of the variability which would have been observed among the individual pieces if only one instead of several pieces had been taken from each tree. It is the value which should be used in estimating the variation among individual pieces of unknown origin.

TABLE 6. STANDARD DEVIATION OF PIECES FROM THE TREE MEAN
(from static bending tests and specific gravity determinations)

	European larch	Austrian pine	Jack pine	Red pine	Scotch pine	White pine	Norway spruce
Stress at proportional limit							
Tree mean, p.s.i.	4300	4300	5400	4200	5700	4100	5200
Standard deviation of pieces, p.s.i.	1210	1130	820	660	1050	720	990
Modulus of rupture							
Tree mean, p.s.i.	8500	8900	8700	8500	9400	6800	8500
Standard deviation of pieces, p.s.i.	1730	2130	1540	910	1430	880	1510
Modulus of elasticity							
Tree mean, 1000 p.s.i.	1010	1020	1170	1100	1390	955	1440
Standard deviation of pieces, 1000 p.s.i.	304	297	237	160	286	168	359
Specific gravity							
Tree mean	.450	.500	.430	.390	.440	.320	.370
Standard deviation of pieces	.037	.053	.038	.013	.045	.023	.023
Number of pieces	122	22	31	28	54	164	54
Number of trees	23	9	13	9	14	25	12

Each standard deviation is the square root of the sum of two components of variance. One represents the variability between pieces within trees; the other component has been based upon the variation among tree averages after excluding that part of the variation which could be attributed to the standard deviation between pieces within trees. In the species studied statistically, pieces cut from the same level of a single tree differed less on the average than comparable pieces from different trees. Difference in level, however, was sometimes a source of greater variation than differences between trees. Since each tree average was adjusted so as to give both A and B levels equal weight, this source of variation did not bias either the means or the tree component in the standard deviation. The effect of the difference in level has been included, however, in the component measuring the variability within trees. In a few cases this component accounted for all of the variation between trees and the standard deviation was then based upon this term alone.

FACTORS CAUSING VARIABILITY

Among the more important factors which may cause variability are rate of growth, specific gravity, position in the tree and anatomical structure.

Rate of Growth

One of the primary difficulties encountered in attempting to evaluate the influence of rate of growth upon the strength of plantation-grown wood is the lack of a uniform growth rate in such material. The small diameter of the trees used necessitated the testing of most of the clear material available and resulted in the selection of individual specimens characterized by varying rates of growth. No definite correlation between rate of growth and strength was shown by this study. Kraemer (6), who tested sub-standard sized beams and columns of plantation-grown red pine of uniform growth rate, found a closer correlation between rate of growth and strength in static bending and compression parallel to the grain, than between specific gravity and these properties. He also found a close correlation between the fibril alinement in the secondary wall and the strength properties tested.

Specific Gravity

The specific gravity of solid wood substance has been determined to be about 1.5, regardless of species. Very few woods even approach this value, the majority having a specific gravity of less than 1.00. Specific gravity is usually considered a good indicator of the strength of wood because the greater the amount of wood substance, the higher the specific gravity and, therefore, the higher the strength. Previous investigators (7) have found that some properties increase approximately in direct proportion to the increase in specific gravity; others increase more rapidly. While specific gravity can be used as a basis in predicting strength among species, it is considerably more reliable when used within a species.

Markwardt and Wilson (7) have shown that the relation between modulus of rupture (R) and specific gravity (G) for 163 species of hardwoods and softwoods at a moisture content of 12 per cent can be expressed by the equation $R = 25,700 G^{1.25}$. Over small ranges of specific gravity, this equation is practically linear. Between specific gravity values 0.30 and 0.40, they show a maximum range in values for modulus of rupture of approximately 4,200 p.s.i. for the 163 species. An inspection of the modulus of rupture-specific gravity relationship for eastern white pine showed that, between specific gravity values 0.28 and 0.38, the maximum range in modulus of rupture values was approximately 4,600 p.s.i. It appears from this comparison that the relationship between modulus of rupture and specific gravity for eastern white pine shows a trend which is very similar to that of the average for a large number of species.

In addition to making direct comparisons of the strength values of the wood from plantation-grown and forest-grown trees, these two types of material were compared on the basis of "specific strength". Specific strength is derived by dividing the value for a given strength property by the specific gravity of the wood. The resultant value affords a means of comparing the relative quality of the clear wood of two types of material independent of the effect of any differences in specific gravity that may exist.

