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FABRICATION AND DESIGN OF GLUED LAMINATED WOOD STRUCTURAL MEMBERS
FREAS, A D , SELBO, M L 1 OF 3

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CONTENTS

Part II. Design

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Fabrication and Design of Glued Laminated Wood Structural Members[1]

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INTRODUCTION

Widespread developments in the field of glued laminated wood construction in the United States during the past two decades have directed attention of architects and engineers to a new product admirably adapted to a wide variety of building and construction uses and, in effect, have launched a new industry. Factors that favored the ready acceptance of laminated construction, aside from its unlimited architectural possibilities, were the significant improvements in glues and the development through research of the necessary engineering design data.

The term "glued laminated construction," as applied to structural members, refers to material glued up from smaller pieces of wood, either in straight or curved form, with the grain of all the laminations essentially parallel to the length of the member. It is thus basically different from plywood, in which the grain direction of adjacent plies is usually at right angles. The laminations may be of any thickness or length, of narrow pieces glued edge to edge to make wide ones, of different wood species, or of pieces bent to curved form during gluing—all of which afford infinite choice in design, subject only to economic factors involved in production and use.

Bonding wood with glue is, of course, an old art that has made possible the fabrication of wood products in various forms and shapes. The usefulness of such products has in general been dependent on the strength of the joints and on the ability of the glue to maintain strength in service. Improved glues have increased the serviceability of conventional glued wood products and provided an opportunity for using wood for many purposes. Recently developed highly water-resistant resins that set at moderate temperatures have made possible the production of laminated wood suitable for use under severe service conditions, including exterior exposure.

The Forest Products Laboratory has long been active in research on the gluing of wood. The first research at the Laboratory on engineering design data for glued laminated arches was undertaken

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[2] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

in 1934, when a number of three-hinged arches were fabricated and installed in a building erected for the Laboratory at Madison, Wis. It included tests of structural units to check such factors as design formulas and working stresses, and the effect on strength of curvature, scarf joints, and knots in the inner laminations. Results of this research are presented in United States Department of Agriculture Technical Bulletin 691, The Glued Laminated Wooden Arch, which provides the technical data necessary for the use of laminated arches on a sound basis.

The great demand during World War II for heavy timbers for military and industrial uses hastened the development of laminated wood products, since the supply of solid timbers was inadequate. Some of these uses required hardwoods rather than the softwoods that had customarily been laminated with casein glue, and many members were needed for use under exterior or wet-exposure conditions, where casein glue would not be durable.

Some of the synthetic resins of the urea-formaldehyde type, developed in the 1930's, can be used at room temperatures and are superior to casein glues in water resistance. However, when they were tried for laminating oak lumber into boat keels, they did not withstand the service conditions imposed. In 1942 attention was turned to the use of the new intermediate-temperature-setting phenol-resorcinol resins for laminating white oak ship keels and frames. Sponsored by the Navy Department's Bureau of Ships and by the War Production Board's Office of Production Research and Development, experimental work on the application and performance of these glues was undertaken at the Forest Products Laboratory and at two commercial pilot plants, those of Gamble Bros., Inc., at Louisville, Ky., and Timber Structures, Inc., at Seattle, Wash. Later the experimental work included similar studies on the more recently developed resorcinol resins. As a result, procedures were worked out for fabricating laminated members, the bonding of which is capable of withstanding all exposures that the wood itself can withstand.

While the procedures for making glued laminated construction were developing to the point where beams and other structural elements could be made, it became increasingly apparent that additional research was necessary to solve new problems relative to strength and design. With the cooperation of the War Production Board and industry, further work on the factors affecting strength was undertaken at the Forest Products Laboratory. This work included the testing of full-sized laminated beams and columns, to provide additional design data and information for technical phases of specifications. Factors investigated included the relative strength of members containing different types of end joints, the effect on strength of defects in different laminations, the effect of varying the thickness of laminations, and like factors.

Advantages of Glued Laminated Construction

Advantages of glued laminated wood construction are many and significant. They include the following:

1. Ease of fabricating large structural elements from standard commercial sizes of lumber. Laminated arches have been erected that

provide buildings with clear spans up to 170 feet, as have laminated beams of 80-foot span. Arches with sections as deep as 7 feet have been projected.

2. Achievement of excellent architectural effects, and the possibility of individualized decorative styling in interiors.

3. Freedom from checks or other seasoning defects associated with large one-piece wood members, in that the laminations are thin enough to be readily seasoned before fabrication.

4. The opportunity of designing on the basis of the strength of seasoned wood, for dry service conditions, inasmuch as the individual laminations can be dried to provide members thoroughly seasoned throughout.

5. The opportunity to design structural elements that vary in cross section along their length in accordance with strength requirements.

6. The possible use of lower-grade material for less highly stressed laminations, without adversely affecting the structural integrity of the member.

7. The fabrication of large laminated structural members from smaller pieces is increasingly adaptable to our future timber economy, when more of our lumber will come in smaller sizes from smaller trees and in lower grades.

Modern glues and gluing techniques provide both adequate and effective means of bonding laminations into an assembly equal in strength to a single-piece member of equivalent section. They may be selected to provide a laminated assembly that is water-resistant or waterproof as conditions of use may dictate. An example is the use for ship construction of laminated oak keels and stems fabricated with phenol-resorcinol, resorcinol, or melamine glues. When properly glued, laminated members may be given preservative treatment by pressure methods much as solid timbers are treated, and thereby have improved resistance to decay when used under adverse conditions of exposure. It is possible also to give the laminations preservative treatment prior to assembly.

Certain factors involved in the production of laminated timbers are not encountered, however, in producing solid timbers. A number of these are:

1. The preparation of lumber for gluing and the gluing usually raise the cost of the final laminated product above that of solid green timbers.

2. For constructions in which green timbers are satisfactory, more time is required to cut and season lumber and to do the laminating than is required to cut solid green timbers.

3. Since the value of a laminated product depends upon the strength of the glue joints, the laminating process requires special equipment, plant facilities, and fabricating skills not needed to produce solid green timbers.

4. Because several extra fabricating operations are involved in manufacturing laminated members, as compared with solid members, greater care must be exercised in each operation to insure a product of high quality.

5. Large curved members are awkward to handle and ship by the usual carriers.

Typical Applications

One of the early applications of glued laminated construction in the United States was in the form of 3-hinged arches of approximately 46-foot span in a building at the Forest Products Laboratory (fig. 1, *A*). These arches were of variable cross section, tapering in depth toward the ridge of the roof and toward the base from a maximum at the knee. The knee was placed at the eaves, with an approximately vertical leg, so that maximum utilization of space up to eave height was possible. Arches having this general shape are also suitable for gymnasiums (fig. 1, *B*) and industrial buildings, since they provide unobstructed floor area usable to a considerable height. An unusual application of glued laminated arches is illustrated by figure 1, *C*. Figure 2 shows laminated arches having an I section.

Glued laminated arches have found considerable acceptance in church construction. The pleasing architectural effects possible with glued laminated arches are illustrated in figure 3.

The form of support for the arch may be varied to suit the requirements imposed by the structure. Where interference above wall height is not critical, tied arches may be used for single spans (fig. 4, *A*) or for multiple spans (fig. 4, *B*). Buttresses may also be used for arch support.

Glued laminated curved rafters are now frequently used in farm structures (figs. 5 and 6), particularly in barns. The rafters, ordinarily of relatively small size and spaced about 2 feet apart, are available from lumberyards and farm cooperatives in stock sizes for a variety of spans. Members of this same general character are also used for small one-story industrial and commercial buildings.

Aircraft hangars employing glued laminated arches of various forms became fairly common during World War II. Such a hangar is illustrated in figure 7, *A*. In bowstring trusses, the curved upper chords are frequently of glued laminated construction. Usually the lower chord and web members are of solid construction, but in some cases both upper and lower chords are laminated, as shown in figure 7, *B*.

Glued laminated structures in exterior applications are less common, but a number of bridge installations have been made on railroads and highways. One such installation, involving laminated stringers, posts, and caps, is shown in figure 8, *A*. Figure 8, *B*, shows a two-lane highway bridge supported by 4 glued laminated arches of 103-foot span. The laminations were treated with a preservative salt before being glued.

Boat and ship construction offers a promising field for the utilization of glued laminated wood. During World War II, the shortage of white oak of proper quality and adequate size for keels, stems, frames, and other parts led to an intensive program of research. Laminated keel-stem assemblies, such as are shown in figure 9, demonstrated adequate durability and considerably improved strength and stiffness as compared with the mechanically joined assemblies commonly used. Boat parts may be formed to various patterns, thus simplifying assembly; for example, bilge stringers and garboards may be formed to a pattern involving compound curvature and twist. Figure 10 shows laminated ship planking.

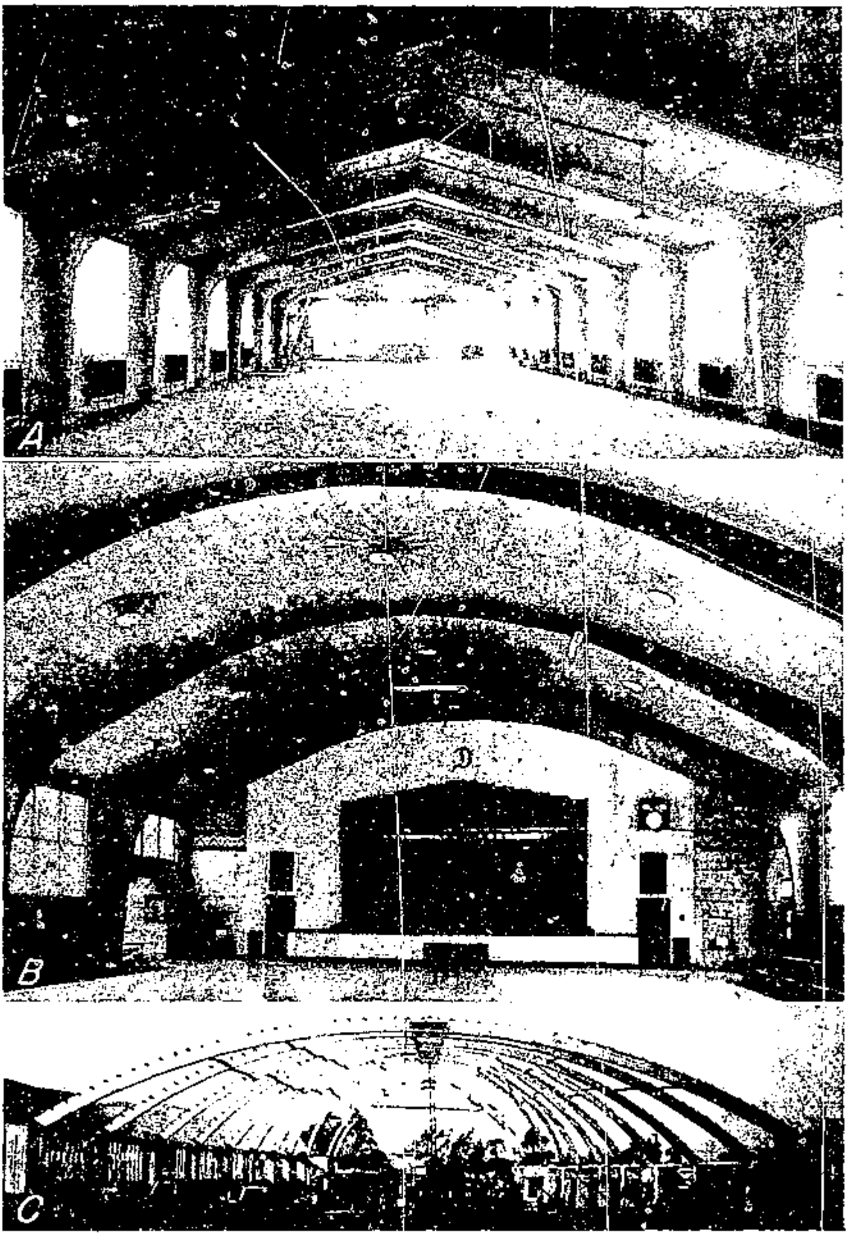

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FIGURE 1.—*A*, Laminated arches span 46-foot-wide service building at Forest Products Laboratory; *B*, laminated arches of 63-foot span in high school gymnasium at Darlington, Wis.; *C*, laminated arches of varying span and shape for theater at Los Angeles, Calif.

