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DEFECTS AND THEIR INFLUENCE ON STRENGTH

June 1924



No. R1041

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
FOREST PRODUCTS LABORATORY
Madison, Wisconsin
In Cooperation with the University of Wisconsin

STRUCTURAL TIMBERS

Defects and Their Influence on Strength¹

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The nonhomogeneous character of wood and the many factors which affect its strength have long caused it to be regarded as an erratic structural material of indefinite strength. On the other hand, its low cost compared with other structural materials, its availability, its exceptionally high strength for weight, and its ease of working, at the mill and in construction, have maintained it in the structural field and will continue to do so. In the past the characteristic variations of wood were not so important as at present, since timbers were cheap and easily obtained in large sizes and almost clear grades. The clear grades, by practically eliminating defects, removed one of the greatest sources of variability, and the large timbers available permitted the use of high factors of safety.

Conditions have changed rapidly in the last 20 years, however. The timber famine now upon a considerable portion of the country is reflected in a scarcity of large and high-grade timbers, a great increase in prices, and the practical disappearance of many species -- white pine, black walnut, yellow poplar, beech, and others -- from the structural field. In spite of these facts, modern construction is requiring larger and better material to carry the increased loads of larger structures and heavier equipment. Hence, the old method of specifying clear timber and using a large factor of safety along with questionable basic strength figures cannot continue. Definite information as to the strength and variability of timber must be made available for the engineer and architect if wood is to maintain its proper place in the structural field.

Practically all of the strength tests which supply such information have been made since the year 1900. The size of test specimens has varied from that of tiny specimens, handled with tweezers, for determining differences in strength between springwood and summerwood to that of large-size bridge stringers² and of columns 12 by 12 inches by 24 feet long. The tests conducted

¹Presented at the annual meeting of the American Society for Testing Materials held at Atlantic City, N. J., June 24-27, 1924; published in 1924 Proc. of the Society.

²Detail data for a large portion of tests of structural timbers are given in U. S. Dept. Agr. Bulletin 108.

at the U. S. Forest Products Laboratory have been of two main types, namely: (1) Tests of small clear specimens, to afford data for the comparison of the inherent qualities of the species³ and to determine strength-moisture relations and the effect of duration of stress, and (2) tests of small and large specimens containing defects, to determine the influence of defects on the strength. The resulting data have been made the basis for the Department of Agriculture's specifications or grading rules which divide timbers into groups or grades to which minimum strength values can be assigned. The test data also determine the proper factors to be applied to the average strength figures derived from small clear specimens in order to obtain safe working stresses.

It is not the intent of the present paper to take up all classes of timbers and the factors which influence the strength of each. It will be confined rather to a discussion of beams, particularly to the influence of defects on their strength, together with suggestions as to how the desired minimum strength may be insured and as to the ultimate possibility of controlling strength by the limiting of defects.

Defects

A defect in a timber is an irregularity occurring in or on wood that may lower any of its strength properties. One of the fundamental characteristics of wood is the difference in its strength with and across the grain. Roughly, wood is 16 times as strong in the direction of the grain as across the grain. It is this difference in the strength with different angles of the grain which accounts for the serious weakening effect of most defects.

Checks and Shakes

Checks and shakes are local wood failures which occur either in the living tree, or during seasoning. Checks are lengthwise separations along the fibers and across the growth rings and shakes lengthwise separations between the growth rings. Checks are commonly due to seasoning; shakes seldom develop unless they were present to a certain degree in the standing tree.

The checks which develop with seasoning are due largely to the drying of the wood from the outside toward the center. Drying is accompanied by shrinkage. With exterior drying faster and shrinking more than the interior, progressively increasing stresses are set up which often result in failure. Because of the greater difference between the moisture content of interior and exterior portions of large timbers as compared with dimension stock, the rupture is more severe in the larger sizes. The failures follow the direction of the grain and consist of longitudinal separations of the wood fibers, mostly across the annual growth rings as checks. While the injurious result of shakes is confined almost entirely to a reduction of the resistance to

³Recorded in U. S. Dept. Agr. Bulletin 556, "Mechanical Properties of Woods Grown in the United States."

shear, the injury from checks, in addition to their effect in shear, quite commonly results in a lowering of other strength properties.