After calculating the specific strength of both plantation-grown and forest-grown wood for each species, the relative specific gravity, relative specific strength and relative strength was computed by dividing forest-grown values by plantation-grown values and multiplying by 100. The results are shown in Table 7 for tests of static bending, compression parallel to the grain and compression perpendicular to the grain.

Although there are some exceptions, the general statement may be made that relative specific gravity, relative specific strength and relative strength of forest-grown material exceed those of plantation-grown wood. These values also indicate that differences in the strength of plantation- and forest-grown material are due in part to differences in specific gravity and in part to other causes.

Position in the Tree

For coniferous species grown under forest conditions it has been found that the wood is often of more rapid growth and lower specific gravity near the center of the tree than near the outside of the tree (7). In the case of material grown under plantation conditions, an evaluation of this relationship is somewhat difficult because of the immature trees involved. The trees in a very young plantation usually show rapid growth and, barring outside influences, growth slows down only after crown closure. The relatively small diameters of the trees used in our tests prevented any extensive evaluation of this relationship, but a number of red pine stems were analyzed for cross-sectional variations in specific gravity. It was found that the inner layers showed an average specific gravity of .312 while the outer layers were approximately .342.

TABLE 7. RELATIVE SPECIFIC GRAVITY, RELATIVE SPECIFIC STRENGTH AND RELATIVE STRENGTH OF FOREST-GROWN MATERIAL COMPARED TO PLANTATION-GROWN MATERIAL AT 100

Species	Static bending							Compression parallel to grain				Compression perpendicular to grain	
	Fiber stress at proportional limit			Modulus of rupture		Modulus of elasticity		Fiber stress at proportional limit		Maximum crushing strength		Fiber stress at proportional limit	
	Relative specific gravity ¹	Relative specific strength ²	Relative strength ³	Relative specific strength	Relative strength	Relative specific strength	Relative strength	Relative specific strength	Relative strength	Relative specific strength	Relative strength	Relative specific strength	Relative strength
European larch	111	119	133	121	134	123	138	128	143	134	149	79	88
Jack pine	107	87	93	85	91	97	104	—	—	121	129	107	114
Scotch pine	111	105	118	112	124	103	115	88	98	111	124	100	112
Eastern white pine	116	127	146	112	129	116	134	—	—	117	134	108	125
Red pine	131	171	224	112	147	125	164	160	209	146	189	94	122

$$^1 \text{ Relative specific gravity} = \frac{\text{Specific gravity of forest-grown}}{\text{Specific gravity of plantation-grown}} \times 100.$$

$$^2 \text{ Relative specific strength} = \frac{\frac{\text{Strength of forest-grown}}{\text{Specific gravity of forest-grown}}}{\frac{\text{Strength of plantation-grown}}{\text{Specific gravity of plantation-grown}}} \times 100.$$

$$^3 \text{ Relative strength} = \frac{\text{Strength of forest-grown}}{\text{Strength of plantation-grown}} \times 100.$$

Markwardt and Wilson (7) also studied the effect of height of the sample above ground as related to mechanical properties. The results are somewhat inconclusive. In general the density of wood is greater at the butt than farther up the tree. This relationship was found to be true for most of our plantation-grown species. A great deal of variation seems to exist among species. This may be due to inherent characteristics and the influence of environmental factors. The seven plantation-grown conifers exhibited the following changes in specific gravity between the section $\frac{1}{2}$ foot to $4\frac{1}{2}$ feet, and the section 8 to 12 feet above ground.

European larch:	—0.005
Austrian pine:	—0.071
Eastern white pine:	—0.110
Norway spruce:	+0.008
Scotch pine:	—0.032
Red pine:	—0.040
Jack pine:	—0.006

Although the trend is, with the exception of Norway spruce, the same as for forest-grown woods, the difference in specific gravity at the two levels is, in most cases, relatively small. Norway spruce shows a reverse trend but the difference is too small to be significant.

Strength, in relation to the height in the tree, was even more inconclusive. Some trees for which the specific gravity at the B level was higher than at the A level showed certain individual strength properties that were higher at the B level than at the A level and vice versa. In all, no consistent relationships were found between strength, and height at which the specimen was taken.