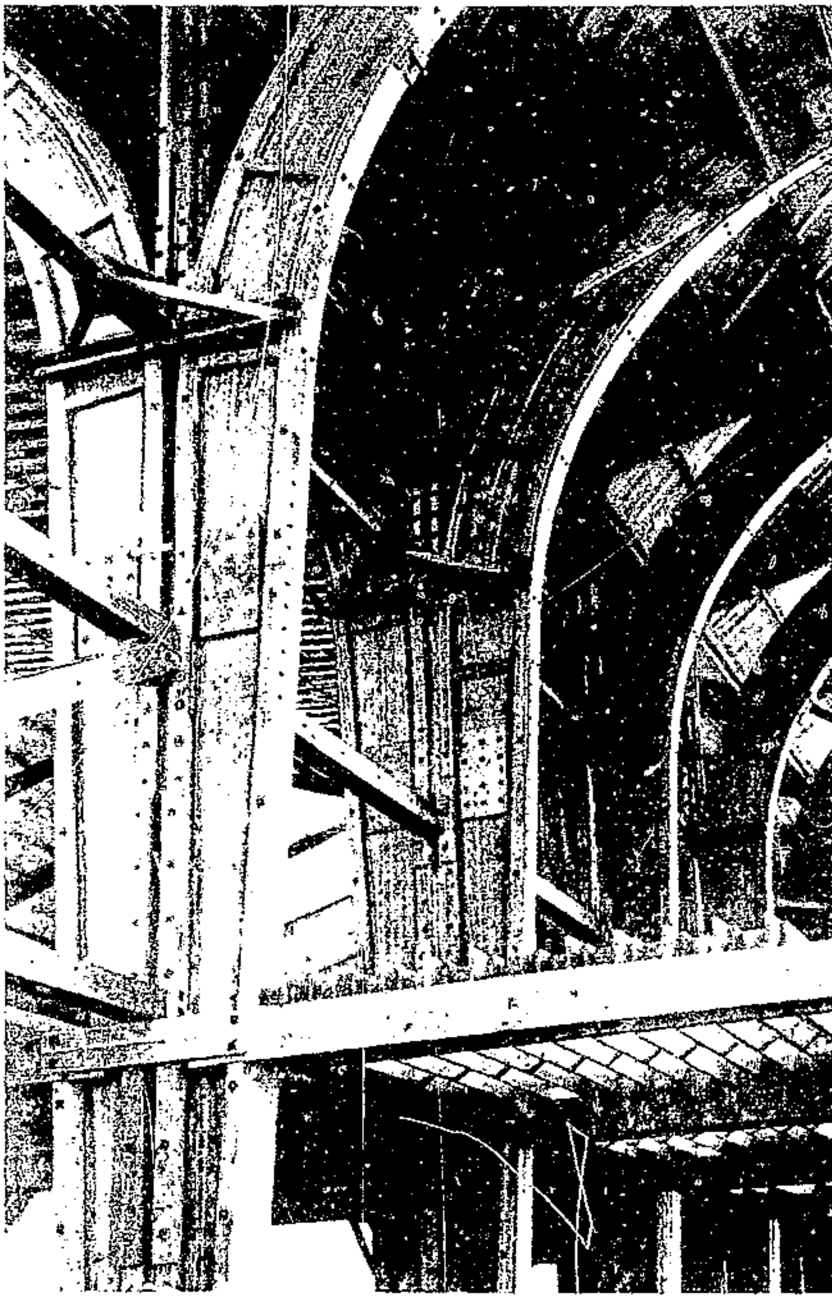

FIGURE 2.—Laminated arches having an I section.

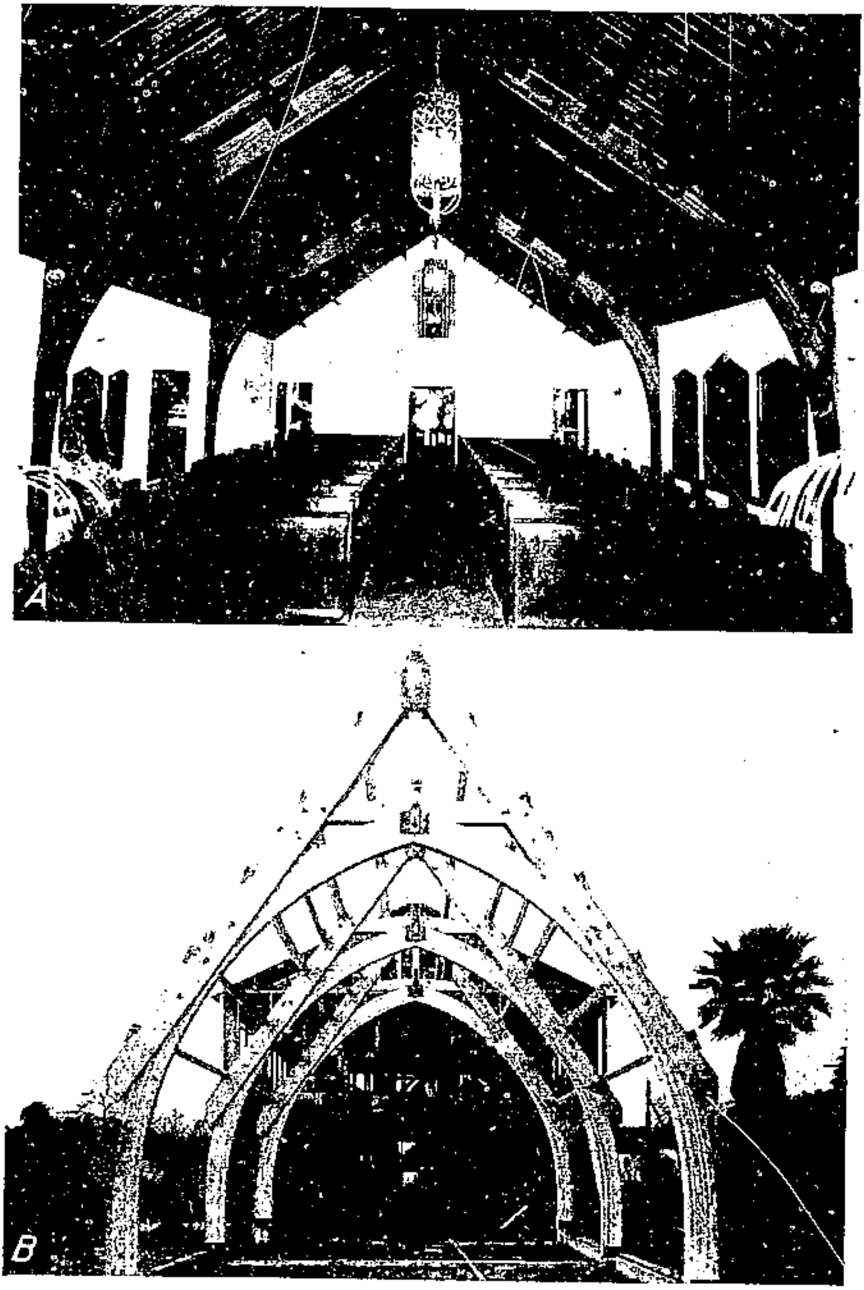

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FIGURE 3.—*A*, Laminated arches in a chapel at Pasadena, Calif.; *B*, laminated arches combined with straight, solid members for architectural effect in church at San Gabriel, Calif.

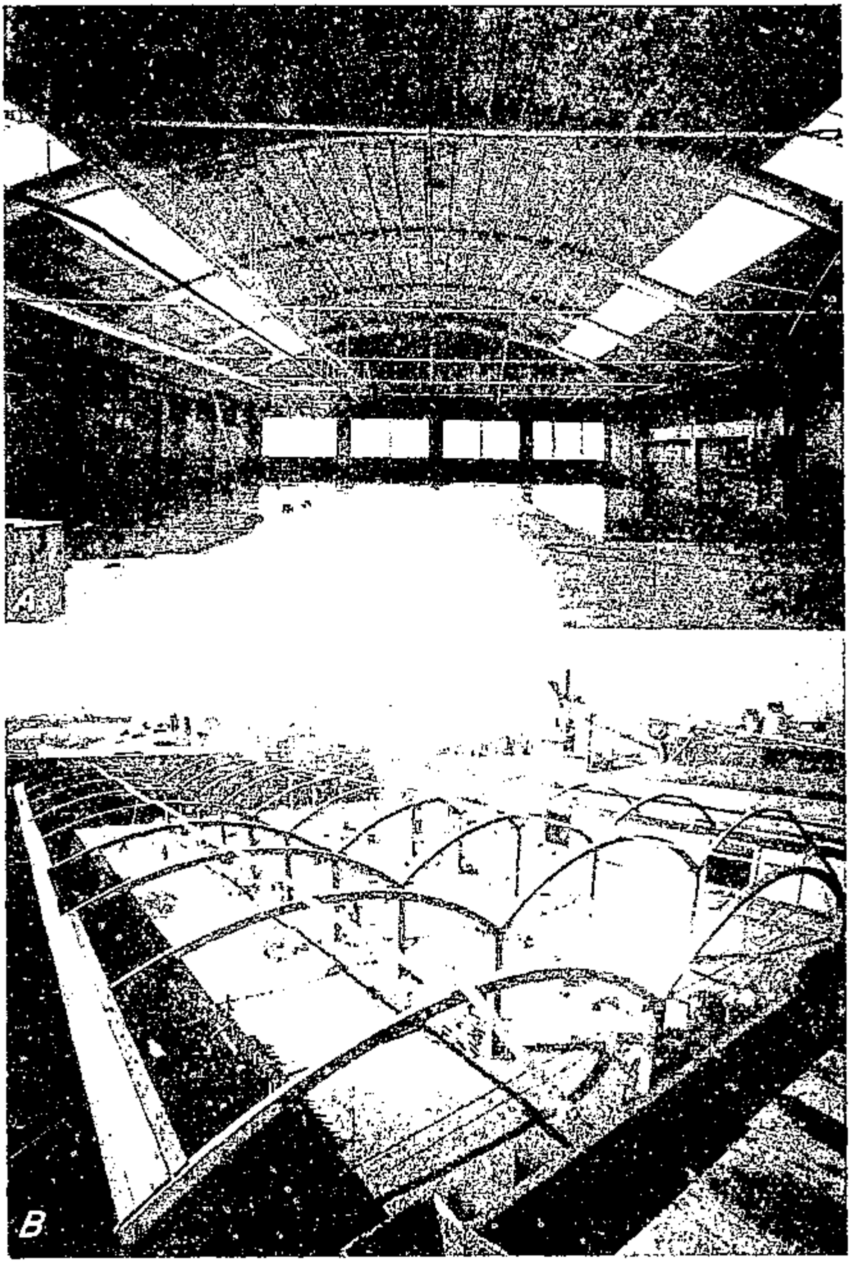

FIGURE 1.—*A*, Glued laminated tied arches, single span, Beverly Hills, Calif.; *B*, laminated tied arches, multiple span, for warehouse at Los Angeles, Calif.