Cross Breaks and Compression Failures

Cross breaks are tension failures usually resulting from local abnormal longitudinal shrinkage. Such shrinkage is characteristic of "proud" or "compression" wood, which can usually be detected in fir and pine by the absence of sharp contrast between spring and summerwood. Compression failures occur as the result of stresses in the standing trees due to wind, stress developed when tree falls, and at times may be the result of rough handling of logs or timbers. These defects are limited in extent and occurrence, and while often difficult to detect they may usually be seen in large timbers before they seriously affect the strength, and the material avoided. See figure 1.

Cross Grain and Knots

The weakening effect of cross grain and knots, two of the most important types of defects, is due primarily to the characteristic difference in the strength of wood with and across the grain, accentuated by the checking introduced.

Cross grain is the general term used to describe any departure of wood cells or fibers from a direction parallel to the axis of the piece. There are a number of kinds, as spiral, diagonal, wavy, dip, and curly and interlocking grain. The defect is best measured in structural timbers by the slopes of checks, which always follow the direction of the grain. Limits on cross grain in structural timbers are intended to apply only to spiral and diagonal grain;⁴ the other forms are usually due to knots, and knot limitations can be depended upon to control them. The damage done by knots is due not to the fact that the material composing them is inherently weaker than normal wood, but to the combined operation of several factors, the most important of which are cross grain and checking. In order better to understand the injury, we must consider the effect of knots in distorting the grain. Figure 3 shows how knots are formed by the wood fibers of the main body of the tree running out into the limb and how cross grain is thus developed. Upon the death of a limb the fibers cease to grow out into it, and the new wood which begins to incase the knot shows a decrease in grain distortion. Figure 2 shows the checking in knots which accompanies drying. It will be noticed that the checks extend entirely across the face of the knot and are very prominent and irregular in direction around it.

Decay is disintegration of wood substance due to the action of wood-destroying fungi. This action consists in a breaking-down of the cell walls which results in a weakening effect even when the presence of the fungus cannot

⁴See "The Effect of Spiral Grain on Strength of Wood," by T. R. C. Wilson, Journal of Forestry, Nov. 1921.

be detected visually. Decay is, therefore, an important factor in the strength of a timber, but the determination of its total injurious effect is difficult because the amount of decay visible on the exterior is not a satisfactory indication of the extent to which the strength is affected. Certain types of decay at times continue their destructive action after the timbers have been placed in use. It is, therefore, necessary to limit decay more rigidly than would seem justified by test.

Other Defects

The defects above discussed are the ones which it is essential to control in specifications intended to establish definite strength grades. There are others which often give indication of the presence of more injurious defects and as such may be of considerable assistance in grading. Thus, bark pockets and gum spots or streaks are indications of concealed knots; collapse of severe drying treatments and probable loss of inherent strength; pitch of shakes and of erratic strength; discoloration and insect holes of decay attack; and warping of cross grain.

The Effect of Defects on Strength

Some defects affect all of the fundamental strength properties, viz., tension, compression, and shear; others affect but one of the properties, while the injury caused by some is due to their combination with still other defects. The manner in which these defects and their combinations affect the strength properties of wood is of fundamental importance in the grading of structural timbers.

Tension

Tension is affected most seriously by cross grain, knots, cross breaks, and compression failures.

The ratio of the strength in tension with an across the grain of wood is larger than for compression and shear, being about 25 to 1 for small clear green specimens and as high as 45 to 1 for air-dry specimens. The amount of injury which will result from cross grain depends upon the angle the grain makes with the axis of the piece. Even a slight departure from straight grain is a source of weakness, although it does not become very apparent until a slope of 1 in 25 is reached.

The separation of the wood fibers by checks has little, if any, effect upon the strength in tension when the load is applied in line with the fibers. On the other hand, when the load is applied perpendicular to the fibers their separation by checks will cause a direct reduction of the area acting in resistance to tension and, consequently, will reduce the strength. The reduction of tensile strength from checking varies between these two extremes,

becoming more and more serious as the angle of grain increases. In small pieces checking may sometimes reduce to 0 the area acting in resistance to tension by actually separating the piece into two parts.