Anatomical Structure

One of the more significant variables which is not completely correlated with specific gravity and which may influence the strength of wood is variation in fibril slope. Generally, as the slope of the fibrils increases, strength decreases. Several specimens which exhibited different strengths but were of the same specific gravity were examined. It was found that the weaker specimens had a higher fibril slope than the stronger specimens. The most pronounced effect of fibril slope was observed in sections containing compression wood (8).

PRACTICAL SIGNIFICANCE OF THE TESTS

The potential user of lumber cut from plantations under 50 years of age will be interested in knowing the conditions under which he may substitute it for the more commonly used structural material with which he is familiar.

For comparison Tables 8 and 9 have been prepared on an index basis. These tables provide a means of quickly comparing the properties of the plantation-grown species with each other and with woods in actual use. Table 8 makes this comparison by assigning forest-grown eastern hemlock an index value of 100 and relating the other species to this index. Table 9 makes a similar comparison by assigning Douglas fir an index value of 100.

TABLE 8. INDEX VALUES¹ FOR THE PROPERTIES OF PLANTATION-GROWN CONIFEROUS WOODS RELATIVE TO FOREST-GROWN EASTERN HEMLOCK² AT 100

Species	Specific gravity	Static bending			Compression parallel to grain		Compression perpendicular to grain	Hardness		Shear parallel to grain	Cleavage
		Stress at proportional limit	Modulus of rupture	Modulus of elasticity	Stress at proportional limit	Maximum crushing strength	Stress at proportional limit	End	Side	Maximum shearing strength	Load to cause splitting
Eastern hemlock	100	100	100	100	100	100	100	100	100	100	100
European larch	104	71	95	84	59	79	111	99	122	142	147
Austrian pine	116	71	100	85	61	74	114	98	156	150	173
Jack pine	100	89	98	97	63	77	90	97	124	133	133
Red pine	91	69	96	92	63	72	85	69	88	124	127
Scotch pine	102	94	106	116	82	93	84	79	100	126	127
Eastern white pine	75	67	77	80	65	67	55	52	62	75	100
Norway spruce	86	85	95	120	84	84	66	68	86	68	—

¹ Comparisons, except specific gravity, made at 12% moisture content.

² Values from Table 1, U.S.D.A. Technical Bulletin #479.

TABLE 9. INDEX VALUES¹ FOR THE PROPERTIES OF PLANTATION-GROWN CONIFEROUS WOODS RELATIVE TO FOREST-GROWN DOUGLAS FIR² AT 100

Species	Specific gravity	Static bending			Compression parallel to grain		Compression perpendicular to grain	Hardness		Shear parallel to grain	Cleavage
		Stress at proportional limit	Modulus of rupture	Modulus of elasticity	Stress at proportional limit	Maximum crushing strength	Stress at proportional limit	End	Side	Maximum shearing strength	Load to cause splitting
Douglas fir ³	100	100	100	100	100	100	100	100	100	100	100
European larch	88	53	73	53	37	58	98	105	91	132	122
Austrian pine	98	53	76	53	38	54	100	104	116	139	144
Jack pine	84	67	74	61	39	56	79	103	93	124	111
Red pine	76	52	73	57	40	52	75	74	66	115	105
Scotch pine	86	70	80	72	51	68	74	84	75	117	105
Eastern white pine	63	51	58	50	41	49	48	55	46	69	83
Norway spruce	73	64	73	75	53	61	58	72	64	63	—

¹ Comparisons, except specific gravity, made at 12% moisture content.

² Values from Table 1, U.S.D.A. Technical Bulletin # 479.

³ Coast Type.

Tables 8 and 9 indicate that the strength of lumber cut from conifers grown in plantations is somewhat lower than that of eastern hemlock and Douglas fir which are commonly used for structural purposes. Substitution of plantation-grown wood for these species may or may not require an increase in dimensions to compensate for the lower strength of the former. Since the plantation trees are of relatively small size at the present time, they will be sawed into boards and small dimension stock and used chiefly in light construction for sheathing, sub-flooring, sills and studding where only a fraction of the strength of the member is utilized. Under such conditions an increase in dimensions will be unnecessary.

As the trees become larger more of them will be sawed into timbers of sufficient size for floor joists, rafters and other members which may be subjected to severe bending stresses. The dimensions of such members should be increased. In timbers subjected to bending loads, deflection rather than strength will usually be the limiting factor. Consequently, comparative values for modulus of elasticity rather than similar values for modulus of rupture, as shown in Tables 8 and 9, should be used as a guide in increasing dimensions. The dimension increased will usually be depth, since stiffness varies as the cube of the depth.