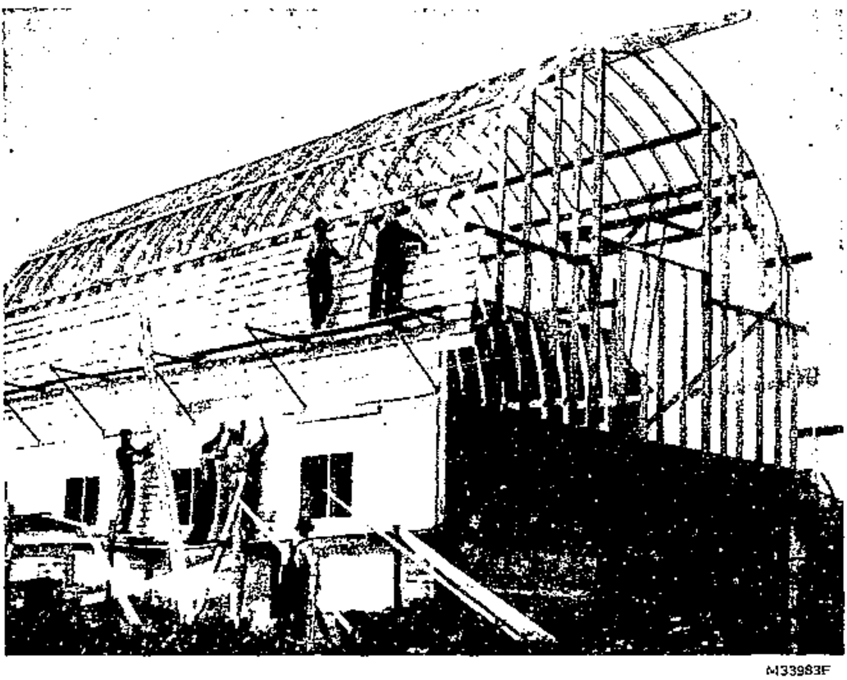

FIGURE 5.—Laminated barn rafters (1⅝ by 5½ inches in cross section) continuous from foundation to peak. Spacing of rafters, 2 feet.

Illustrative of the large sizes and exacting uses possible with glued laminated construction are the dredge spud pictured in figure 11, *A*, and the radar mast in figure 11, *B*. A number of such spuds, 30 by 30 inches in cross section and 85 feet long, have had extensive use in dredging work on the Columbia River. Illustrative also of large size and exacting use are the 80-foot beams supporting the roof of a dye house in Portland, Oreg. This somewhat unusual application of simple beams was dictated by the severe atmospheric conditions within the building. The highly humid, acid atmosphere precluded the use of steel girders and trusses, or even of timber trusses with steel bolts or connectors, because of the certainty of rapid corrosion. Thus a wood beam glued with highly resistant resorcinol glue provided a practical solution to the problem.

Mine guides laminated with the grain of part of the laminations at an angle to the axis of the guide to provide greater wear resistance have seen service in experimental installations. Laminated spars and spar flanges for wing spars of trainer and glider aircraft were used in large numbers during World War II. A laminated airplane propeller is shown in figure 12, *A*. Laminated cross arms (fig. 12, *B*) for electric power lines have been used to some extent.

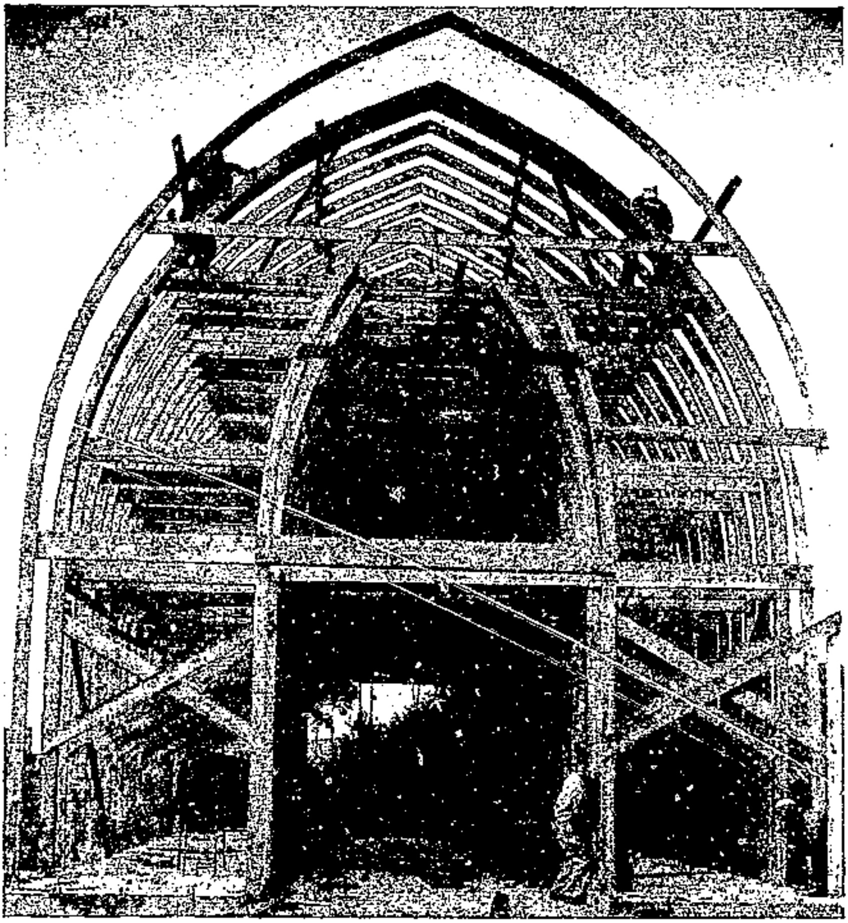

FIGURE 6.—Corn crib in which laminated rafters are used.

PURPOSE AND SCOPE

This publication is intended primarily as a guide to the fabrication and design of glued laminated members of engineering structures, such as beams, arch ribs, and truss parts, although the fabrication principles set forth are applicable to glued laminated articles of all types and sizes. Part I describes the properties and use characteristics of glues suitable for laminating structural wood products, the selection of the proper glue for the intended service, and the most common procedures for the laminating operation. Part II presents principles of design of laminated structural members. No attempt is made to present methods of structural analysis except where design details peculiar to wood or laminated wood structures need discussion for completeness.

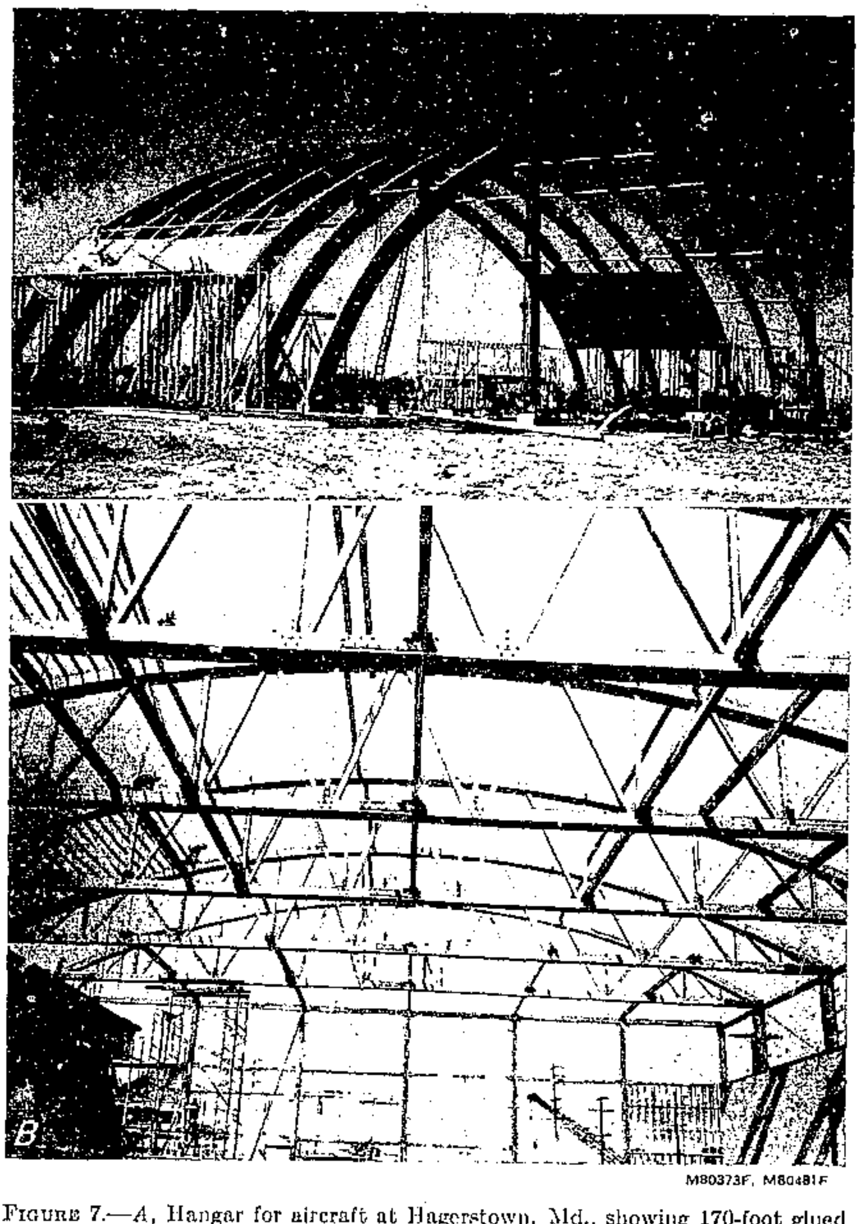

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FIGURE 7.—*A*, Hangar for aircraft at Hagerstown, Md., showing 170-foot glued laminated arches in place; *B*, bowstring trusses of 118-foot span, with glued laminated upper and lower chords, for sound stage of motion-picture set at Hollywood, Calif. Side- and end-wall posts also of glued laminated construction.