The weakening influence of knots on tensile properties is due almost entirely to cross grain and the checking introduced. Cross grain around a knot can be measured on the surface, but that within the knot itself cannot be judged in this way. Usually, however, the grain of a knot is at such a wide angle with the axis of the piece that its strength at best can only be considered as the strength of wood perpendicular to grain. Checking, as a rule, will destroy even this, and the effect of the knot proper becomes the same as that resulting from the removal of an equal amount of wood; and in addition the influence of the checking and irregular grain surrounding the knot must be taken into account.

The shape and other characteristics of a sound knot have little influence upon the amount of injury to be expected, since the injury is dependent to a large extent upon the amount of grain distortion. There is very little difference between the reduction of tensile strength caused by knot holes or incased knots and that caused by intergrown knots. The injury from a lack of bond around an incased knot, or the absence of material in a knot hole, is actually less than the injury resulting from the greater distortion of grain around an intergrown knot and from the checking which accompanies it. The amount of grain distortion is dependent upon the diameter of the limb which caused it, but its increase is greater than the corresponding increase in the diameter of limb.

As in the case of checks, shakes have no effect on tensile properties when the load is applied in line with the grain, but any separation of the annual rings would, of course, destroy the tensile strength across the grain. Cross breaks and compression failures, on the other hand, reduce the strength when the load is parallel to the grain.

Compression

The effect of cross grain and knots is much less in compression than in tension. The effect of checks and shakes is confined largely to causing an unequal distribution of stresses which results in a reduction of strength through the overstressing of some of the fibers before others.

The compressive strength of wood parallel to the grain is from 6 to 10 times that perpendicular to the grain. This ratio is about the same for both the green and the air-dry material and is much smaller than that in the case of tension. While the reduction in compressive strength starts with the slightest deviation of the grain, it does not become appreciable until the grain is at a slope of approximately 1 in 10. This difference in the effect of cross grain accounts primarily for its smaller injury in compression.

Checks in compression parallel to grain tend to close up so that stress is set up over the entire cross section. The stresses, however, are not of uniform intensity, and failures therefore occur at somewhat lower average loads than if the checks were not present. In fact, checks sometimes do not close until failure has started.

The weakening effect of a knot in compression, as in tension, is due primarily to the cross grain that accompanies it. However, the weakening effect of cross grain is considerably less for compression than for tension, and checking in and around the knot is also less injurious. Quite frequently a part or all of the strength across the grain is developed in a knot resisting compression, even when the knot is checked. The net result is a weakening somewhat less than would occur by the removal of the knot proper.

Shear

Reduction in shearing strength is due almost entirely to the presence of shakes and checks, the presence of knots and cross grain exerting but little influence in this respect. In fact, knots and cross grain break up the continuity of checks and thus tend to reduce their injurious effects in shear.

Weakening in shear from checks and shakes consists in a direct reduction of the area acting in resistance to shear. Moreover, shakes are usually accompanied by a general weakness in bond between the annual growth rings which seriously affects the shear strength.

Influence of Position of Defects on Strength

In the past, grading rules have been based upon the size and nature of defects. Their location, which is equally important, has been largely ignored. With uniform or rolling loads the tension and compression stresses decrease from the center of the length of a beam towards the ends and from the narrow faces to center of height. The distribution of stress is the same for both types of loading, although for the same load the stress resulting from the rolling load is twice that of the uniform. The stresses developed by the third-point method of loading used in testing are constant over the center one-third of the length and decrease from the center third towards the ends. While this distribution of stresses is different from that under rolling or uniform loading, the presence of uniform stresses in the center third of the length facilitates a study of the influence of defects.

With the same intensity of stress at the center of the length, the uniform, rolling, and third-point loading will give identical stresses at the quarter points. The maximum difference is at the third points, where the third-point loading gives 11 percent higher stresses. In the direction of height all types of loading give the same distribution of stresses. The longitudinal distribution of the shear stresses is the same for rolling as

for uniform loads, increasing in intensity towards the ends. The vertical distribution is the same for all types of loading and increases in intensity from the edges to the center of height. Checks and shakes along the neutral axis greatly increase the intensity of shear stresses by reducing the area acting in resistance to it.

It is evident from the foregoing considerations that the size of defect allowable is dependent upon the part of the timber in which it is located. The ideal specification would control the location of defects so that a beam containing all of the maximum allowable defects would be equally likely to fail at any of them regardless of their location.