Likewise, main supporting columns, either round or square in cross section, which may be heavily loaded, should be increased in size. In this case comparative values for maximum crushing strength from Tables 8 or 9 should be used.

The following formulae may be used to make approximate computations of the dimensions of plantation-grown wood from the index figures in Tables 8 or 9.

For the depth of joists, rafters and other members subject to bending loads:

$$d' = d \left(1 + \frac{100-a}{4a} \right)$$

Where:

d' = depth the member cut from plantation-grown wood.

d = depth the member cut from hemlock or Douglas fir.

100 = index for hemlock or Douglas fir.

a = index for the plantation-grown wood that is being compared.

Example: The index value for modulus of elasticity of white pine as compared with hemlock is given in Table 8 as 80. What should be the depth (d') of a white pine beam to give a stiffness value approximately equal to a hemlock beam six inches in depth?

$$d' = 6 \left(1 + \frac{100-80}{320} \right) = 6 \left(1 + \frac{20}{320} \right) = 6 \times 1.0625 = 6.375 \text{ inches}$$

For the diameter (or side, if square) of posts and supporting columns subject to compressive loads:

$$S' = S \left(1 + \frac{100-a}{2a} \right)$$

Where:

S' = diameter (if round) or side of x-section (if square) of member cut from plantation-grown wood.

S = diameter (if round) or one side of x-section (if square) of member cut from hemlock or Douglas fir.

100 = index for hemlock or Douglas fir.

a = index for the plantation-grown wood that is being compared.

Example: The index value for maximum crushing strength of white pine as compared with hemlock is given in Table 8 as 67. What should be the diameter (or side of x-section, if square) of a white pine column to provide for maximum crushing strength approximately equal to a hemlock column 8 inches in diameter or 8 inches square?

$$S' = S \left(1 + \frac{100-67}{134} \right) = 8 \left(1 + \frac{33}{134} \right) = 8 \times 1.246 = 9.968 \text{ inches}$$

Plantation-grown material may ordinarily be used in the round for posts, small poles, cribbing and similar purposes without increasing the dimensions usually specified. However, if it is known that the timber may be subjected to exceptional loads, sizes should be increased.

REFERENCE LIST

1. AMERICAN SOCIETY FOR TESTING MATERIALS
Standard Methods of Testing Small Clear Specimens of Timber, A.S.T.M. Designation D 143-27, Philadelphia, 1927.
2. CHAPLIN, C. J. AND F. M. MOONEY
Tests of Some Home Grown Timbers In Their Green and Seasoned Conditions. Project 1. Progress Reports, Forest Products Laboratory, Princes Risborough, Bucks, England, 1929.
3. FOREST PRODUCTS LABORATORY
The Forest Products Laboratory's Toughness Testing Machine, U.S.D.A. Forest Service Mimeo 1308, 1941.
4. JOHNSON, JR., C. A.
Strength of Plantation Grown Norway Spruce, Unpublished Thesis, Yale School of Forestry, New Haven, Conn., 1941.
5. JONES, K. E.
A Study of Plantation-Grown Red or Norway Pine Wood. Unpublished Thesis, Yale School of Forestry, New Haven, Conn., 1938.
6. KRAEMER, J. G.
Growth-Strength Relations of Red-Pine, Unpublished Dissertation, Yale University, New Haven, Conn., 1943.
7. MARKWARDT, L. J. AND T. R. C. WILSON
Strength and Related Properties of Woods Grown in the United States, U.S.D.A., Tech. Bul. 479, 1935.
8. POLETIKA, N. V.
A Study of Compression Wood In Plantation Grown Northern White Pine. Unpublished report, Yale School of Forestry, New Haven, Conn., 1946.
9. REHDER, A.
Manual of Cultivated Trees and Shrubs, Macmillan Co., New York, 1927, pp. 1 to 861.
10. SCHLYTER, C. E.
Researches Into the Durability and Strength Properties of Swedish Coniferous Timber, Government Testing Institute, Stockholm, 1931.
11. TRACEY, W. M.
A Study of Plantation-Grown Northern White Pine Wood. Unpublished Thesis, Yale School of Forestry, New Haven, Conn., 1939.
12. WEHRLE, A. A.
Strength Tests of Plantation-Grown Northern White Pine, Unpublished Thesis, Yale School of Forestry, New Haven, Conn., 1940.