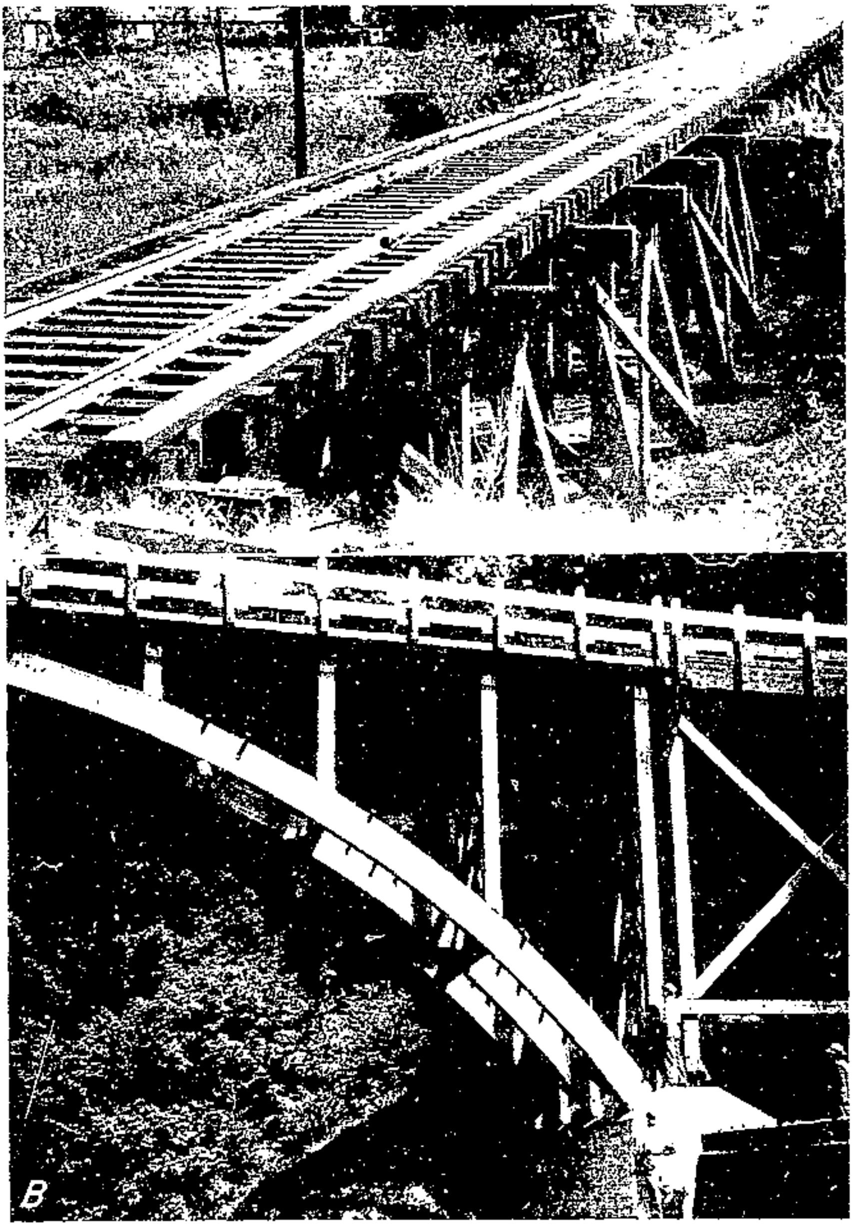

FIGURE 8.—*A*, Railway trestle of laminated southern yellow pine timbers; stringers, posts, and caps glued with intermediate-temperature-setting phenol-resorcinol resin and pressure-treated with creosote. *B*, Loon Lake bridge, in Oregon, supported by four 103-foot-span glued laminated arches; inner members 11 by 24½ inches in cross section, outer members 9 by 21½ inches in cross section; members glued with phenol-resorcinol, laminations pressure treated with Wolman salts before gluing.

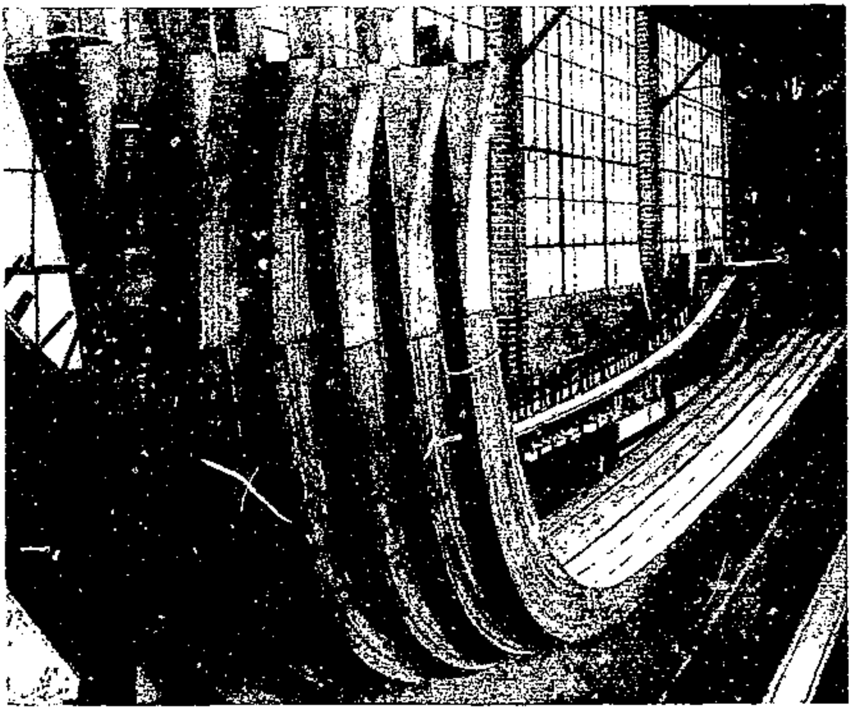

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FIGURE 9.—Glued laminated keel-stem assembly for boats.

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FIGURE 10.—Laminated 28-foot white oak ship planking glued with intermediate-temperature-setting phenol-resorcinol resin. Individual laminations ¾ inch thick.

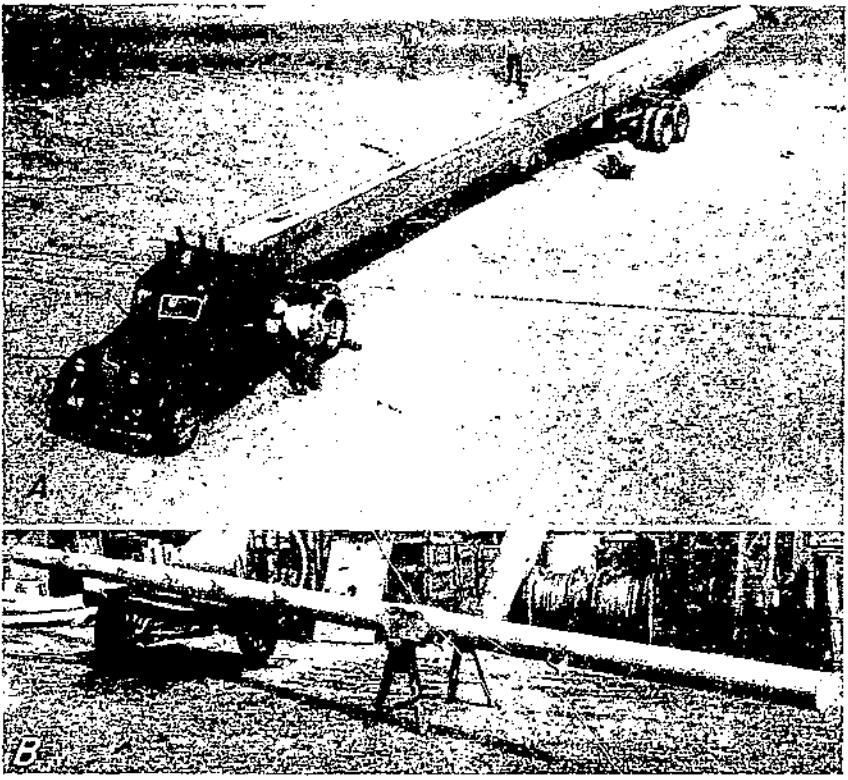

FIGURE 11.—*A*, Glued laminated dredge spud, 30 by 30 inches in cross section, and 85 feet long; *B*, laminated radar mast [illegible] inches in diameter, 56 feet long.

All design recommendations contained herein are dependent upon the preparation of laminations and the selection of glue and curing techniques in accordance with accepted fabrication procedures that assure adequate glue bonds. The provisions of this publication apply to any species of wood, but are limited to laminated members that are prepared from lumber seasoned in a thickness small enough to assure uniform drying without seasoning degrade.

Some fabricators have proposed the use of structural members consisting of sheets of plywood glued together. Members so fabricated contain cross bands and thus do not come within the scope of this publication. In such construction, it is impossible to have the direction of grain coincide with that of the principal stress in more than a part of the volume of the member. Plywood can be used effectively, however, for the webs of beams, girders, and columns having solid or laminated wood flanges.

There are innumerable combinations of features that are important in laminating, such as wood of different species and densities, types of end joints and their placement in the assembly, sizes of knots and their location in the length and width of a lamination, and the position of the lamination in the assembly. It is obviously impractical to

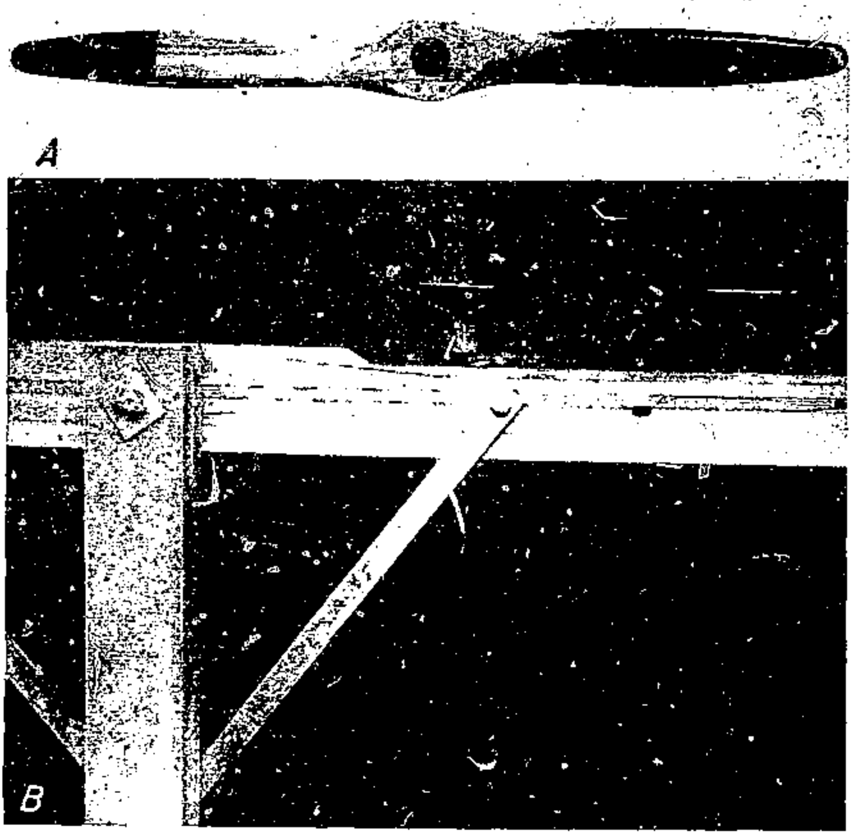

FIGURE 12.—*A*, Laminated-wood fixed-pitch propeller; *B*, laminated cross arm of Douglas-fir glued with intermediate-temperature-setting phenol-resorcinol resin.

determine by test the effects of all combinations of variables. In setting up recommended practices, it has therefore been necessary to assume that findings from tests on a few species and on a few of the combinations of variables are generally applicable. Furthermore, some features of design and construction are recommended that have not been studied experimentally. In such instances, the requirements are based on estimates, judgment, and such evidence from other tests as appears to be applicable.