Effect of Factors Other Than Defects

In order to fully understand the effect of defects on strength, it is necessary to consider briefly other factors such as, density, species, moisture content, form, size of shape, and duration of stress. Taken together, these factors account for all of the chief variations in the strength of wood.

Density

The specific gravity of the wood substance of all species being practically the same, the density becomes a measure of the amount of wood substance present in a given volume, and hence a measure of the inherent strength of the wood. Dense material of Douglas-fir and Southern yellow pine has been defined in detail in specifications of the Society.⁵ Applied to these species, the density rules laid down afford a visual method of estimating the quality of inherent strength of timbers.

Although density is the best indication of the strength of clear wood, it cannot readily be applied to other species than Douglas-fir and Southern pine because there is no satisfactory visual method of determining it.

The number of rings per inch as an indication of strength has been much overrated. It cannot be considered as a satisfactory substitute for the density rules previously referred to. However, the maximum and minimum limitation on rings per inch will eliminate the poorest timbers of both Douglas-fir and Southern yellow pine. Like density, it is inapplicable to other species, especially hardwoods, in which a rapid rate of growth is quite frequently accompanied by better than average strength values.

⁵Serial D23-207, A.S.T.M., Tentative Standard 1920 for Douglas-fir;
Serial D10-15, A.S.T.M., Standard 1921 for Southern Pine.

Species

The difference in strength due to species has been greatly overstressed in the selection of structural timbers. In any given species it is not uncommon to find pieces twice as strong as others, although both are sound, clear, and straight-grained. This matter is not as serious as it appears, since the strong pieces are farther above the average than the weak ones are below. The difference in the strength of species ordinarily used for structural timbers is less than this variation within a species. Even the average strength of hickory as compared with that of Eastern hemlock, when used as a beam or post, is less than 2 to 1.

Moisture Content

The strength of wood varies with its moisture content.⁶ Furthermore, the shrinking and swelling of wood which always accompanies drying and soaking increases the injury resulting from defects, particularly by opening checks along cross grain and in knots, and by extending shakes.

Size Factor

Tests have shown that large structural timbers do not show quite the strength that would be expected of them as compared with small clear pieces, even when failure of the large timber occurs in clear wood.⁷ The variation in the strength of beams is a function of their height and this factor has been considered in comparing the strength of beams of different sizes.

Grading Rules

Selection of timbers exactly in accordance with their strength as indicated by theory and by the results of tests involves too great an amount of work, education, and money to be justified at the present time. The present price and limited available supply of lumber, however, do warrant a change from the present very general grading rules to rules which will insure minimum strength values. Grades which in the opinion of your committee meet present practical conditions have been formulated. These rules neglect the difference in the intensity of the stresses which occur near the ends as compared with those in the center of the length, the difference in the influence of knots under tension and compression, and the relative distance of shakes and checks from the neutral axis. They do, however, recognize the relation of size of defects to size of timber, and the distance of knots from the neutral axis. They insure minimum strength values and are therefore far in advance of most of the commercial rules in use at the present time.

⁶See U. S. Dept. Agr. Bul. 70, "Effect of Moisture Upon the Strength and Stiffness of Wood," by H. D. Tiemann.

⁷See "Influence of the Form of Wood Beams on Stiffness and Strength -- Part II -- Form Factors of Beams Subjected to Transverse Loading Only"; National Advisory Committee Report No. 181.

The correctness of the theory involved and the efficiency of different grading rules were tested by applying them to a number of groups of structural timbers tested, and studying the results. A to F in the accompanying Figure 4 show the results of the application of three rules to Western yellow pine (called ponderosa pine in American Lumber Standards classification, 1929) timbers for the purpose of studying their relative efficiency. This group of tests was chosen for the illustration because complete data on both green and air-dry material were available. This being the last group of structural timbers tested at the Forest Products Laboratory, a portion of the beams including the failures was still available for examination.⁸

The diagram shows the percentage of the clear strength developed by structural timber, as given by the ratios of the modulus of rupture of the structural specimen to the modulus of rupture of small clear specimens cut from them. This eliminates largely the factor of density and shows the efficiency of the defect classification.

The structural specimens were divided into four grades designated as S1, S2, S3, and S4. These grades are based on those given in U. S. Department of Agriculture Circular 295,⁹ but vary in the degree to which they conform with theory. A and B show the application of the principles of the American Society for Testing Materials rule, since they are on the same basis in that they neglect the difference in stress intensity at the ends and center of the length. Also, this rule does not recognize any difference in the effect resulting from character of stresses in the upper and lower faces of the beams. C and D show the application of the rules given in U. S. Department of Agriculture Circular 295. These rules allow an increase in size of knots toward the ends of the beam, but not to the extent that theory and analysis indicate is possible. They do not recognize a difference in effect of knots occurring on the upper and lower faces, nor the position of shakes and checks with reference to the neutral axis.

E and F give the efficiency of the rule which takes into consideration not only position in length but the difference in effect of knots on tension and compression faces. This rule represents approximately the ultimate possible limit in grading for strength.

There are excellent reasons for the departure from theory in practical rules. The knots in the A.S.T.M. Rules are not permitted to increase in size toward the ends because of practical difficulties in grading. The upper and lower faces are graded alike because of the likelihood of a beam being placed wrong side up through carelessness or lack of knowledge on the part of workmen. Control of the position of checks and shakes relative to the neutral axis is

⁸The Forest Products Laboratory has analyzed many other groups of timbers along same line as the Western yellow pine, and this analysis is available to those who wish to examine it at the Laboratory. It is not yet determined whether or not this material will be published, and if so, in what form.

⁹U. S. Dept. Agr. Circ. 295, "Basic Grading Rules and Working Stresses for Structural Timbers," 1923.

not provided for, because of the small difference in intensity of stresses over the center half of height. When these defects occur in the upper or lower quarter of a beam, there is the added danger of their running into the edge, or into the tension and compression failures.

A and B, Figure 4 show the grades to be badly mixed. They err, however, on the side of safety. They are intended to insure a certain percent of the clear strength and are not expected to prevent overlapping of grades. The overlapping shown is due largely to the defects which determined the grade occurring near the end or top. Thus, a grade made to secure a minimum strength ignores known influences, and therefore includes many timbers of much higher strength than is required for the grade. The poorer classification of the green timbers by all the rules, as is shown in the diagram, is accounted for by the fact that grading rules must consider the strength of timber after it has been in service for a considerable time. This consideration requires that in grading green timbers the rules must anticipate injury which has not taken place but which will undoubtedly occur.

C and D show considerable improvement in the classification over A and B, Figure 4. The raising of the grade of the timbers with large defects at or near the ends is responsible for the better strength classification shown in C and D. It has raised 40 percent of the timbers the equivalent of one grade which permits a 6-1/2 percent increase in the allowable loads.

The classification shown by E and F is what we can expect to obtain with practically complete application of the foregoing principles, the timbers being placed right side up and the defects controlled in accordance with their position in the length. This refinement appears to be in advance of what is justified under present economic conditions. The application of this rule to the test specimens of Western yellow pine raised 75 percent of the timbers the equivalent of one grade, and the balance of them the equivalent of two grades, above that obtained by applying the principles used by Committee D-7; that is the allowable loads have been increased 20 percent.

It is practically impossible to estimate the correctness of fundamental theories back of grading rules when the rules take into consideration only a part of the elements which affect the strength of timber. It is also impossible to check the correctness of the theory and efficiency of grading rules from the results of tests of green material, as previously pointed out, for in interpreting the strength data the ultimate condition of the timber after it has been in service for some time is of great importance. Thus A, C, and E of Figure 4 show many low-grade timbers with high strength ratios. This is partially due to the fact that defects did not develop their full weakness and to the fact that the defects in A and C which determined the grade were not in a position to influence the strength to any marked degree.

This lack of agreement between the grade and the test data have often led to the erroneous conclusion that the theories back of the grade were in error. F, however, shows the results of applying the theory as closely as it is thought will ever be practicable. This figure also shows that when the theory is closely followed the rules give almost perfect segregation of the timbers in so far as their control of the influence of defects on the strength is concerned. The rules which give the results shown in F would require considerable refinement in grading and would require the use of branding or other methods to insure timbers being placed with the best side down. In general, Figure 4 shows what might be expected from a segregation of timbers by each of the three methods. It shows that the injury from defects increases with seasoning, and that the efficiency of the rules should not be judged by the results of tests on green material. It also demonstrates the correctness of the theory on which the rules are based.