PART I. FABRICATION

PERFORMANCE REQUIRED OF GLUE JOINTS IN LAMINATED CONSTRUCTION

The glues in laminated wood products must have sufficient original bonding strength and durability to enable the glued member to perform as a structural unit throughout its service life. The service life of wood is usually determined by its resistance to decay and to other causes of deterioration. Although the glue bond of a laminated product must be equally resistant to deterioration, any superior resistance cannot be expected to extent the normal service life of the wood. Glues used for bonding must not damage or weaken the wood, and they should permit machining of the product without serious damage to surfacing equipment.

Glued Laminated Products for Service Under Normally Dry Conditions

Glued laminated wood used either in the construction of buildings or in equipment for use inside of buildings is usually protected from exposure to moisture so that there is little danger of its deterioration from decay or similar hazards. Under such conditions, the mechanical strength of the wood and the glue joints determine the useful life of the product.

A glue should be as durable as the wood in the member to be suitable for use in permanent structures, and in most cases its bonding strength must be as great as that of the wood in shear parallel to the grain and in tension across the grain. Some ordinarily dry exposures may involve temporary high-humidity conditions. When the moisture content of laminated wood is temporarily raised higher than about 20 percent, bacteria, molds, or other decay organisms can cause deterioration of glues containing either protein or starch. It is desirable, therefore, that such glues be treated with preservatives to develop some degree of resistance to the organisms. Under some exposure conditions the glue must also be durable to heat.

Glued Laminated Products for Service Under Moist or Wet Conditions, Including Exterior Exposure

Laminated products used under exterior exposure conditions, such as bridges, boat framing, and implement parts, are subject to wide variations in temperature, to drying and wetting, and even to soaking. Generally, wood of high natural durability, or wood that has received preservative treatment, is used for laminating such products, and the strength and durability of the glue bonds must equal that of the wood. The glue, then, must possess high resistance to water, heat, molds, fungi, and sometimes to chemicals.

PROPERTIES AND USE CHARACTERISTICS OF WOODWORKING GLUES

Prior to the development of synthetic resins, the glues (*8, 27*)[3] most used in woodworking included the animal, vegetable-starch, casein, vegetable-protein, and blood-albumin types. In recent years, however, an increasing number of synthetic-resin glues have become available (*9*). Their use has resulted in improved performance of many glued wood products and has facilitated the adaptation of glued products to new uses. Plywood for exterior uses, laminated wood for bridge timbers, ship keels, and other members for use under severe service conditions are among those products.

Resin glues in most common use at present are the urea-formaldehyde and phenol-formaldehyde glues. Melamine and resorcinol-resin glues are among the latest developments, and the use of resorcinol resins and phenol-resorcinol combinations is rapidly increasing, particularly for laminating. To a limited extent, emulsified vinyl-ester resins are finding specialized use as woodworking glues. A number of special synthetic-resin glues have also been developed for the bonding of wood and wood products to metal, plastics, and other materials.

With the exception of the vinyl-ester resins, the synthetic-resin glues that have been used for bonding wood to wood are classified as thermosetting; that is, the cured glues do not soften appreciably when exposed to temperatures that are higher than the original setting temperature. In general, any thermosetting glue can be made to harden or cure more rapidly by raising the curing temperature and thus decreasing the length of time required under pressure. Thermoplastic resins, on the other hand, must first be heated to the point where they flow and then usually be cooled under pressure. Subsequent heating above the softening range will weaken them and permit joints to open. Because of their tendency to flow at elevated temperatures and to creep under sustained load, resins of this type are not recommended for laminated structural wood members.

Thermosetting resin glues may be classified according to the temperature required to cure them in a reasonable length of time.

Glue classification:	*Required temperature for satisfactory curing within practical time limits*
Hot-setting	Require higher temperatures than those commonly attained in heated chambers, for which the maximum is about 210 ° F.
Intermediate-temperature-setting.	Require heating in excess of normal room temperatures (about 65° to 80° F.), but do not require temperatures above 210°, the maximum that can ordinarily be attained in heated chambers.
Room-temperature-setting.	Require no heating above normal room temperatures (about 65° to 80° F.), but do not cure satisfactorily at lower temperatures.
Cold-setting [4]	Set or cure below normal workroom temperatures (minimum about 65° F.), and some may set satisfactorily at temperatures as low as 32°.

[3] Italic figures in parentheses refer to literature cited, page 145.

[4] This term is often misused in that certain glues are referred to as cold-setting that actually require at least 70° F. for satisfactory cure.

This classification is made merely for convenience in discussing the glues and does not imply that every glue represented as belonging to a certain class necessarily cures at every temperature within the range given for the class. It has been established that an adhesive may require different curing temperatures when used with different species for the same type of construction. Therefore, certain glues may fall under one classification when used with some species and under another when used with other species. Also, when different times for curing are allowed, the temperature requirements may vary from the range of one class to that of another.

Since blood-albumin, vegetable-protein, vegetable-starch, and animal glues are not suitable for the gluing of laminated structural members, they are not discussed in this bulletin.

Casein Glues

Casein glue is classed as water-resistant because of its relatively high resistance to moisture, compared with that of vegetable and animal glues. Its basic constituent is dried casein, which, combined with alkaline chemicals—usually lime and one or more sodium salts—is water-soluble. Prepared casein glue comes in powder form, and, when mixed with water in the correct proportions, is ready for use. It sets as a result of chemical reaction and of loss of moisture to wood and air. Well-made casein glue joints will develop the full strength of the wood, especially in softwood species (*27*), and will retain a large part of their strength even when submerged in water for a few days.

In laboratory tests of plywood continuously soaked in water, however, casein glue joints dropped in strength and ultimately failed completely. Casein glue (unpreserved) performed well in all tests where protection from high humidity or direct wetting was afforded. Under outdoor conditions, however, or where high humidities, either continuous or intermittent, were involved, casein glue joints failed. Casein glue containing preservative showed greater resistance to high humidities than unpreserved casein, but the preservative did not prevent destruction of the glue bonds under damp conditions. Consequently, casein glue is not considered suitable for laminated members intended for exterior use or for interior use where the moisture content of the wood may exceed about 20 percent for repeated or prolonged periods.

Casein glue joints have demonstrated good resistance to dry heat. Results of test exposures to temperatures as high as 158° F. for periods up to 4 years have indicated that the glue bonds are about as resistant as the wood to this type of exposure. Temperatures that char and burn wood will cause decomposition of casein glue. Charred wood exposed to fire, however, conducts heat to its interior very slowly, so that softening of casein glue joints takes place only next to the burning wood.

Mechanical spreaders are required for best control of the spread and uniformity of application of casein glue, although it can be spread on small areas by brush or serrated paddle. The glue spread required depends in part upon the type of construction, species of wood, and length of assembly period. A spread of 60 to 90 pounds of wet glue per 1,000 square feet of joint area is usually adequate when 1 contact area of the joints is coated (single spreading), and of 75 to 110 pounds when both contact areas are coated (double spreading). The maximum permissible closed-assembly time for casein glue is usually about 30 minutes at 70° F. Assembly periods may vary somewhat, depending mainly upon the temperature of the room and wood, the moisture content of the wood, the remaining working life of the glue, and whether spreading is single or double. Higher temperatures, extremely dry wood, and species of wood that readily absorb moisture will reduce assembly time. Lower temperatures, moisture content in the upper permissible range (15 to 18 percent), double spreading, and freshly mixed glue will permit the longest assembly periods. The glue must still wet the wood and be sufficiently plastic to flow freely when the assembly is put under pressure.

Casein glue will set at temperatures almost as low as the freezing point of water; but to develop strong joints at such temperatures its setting requires a period that varies from several days to several weeks, according to the species glued and the moisture content of the wood. The wet strength developed at low temperatures may never be so good as that developed at room temperatures. A pressing period of 4 hours at 70° F. is considered the minimum for straight members, and for curved members a somewhat longer period is desirable.

Gluing pressures of 100 to 200 pounds per square inch are satisfactory for low-density hardwoods and softwood species, such as Douglas-fir and southern yellow pine. Pressures of 150 to 250 pounds are recommended for species of higher densities. Glue lines produced with these pressures on well-surfaced laminations are relatively thin and strong. However, when thin glue lines of good strength can be produced uniformly with pressures below the foregoing ranges, such pressure will be adequate. Thick glue lines indicate low gluing pressure and usually are weaker. After removal of pressure, a conditioning period of about a week at room temperature is required for development of maximum joint strength.

Casein glue will produce adequate bonds with wood that has a moisture content within the range of about 2 to 18 percent. A range of 6 to 12 percent, however, is usually preferred, because it approximates the moisture content of the glued member in service. It is also desirable that all laminations for one assembly be of approximately the same moisture content (allowable differences between boards up to 5 percentage points) to avoid unequal shrinking or swelling as the moisture content equalizes in service.

Casein glue, in general, has a storage life of a year or more when kept dry. Its working life varies with the different formulations, but is usually at least 5 hours at 70° to 75° F.

To assure high quality, casein glue should meet the requirements of of Federal Specification C-G-456,[5] and mold-resistant casein glue should pass the performance tests of United States Air Force Specification No. 14122.[6]

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[5] Obtainable from the Superintendent of Documents, Government Printing Office, Washington, D. C.

[6] Obtainable from the Air Materiel Command, U. S. Air Force, Wright-Patterson Air Force Base, Dayton, Ohio.

Urea-Formaldehyde Resin Glues

Urea resins are available both as dry powders and in water as solid suspensions that ordinarily form 60 to 70 percent of the mixture by weight. The powder forms are prepared for use by mixing with water to produce suspensions of approximately these concentrations. The powdered glues usually contain some filler, for which walnut-shell flour and wood flour are most commonly used, and mixing directions for the liquid glues normally call for the addition of some filler to improve their working properties. For certain types of plywood, urea resins are extended with rye or wheat flour, primarily to lower cost, but the resistance of the glue to water and to attack by micro-organisms is thereby reduced. Although high joint strengths can be obtained in hot-press plywood with extended ureas, the value of extended glues for laminating lumber has not been established.

Some urea-resin glues are formulated to set at room temperature, with a catalyst (sometimes called hardener) either incorporated with the resin powder or added during mixing. Other formulations serve either for room-temperature-setting or hot-setting operation, depending upon the amount and type of catalyst. In general, powdered urea-resin glues with a separate catalyst have longer storage lives than do the liquid resins or the powdered urea resins in which catalysts are incorporated. The storage life of powdered urea resins with a catalyst incorporated is usually at least 1 year when kept dry in closed containers at room temperature. Those having a separate catalyst generally are usable somewhat longer. The storage life of liquid urea resins is usually from 2 to 3 months at 70° to 75° F.

All urea-resin glues are acid in reaction, and the room-temperature-setting glues are more strongly acid than the hot-setting glues. Current specifications limit the acidity of these glues. Since hot-setting glues have found little application in laminating lumber for structural use, the discussion in the three following paragraphs is mainly confined to room-temperature-setting urea resins, and the statements do not necessarily apply to hot-setting ureas.

Urea-resin glue joints in most woods are highly water-resistant at ordinary temperatures. Tests on birch plywood have shown that glue joints of this type retain reasonably good strength values after several years of continuous soaking in cold water. These glues, however, are low in durability under conditions involving high temperatures, and especially combinations of high temperatures and high relative humidities. Exposures of birch plywood have shown that limited weakening of urea-resin glue joints occurs under dry conditions at 80° F. and more rapid weakening at 160°, and that the rate of strength loss is accelerated at high relative humidities. Delamination usually occurs rapidly in boiling water; and when exposed to fire, urea-resin-bonded joints delaminate as high temperatures char the adjacent wood.