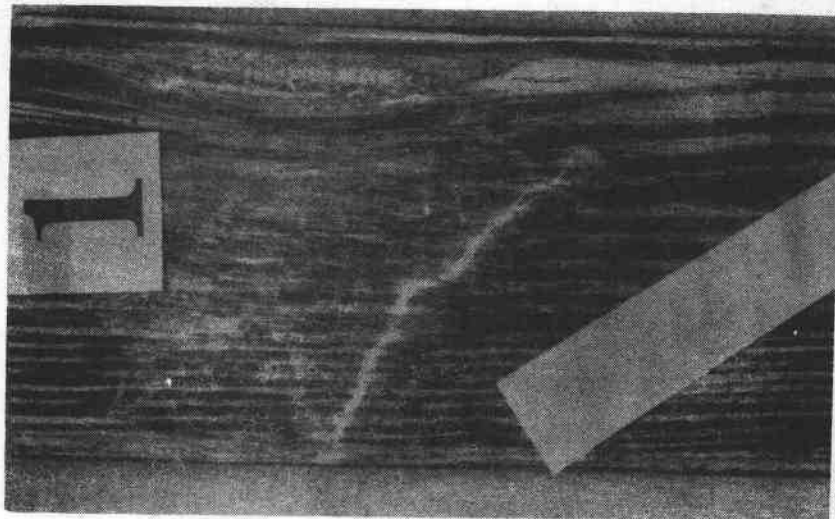


Figure 1.—"Compression failures" in southern yellow pine that occurred in the living tree.

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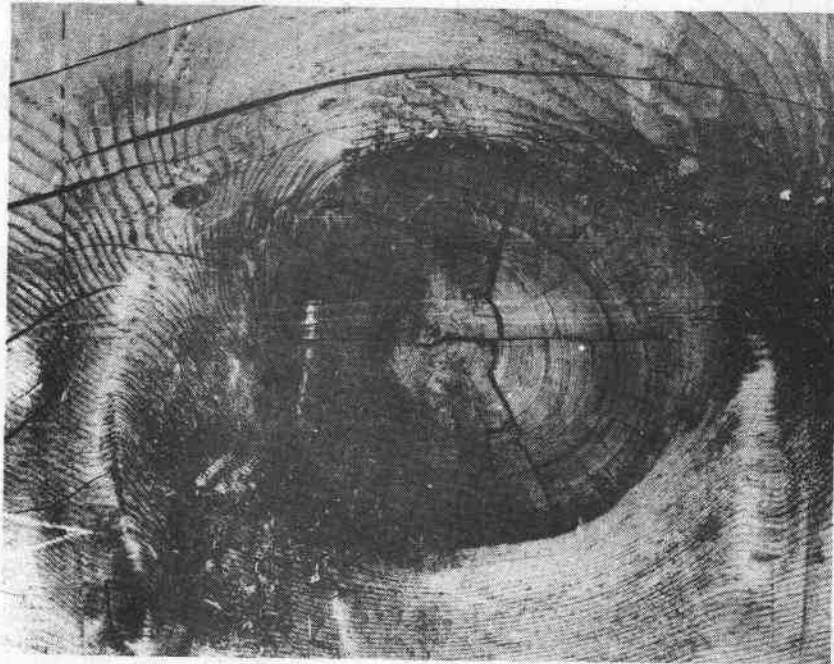


Figure 2.—Illustration of the injurious effect of checking in and surrounding knots.

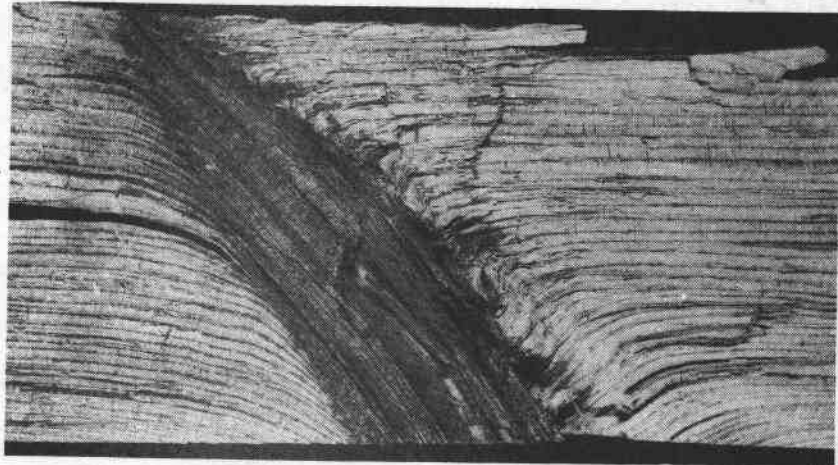


Figure 3.—Distortions of grain in and surrounding knots. Note effect of checking.