Although highly resistant to continuous soaking when used to glue yellow birch in the form of veneer, room-temperature-setting urea resins have performed unsatisfactorily in laboratory water-exposure tests when used to glue certain other woods, including white oak and Douglas-fir in the form of heavy laminations. These results are confirmed by reports of partial delamination of experimental white oak laminated ship keels within 9 months when exposed to salt water.

Laminated red oak truck sills, glued with urea resins and exposed to the weather, also developed considerable delamination during a period of 12 months.

In low-density species, well-made urea-resin glue joints can be expected to give good performance for many years under normal humidity and temperature conditions. In one exposure test, urea glue joints in laminated Douglas-fir and southern yellow pine beams exposed under a roof in an open shed in Wisconsin, showed high joint strength and high wood failures after 8 years.

Some urea-resin glues have been formulated primarily to improve the resistance of glue joints to high temperatures or to a combination of high temperatures and moisture. These glues may be combinations of urea resin with melamine resin or resorcinol and are referred to as "fortified" or "modified." These special urea-resin glues appear to be somewhat more resistant to deterioration at high temperatures than either the room-temperature-setting or hot-setting urea resins, and exposure tests have indicated that they offer some improvement in their resistance to high humidity.

The working life of the mixed glue depends upon the temperature of the glue and varies with the different formulations, but it is usually within the range of 2 to 6 hours at ordinary room temperatures. To increase the working life of these glues during hot weather, the glue container may be kept in cold water to maintain the temperature of the glue at about 70° F.

The quantity of glue required may vary somewhat, depending on the species glued and the type of construction, but it should usually be within the range of 45 to 65 pounds per 1,000 square feet of joint area. Rubber-roll spreaders are the most satisfactory means for applying the glue. The maximum permissible assembly time is usually about 20 minutes at 70° F., but this will vary according to the temperature of the room and wood, the moisture content of the wood, and the remaining working life of the glue. When lumber is laminated with urea resin, best results are obtained with the wood at a moisture content between 8 and 12 percent, but strong bonds can be obtained between 7 and 15 percent. Urea glues often behave unsatisfactorily on wood that is below 6 percent in moisture content. Pressure requirements are in general the same as for casein glues, with 100 to 200 pounds per square inch recommended for most softwood species and 150 to 250 pounds for hardwood species.

Urea-resin glues formulated for hot-pressing generally set at temperatures within the range of 220° to 260° F. The rate of setting of urea resins that cure at room temperatures is reasonably rapid at a temperature of 75° (*4*). At this temperature, the pressure can usually be removed after 4 hours when gluing thin straight pieces, and after 5 to 8 hours when gluing heavy or curved pieces. At higher temperatures, the setting is appreciably accelerated; at lower temperatures, the setting is retarded, and there is little or no development of water resistance. Consequently, setting temperatures below 70° are not recommended for urea-resin glues.

At room temperatures, a conditioning period of 1 week is usually required for development of maximum joint strength and, particularly, of maximum wet strength.

Federal Specification C-G-496 sets forth requirements for high-quality urea-resin glues.

Phenol-Formaldehyde Resin Glues

The phenol-formaldehyde glues may be classified, on the basis of setting-temperature requirements, as hot-setting and intermediate-temperature-setting glues. Phenol-resin glues are formed by the reaction of phenol or cresol with formaldehyde. For the production of woodworking glues, the reaction is stopped at an intermediate stage, and the product is then marketed in the forms of a film with paper base, a dry powder, or a suspension of resin in water-alcohol mixtures or other solvents. After the resin in either film or liquid form has been applied to the surfaces to be glued, the setting reaction is completed by the application of heat.

As a class, phenol-resin glue joints are extremely durable over a wide range of moisture and temperature conditions. They are not attacked by micro-organisms and are highly durable under such adverse conditions as continuous soaking in fresh or salt water, continuous exposure at high humidity, cyclic exposures involving wetting and drying, and exposure to high temperature at low and at high humidities. In exposures to fire, phenol-resin glue bonds are fully as resistant to charring and deterioration as the wood. The glues do not afford an appreciable protection to the adjacent wood, however, and for this reason wood products glued with phenol resins should be considered no more fire-, decay-, or insect-resistant than unglued wood of the same species. Thoroughly cured phenol-resin glue joints also are highly resistant to the action of various solvents, oils, wood preservatives, and fire-retardant chemicals. In general, hot-press phenol-resin glue joints properly glued and cured are as durable as the wood.

HOT-SETTING AND ACID-CATALYZED PHENOL-RESIN GLUES

Most hot-setting phenol-resin glues are alkaline in reaction and are available in film, powder, or liquid forms. When the glue is spread as a liquid, pressing may be done immediately, or, in some cases, delayed several days. Platen temperatures for gluing with hot-setting phenol-resin glues of either film or liquid form in the usual hot-press operation are normally from 240° to 320° F. Due to the high-curing-temperature requirement, these glues are not well adapted for laminating lumber. They have been used, however, for nearly 15 years in this country for producing highly water-resistant (exterior-type) hot pressed plywood, and the excellent performance of such glue joints under exposures involving moisture and heat indicates what may be expected of phenolic-type glues.

Some phenol-resin glues have been formulated to set at intermediate to low temperatures by use of acid catalysts. Their use, however, has not been nearly so extensive as the hot-press phenols.

Weathering tests and cyclic soaking-drying tests on white oak glued with highly acid intermediate-temperature-setting phenols, cured at elevated temperatures, indicate that the glue damages the wood adjacent to the glue lines, causing reduced strength and shallow wood failures. Acid damage has also been observed in yellow birch plywood and hard maple block joints. Recently, acid-catalyzed phenols have been offered that are supposed to be an improvement over older formulations of these glues, but not much information is available on their durability. Highly alkaline phenol-resin glues have not been offered for laminating purposes.

INTERMEDIATE-TEMPERATURE-SETTING PHENOL-RESORCINOL RESIN GLUES

Several phenol-resorcinol resin combinations set at substantially lower temperatures than those required for hot-setting phenols. These glues are generally made by combining resorcinol resin with phenol resin in various proportions and are marketed in liquid form, usually with a separate hardener that is mixed with the resin prior to use. A filler, commonly walnut-shell flour, often is added with the hardener. Most of these modified glues are nearly neutral or slightly alkaline in reaction. They cure at temperatures of about 80° to 200° F., depending on the particular formulation, the time allowed for setting, the species of wood glued, and the type of construction.

The durability of well-made phenol-resorcinol resin glue joints, based on 8 years of experience, appears to be essentially equal to that of hot-press phenol-resin glue joints.

Glues of the phenol-resorcinol combination type have a relatively short storage life, often only 2 to 6 months, but sometimes as much as a year, at ordinary room temperature, depending on their specific formulation, but cold storage (30° to 50° F.) prolongs their useful life. They should be kept in airtight containers to avoid loss of solvent.

The usual working life of these glues is between 2 and 8 hours at 75° F. Maximum assembly periods vary considerably among them, but 1 to 2 hours of closed assembly at 75° F. is usual. The amount of glue spread required depends on the species of wood used and the type of construction. When laminating heavy members of dense, porous woods, such as oak, spreads of about 60 pounds per 1,000 square feet of glue-joint area are usually satisfactory. With lower-density species, such as Douglas-fir, a glue spread of 40 to 50 pounds is usually adequate. The use of rubber-roll spreaders is recommended. These glues satisfactorily bond wood at moisture content values ranging from 6 to 17 percent, and the preferable moisture content within this range would be determined by the service conditions to which the laminated member would be exposed.

The curing requirements for these glues vary with the species of wood used, the type of material glued, and the service conditions to which the product may be exposed. For such severe uses as ship timbers, a curing period of as much as 10 hours at a temperature as high as 190° F. at the innermost glue line is sometimes necessary for white oak; and a 20-hour period at 110° for southern yellow pine and a 20-hour period at 80° for Douglas-fir are adequate with some of these glues. A somewhat higher temperature or longer curing time may be necessary for curved members of southern yellow pine and Douglas-fir, and in no case should the clamps be removed until the glue squeeze-out is set hard. Gluing pressure of 100 to 200 pounds per square inch is adequate for low-density hardwoods and most softwood species. When gluing dense woods, pressures of 150 to 250 pounds are generally recommended.

If high temperatures, such as 190° F. or greater, are used in curing, conditioning after removal of pressure need not extend beyond complete cooling of the members. When temperatures only slightly above room temperature are used, conditioning for approximately 1 week is recommended.

Military Specification MIL-A-397 sets forth requirements for high-quality intermediate-temperature-setting phenol and phenol-resorcinol resin glues.

Resorcinol-Formaldehyde Resin Glues

Resorcinol-formaldehyde resin glues have a combination of the moderate-temperature curing requirements of the urea resins and the high-quality and durability characteristics of the phenol resins. These resins are produced by the reaction of resorcinol with formaldehyde and are marketed as liquids consisting of partly polymerized resin in a water-alcohol solution. The solids content of the solution is usually about 60 percent by weight. The glue is dark red and makes dark joints when set. A hardener, usually paraformaldehyde but sometimes formalin, and a filler, commonly walnut-shell flour, are mixed with the resin prior to use. In most cases, a mixture of hardener and filler is furnished by the manufacturer. Both resin and hardener may be stored for a year or more at ordinary room temperatures when kept in airtight containers.

The resorcinol glues are of rather recent development, and extended service records on their performance are not available. However, test data covering a period of about 8 years for some of them indicate that, when properly cured, they compare favorably with phenols in resistance to moisture, high temperatures, chemicals, and micro-organisms.

Like the intermediate-temperature-setting phenol-resorcinols, these glues produce a satisfactory bond on wood at a moisture content ranging from 6 to 17 percent, but the preferable moisture content within this range is that expected for the laminated member under the service conditions to which it will be exposed.

The working life of resorcinol adhesives varies for the different glues, but is usually from 2 to 5 hours at 70° to 75° F. and is considerably reduced as the temperature increases. Assembly periods also vary for the different glues, according to the temperature and to the type of assembly, whether open or closed. At 75°, with the glue applied to both surfaces to be joined, open-assembly periods of 15 to 30 minutes or closed-assembly periods of 1 to 2 hours are usually permissible. When only 1 joining surface is spread with glue, the permissible assembly periods are considerably reduced, and approximately 15 minutes in open assembly or about 50 minutes in closed assembly is satisfactory with some glues; but with certain resorcinol glues the maximum permissible open-assembly period may be as short as 12 minutes. Very short closed-assembly periods, less than 10 minutes, often are not so satisfactory as somewhat longer ones; and for very exacting uses, such as laminating oak ship frames and keels, manufacturers often recommend a minimum of 10 to 25 minutes. Glue spreads and pressure requirements are similar to those recommended for intermediate-temperature-setting phenol-resorcinol resin glues, although somewhat higher spreads and lower pressures are sometimes recommended by the manufacturers.

Resorcinol glues are very nearly neutral in reaction. They will cure at temperatures of 70° to 80° F.; and when used with soft-textured woods, temperatures as low as 40° develop joint strengths equal to the strength of the wood when relatively long pressing periods (several days to several weeks) are used. Temperatures higher than room temperatures are recommended, however, when gluing heavy laminated members of such dense species as white oak for use under severe exposures. Tests on laminated members for ship timbers and other exterior uses show that, for several of the resorcinol glues, curing for as long as 10 hours at a glue-line temperature of 140° with white oak and 10 hours at 80° with southern yellow pine and Douglas-fir, with at least 1 week of additional conditioning, produces glue joints that are highly resistant to delamination under severe exposure conditions.

In light constructions intended for less severe exposures where a curing temperature of 75° F. would be adequate, pressure should be maintained for 4 to 8 hours. The full joint strength is not, however, developed in this period, and a conditioning period of 3 to 6 days should be allowed before the joints are highly stressed.

Military Specification MIL–A–397 sets forth the requirements for high-quality resorcinol-resin glues.

Melamine-Formaldehyde Resin Glues

Melamine-formaldehyde resin glues are produced by the reaction of melamine and formaldehyde and are available either as hot-setting or intermediate-temperature-setting types. Most of the melamine-resin glues are marketed as powders and are prepared for use by mixing with water. Sometimes a hardener and a filler, usually walnut-shell flour, are added. The melamine resins are almost white, but the addition of filler usually gives them some color. Concentrations of the glue mixtures when ready for use are generally within the range of 60 to 70 percent of solids by weight, or about the same as for most other resin glues when ready for spreading.

The melamine-resin glues are of relatively recent development, but test data accumulated over the last 8 years indicate that the durability of their joints, when set at about 190° F., is similar to that of joints made with phenolic resins. Well-made melamine glue joints show excellent resistance to micro-organisms, weathering, high temperatures, high relative humidities, continuous soaking, cyclic soaking and drying, and to oils and most chemicals, including wood preservatives and fire retardants. Some intermediate-temperature-setting melamine resins have been formulated recently to set at lower temperatures by the use of acid catalysts. Test data show that the durability of these resins is somewhat inferior to that of melamine resins requiring higher curing temperatures.

With some exceptions, the use characteristics of melamine glues are similar to those of the phenol glues. When kept in closed containers under dry and cool conditions, the melamines usually have a storage life of 6 months to a year or more. The working life of these adhesives ranges from 2 to 36 hours at ordinary room temperatures, depending on the catalyst used with them. The moisture content of wood appears to be somewhat more critical with melamine than with phenolic-type glues, but satisfactory results are usually obtained within the range of 7 to 15 percent. Most of the melamine glues are not critical with respect to assembly periods, but where curved members are glued, clamping must be completed before the glue becomes too tacky to permit free slippage of the laminations. Glue-spread and pressure requirements are similar to those for phenol- and resorcinol-resin glues.

The melamine glues cure at about the same temperatures as the intermediate-temperature-setting phenol-resorcinols, although when used with softwoods, such as Douglas-fir and southern yellow pine, somewhat higher temperatures may be required for the melamines. To laminate white oak for exterior service with certain melamine resins, a cure of 10 hours at 190° F. has been found adequate. With southern yellow pine and Douglas-fir, a temperature of 140° for 10 hours is satisfactory.

Most melamine glues are difficult to remove from gluing equipment if water alone is used for cleaning. Cleaning of mixers and spreaders is readily facilitated, however, by use of dilute acetic acid. Soapsuds or 30-percent calcium chloride solution have also been recommended.

Military Specification MIL–A–397 sets forth the requirements for high-quality melamine-resin glues.

SELECTION OF GLUES FOR LAMINATING

The properties and use characteristics of various types of glue discussed in the preceding pages should serve as a guide to the user in his choice of adhesive for specific purposes. For convenient reference, the general use characteristics of the different types of glues are summarized in table 1. Certain types of glues may be used under any exposure for which wood is a suitable material, while other types are adequate only under limited exposure or where protection from the elements is provided.

For laminated members that are protected from appreciable amounts of moisture and high relative humidity, casein or urea-resin glues might serve well. If the joints never become wet, the casein glue may prove to be more durable than the urea. Urea resins should not be used if exposures to temperatures appreciably higher than room temperatures are expected. As previously indicated, their long-time durability at ordinary temperatures and relative humidities has not been fully established—a fact that makes their suitability for permanent structures somewhat uncertain, especially if used with dense hardwoods. Where atmospheric conditions are such that the moisture content of the wood exceeds 20 percent, neither casein nor urea-resin glue is recommended.

For continuous immersion in water or intermittent wetting and drying, as outdoors or in buildings where high humidities are encountered for a considerable time, highly water-resistant resin adhesives, such as phenol-resorcinol, resorcinol, or melamine glues, should be used. Within this group, choice will depend on the type most readily available, storage life required, curing facilities, convenience of use, and cost.

Intermediate-temperature-setting phenol-resorcinols have a relatively short storage life at ordinary room temperatures and require considerable heat for curing. The resorcinols have long storage life and for many purposes, cure adequately at 70° to 80° F. The cost of the resorcinol glues is at present considerably higher than that of the phenol-resorcinols. The melamines have a reasonably long stor-

TABLE 1.—*Approximate use characteristics of laminating glues* [1]

Exposure and glue type	Storage life at 80° F.	Working life at 70° to 75° F.	Maximum permissible assembly time at 70° F.		Moisture content of wood	Conditioning period [2]	Setting characteristics		
			Open	Closed			Cold [3]	Room temperature	Intermediate temperature
	Months	*Hours*	*Minutes*	*Minutes*	*Percent*	*Days*			
Normal interior:									
Casein	12	5	15	30	2–18	5–7	Yes	Yes	Yes.
Urea, powdered, with catalyst	12	2–6	10	20	7–15	5–7	No	Yes	Yes.
Interior and exterior:									
Intermediate-temperature-setting phenol-resorcinol.	2 to 6	2–8	30–60	60–120	6–17	1–7	No	No [4]	Yes.
Resorcinol	12 or more	2–5	15–90	50–150	6–17	1–7	No [4]	Yes	Yes.
Melamine [5]	6 to 18	2–36	30–60	60–120	7–15	1–7	No	No	Yes.

[1] Laminating pressures of 100–250 p. s. i.

[2] Where glue is completely cured by heat before pressure is removed, cooling to room temperature is sufficient; where no heat is applied, a 5- to 7-day conditioning period is desirable.

[3] Cold: below normal workroom temperatures. Room temperature: 65° to 80° F. Intermediate temperature: 80° to 210°.

[4] Except with some low-density species.

[5] Includes glues both with and without separate catalyst.

age life and require about the same cure as some of the phenol-resorcinols, but they are not so convenient to use as resorcinols or some phenol-resorcinols because cleaning of gluing equipment is more difficult.

SELECTION AND PREPARATION OF LUMBER FOR LAMINATING

Lumber used in fabricating a laminated member must be properly selected and adequately prepared for gluing. It is essential to give attention to the intended use of the laminated product, the strength, durability, and gluing properties of the species, the dryness of the wood, and the quality of the machined surfaces to be glued. It is also necessary to consider defects that may impair the quality of the bond, interfere with bending laminations to the desired shape, or otherwise reduce the serviceability of the finished product. Sometimes it is necessary also to consider the appearance of the finished member when selecting the lumber.

SPECIES AND QUALITY

The gluability of various species of wood under favorable gluing conditions is shown in figure 13 (*3*, *27*). Block-shear test values show that glue joints of high strength, comparable to the shear strength of the wood, can be produced in most commercial species of wood with casein and synthetic-resin glues. Wood-failure values of approximately 100 percent can be obtained with most softwoods. Casein glue bonds fail to develop high wood-failure values on dense, strong hardwood species, while synthetic resins generally show moderately high values for these species. Glues, however, are generally chosen on the basis of their durability under service conditions.

Softwood species, principally southern yellow pine and Douglas-fir, have been used largely in the laminating of members such as arches, beams, and chords for trusses, because of the more favorable cost and availability of the lumber and the ability of these species to meet strength requirements. Boat timbers, on the other hand, are often made of white oak because it is durable under wet exposures. Other species can also be used when their mechanical and physical properties are suited to the purpose.

Severely curved parts of high-strength laminated members generally require clear and straight-grained wood, free of sizeable defects, in order that the laminations may be bent to the desired curvature without breaking. Defects such as large holes, knots, and decay reduce the effective glue-joint area. Surfaces containing pitch, cross grain, and knots do not glue so well as clear wood. Such material must be limited in accordance with the strength requirements of the product.

Sapwood is as durable as heartwood under continuously dry conditions. However, under conditions developing more than 20-percent moisture content, sapwood of even the durable species is readily susceptible to attack by wood-destroying fungi and often by insects. On the other hand, sapwood of most species used in laminating takes preservative treatment readily.

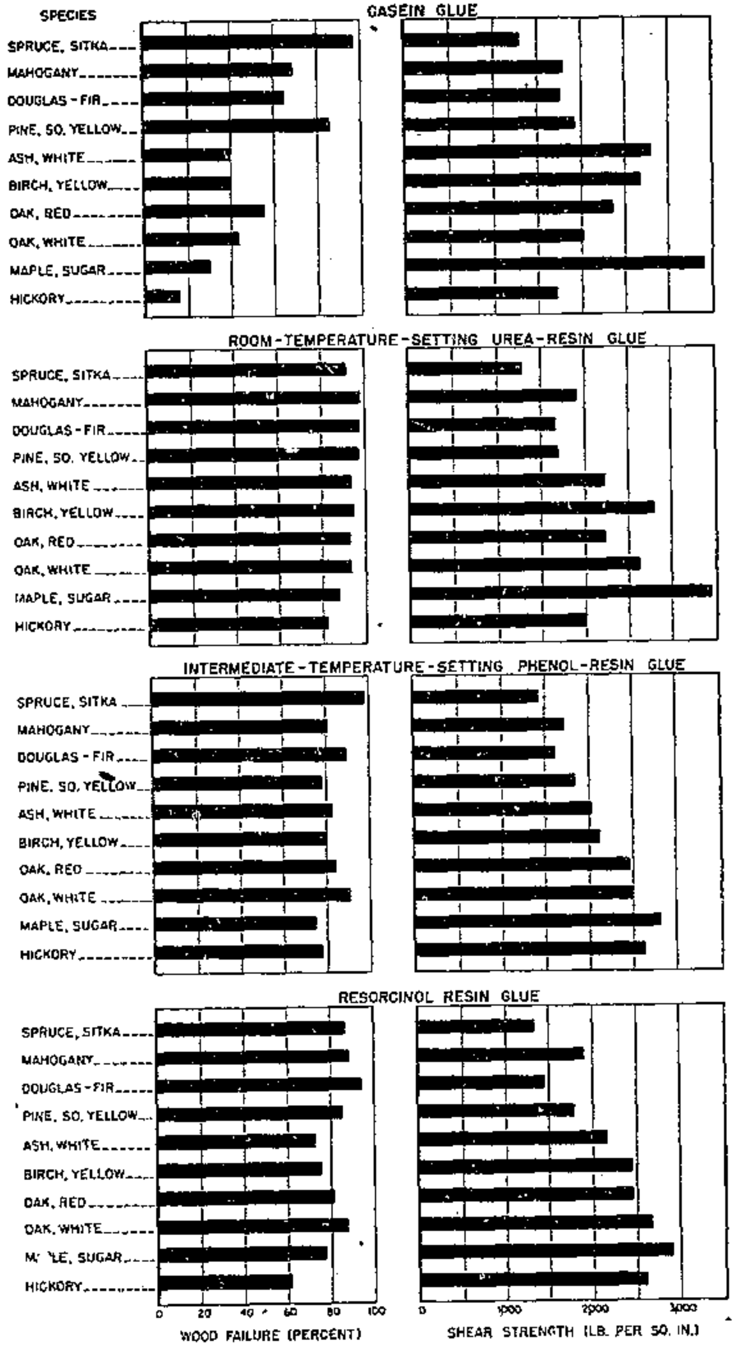

FIGURE 13.—Results of joint-strength tests for various woods glued with casein, urea resin, resorcinol resin, and intermediate-temperature phenol-resorcinol resin glues.