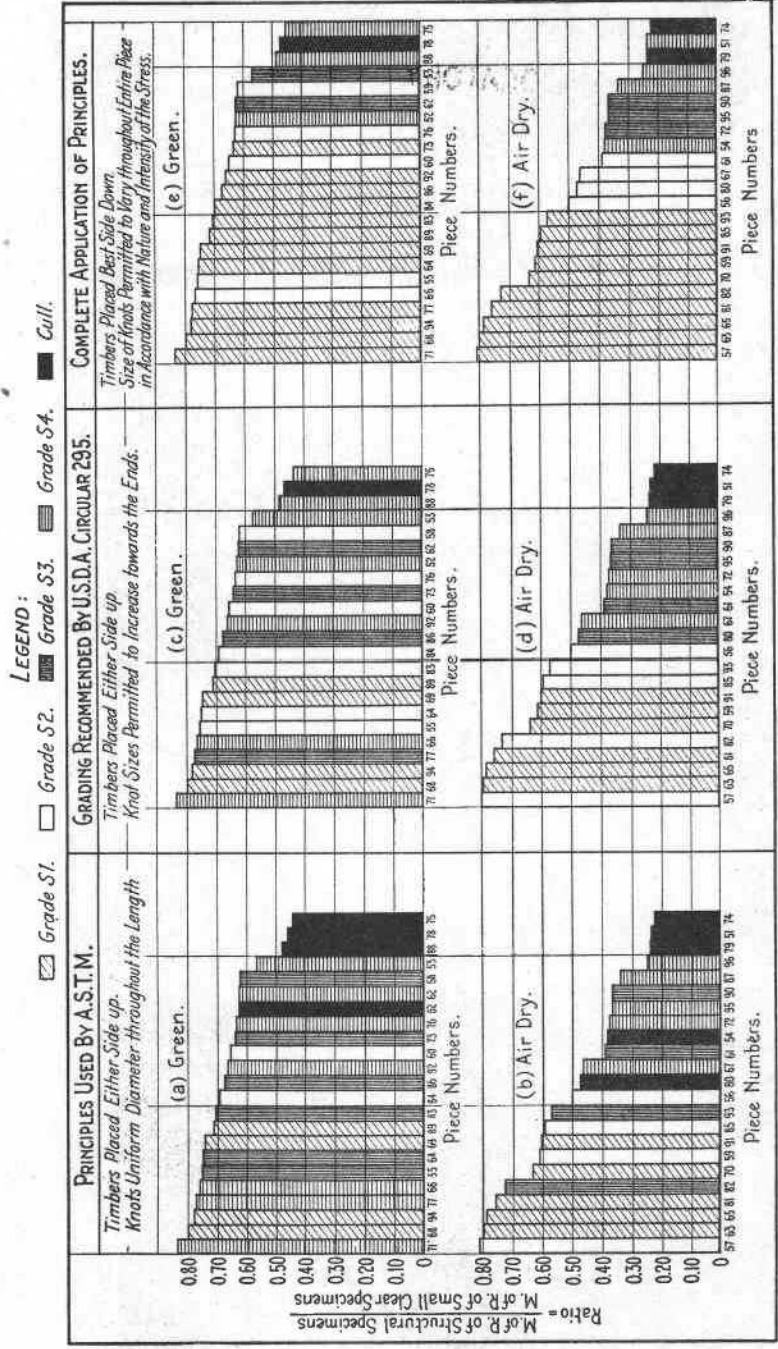


FIG. 4.—Application of Fundamental Principles of Grading to Western Yellow-Pine Structural Timbers. Efficiency of various degrees of application of theory as shown by ratio of modulus of rupture of structural to small clear specimens.

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