Seasoning and Moisture Content of Lumber

The moisture content of lumber at the time of gluing is of great importance in the fabrication of laminated products. The desirable moisture content in the lumber is that which will produce strong glue joints and, as nearly as practicable, approximate the average moisture content the laminated product will attain in service. All the laminating glues described in this report will produce strong bonds when the wood has a moisture content between 7 and 15 percent, and a few bond satisfactorily even when the moisture content is slightly above or below this range. Serious changes in moisture content after gluing will result in shrinking or swelling of the wood, and stresses may develop in both glue joint and wood that will cause checking in the wood or along the glue line.

In general, it is desirable to produce the laminated member at a slightly lower moisture content than that expected in service, and thereby avoid not only surface drying in use but a serious change in the entire member. Wood used in the interior of dry, heated buildings throughout the United States has been found generally to have a moisture content varying from 6 to 11 percent according to the season and location. The moisture content of wood in normally dry, unheated buildings is somewhat higher, probably from 8 to 14 percent, and in extreme cases may be higher.

A moisture content level of between 8 and 10 percent at the time of gluing is considered satisfactory for laminated members intended for normal interior use. Members produced at a moisture content of 12 to 15 percent will dry out to some extent in such service, and some surface checking can be expected. In moist, wet, and exterior exposures, laminated members may develop higher moisture content values than the maximum at which good glue bonds can be produced. Consequently, lumber with a moisture content range of 12 to 15 percent is desirable for such gluing. Members glued at 8 to 10 percent will show an appreciable increase in moisture content if used in exterior service.

The uniformity of moisture content between the laminations of any one assembly, and throughout the cross section of each board, is also important. If adjacent laminations differ widely in moisture content at the time of gluing, subsequent moisture equalization will cause them to swell or shrink unequally, with consequent development of stresses in the glue line, possible separation of laminations, and distortion of the finished member. A range in percent of moisture content of not more than 5 (for example, 6 to 11 percent or 10 to 15 per cent) between laminations in a single assembly is recommended. Stresses will also be created if the interior part of any one board differs greatly in moisture content from the outer part or shell (fig. 14), and it is recommended that such differences in percent not exceed 5.

The most practical method of seasoning lumber to these moisture-content requirements is by kiln drying, which lends itself to control of humidity and the final dryness of the stock (*24*). Air-dried lumber is equally suitable when it meets these limitations on moisture content (*16*).

The moisture content of the lumber should be determined before machining operations are begun, by selecting sufficient random samples to insure that the entire lot of stock meets the moisture content

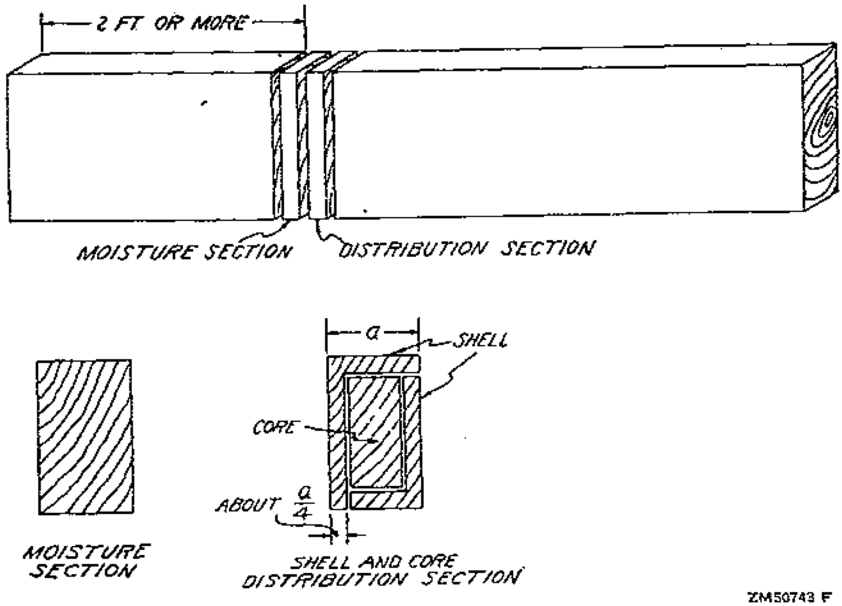

FIGURE 14.—Methods of cutting sections from lumber for moisture-content and moisture-distribution determinations.

requirements. Determinations should be made of the moisture content of individual boards and for uniformity between the shell and core. Such determinations will normally have been made in connection with the kiln-drying operations, but a check should be made immediately prior to laminating.

The most accurate means of determining moisture content of untreated wood is by the oven-drying method. Electrical moisture meters (*2*), although less accurate, are very useful, since with them measurements can be made more rapidly than by oven methods, which require several hours. The resistance type of electrical moisture meter is generally limited in application to moisture content values ranging between 7 and 25 percent and cannot be used dependably on lumber dried below this range. These meters are useful for spot checking untreated lumber at the laminating operation, where their frequent use is recommended. The moisture content of lumber treated with preservative salts can usually be determined by oven drying, but special methods are required for lumber treated with oilborne preservatives.

Storage of Lumber

Since it is desirable to have lumber for laminating uniformly dry at the time of gluing, it is necessary that conditions of storage following drying be such that there will be no appreciable change in its moisture content (*17, 18*). Bulk piling affords additional protection to the lumber from moisture changes, except at the surfaces of the pile. If the dry lumber is to be stored for a long time, control of the humidity in the storage rooms is helpful. Ordinarily, it is satisfactory to keep the lumber well protected from the weather and to use it promptly.

If lumber is taken from unheated storage during cold weather, it is desirable to allow it to warm up to approximate room conditions before spreading glue on it. Gluing of cold lumber may seriously retard the curing of certain types of glues, especially room-temperature-setting ones. The time required for planing the lumber may not be sufficient to allow it to warm up enough.

Rough Surfacing

Preliminary rough surfacing of the lumber to be used for gluing, although not always necessary, helps to obtain uniform thickness of laminations in the final surfacing. The use of a rough planer is also sometimes desirable as a first step in the machining and sorting of lumber of variable thickness. In hardwoods, particularly, this operation will help to disclose natural and seasoning defects, aid in segregation of the wood according to grain, sapwood, and heartwood, and greatly facilitate the elimination of undesirable pieces. Rough planing reduces stock to an approximately uniform thickness that is an advantage in later ripping and resurfacing. In order to keep the lumber flat and to avoid unbalancing any seasoning stresses that may be in the lumber, rough planing should be done on both faces, with removal of an equal amount of wood from each. Double surfacers are convenient for this operation. Rough surfacing, or "blanking," of the lumber may be done at any time, even well in advance of the laminating, since resurfacing will be required before gluing.

Cutting Out Defects

The operation of cutting out defects involves crosscutting and ripping. This is often done at the sawmill, so that the finished boards can be used as graded without further cutting out of defects; for example, pine and fir lumber of relatively long lengths may be available in suitable grades. In other cases, as with most hardwoods, only short lengths can usually be cut from available lumber, and further cutting is necessary at the laminating plant to produce clear grades.

The layout and facilities at the plant will determine the sequence of the crosscutting and ripping operations to obtain stock of the required grade and to reduce it to the lengths and widths needed.

Selection for Grain

In the seasoning process, flat-grain or plain-sawed lumber shrinks more in width than vertical-grain or quarter-sawed lumber of equal size. The same relationship applies when changes in moisture content take place after the laminated product is placed in service. For example, a 10-inch-wide flat-grain board of white oak having a moisture content of 8 percent will swell about 0.35 inch when its moisture content is raised to 18 percent, while a similar vertical-grain board will swell only about 0.21 inch. This difference in expansion, which can result in severe stress on the glue line in a laminated member exposed to exterior conditions, can be minimized by segregating the stock into quarter-sawed and plain-sawed lots. Lumber with growth rings predominantly at an angle of 45° or more to the face of the board may be classified as quarter-sawed, and that with growth rings at an angle of less than 45° as plain-sawed. With dense hardwoods it is advantageous to keep these groups segregated in all subsequent operations and not to mix the two classes in any single laminated assembly. This segregation may be done at any time prior to edge- or end-joint gluing, or to final surfacing.

In softwood species the stresses due to shrinking and swelling are lower than in the dense hardwoods, and segregation for grain may not be necessary for most uses, including exterior service. Some surface coating is recommended to reduce the rate of moisture change, and thus the stresses that cause checking.

Laminating glues will bond plain-sawed and quarter-sawed lumber equally well, so that the segregation for grain in dense hardwood species is recommended primarily to reduce the subsequent development of stresses in members subject to severe moisture changes. In normally dry interior use, the moisture changes are usually too small to require segregation of grain.

Cutting Laminating Stock

In preparing stock for laminating, it is sometimes important that narrow pieces used to produce a lamination the full width of the member be edge glued to increase strength properties. Edge gluing is also important because open edge joints may induce further checking and splitting and constitute a decay hazard in damp or exterior service. Where the added strength is not required, edge gluing would not be necessary in members used under normally dry conditions.

When it is necessary that laminations be of one piece in width, and lumber of the required width is not available, the full width may be obtained by edge gluing strips or boards of the desired quality. In preparing lumber for edge gluing, proper machining of the edges is necessary to enable the production of joints of maximum strength. The machined edge should be square and straight to permit a tight fit of the wood surfaces. Certain types of tongue-and-groove joints have often been used to obtain lumber of a desired width. The advantage of the tongue-and-groove cutting is mainly in facilitating alinement, but these joints involve greater loss of material, require special equipment for their preparation, and usually offer less effective gluing surface than do plain joints.

Machining with a cutter head, either in a jointer or a molder, produces the best gluing surfaces. A disadvantage of edge jointers is the difficulty of obtaining a perfectly straight edge for the full length of the strip. Saws are also used to prepare edges of lumber for gluing, and in many cases are satisfactory, especially where glued joints are required merely to permit handling laminations as units during the gluing assembly. For best results in gluing sawed edges, the ripsaw must be in first-class condition, the chain ways true, and the saw round and jointed. Machined surfaces produced by cutter heads properly equipped with sharp knives have been found superior to sawed edges for gluing purposes, especially in the dense hardwood species.

When ripping stock preparatory to edge gluing, it has been found practical to select a number of standard widths in order to conform to requirements for the spacing of edge joints in the laminated assembly. For example, if nominal 1-inch hardwood lumber is being prepared for an 8-inch-wide member, the proportion of 8-inch stock is likely to be small. The narrowest piece practical for edge gluing would probably be about 1½ inches. A number of width combinations could be edge glued to meet the requirements. The following combinations of widths in inches serve as an example: 3, 2, 3; 2, 4, 2; 5, 3; 1½, 5, 1½; 2½, 3, 2½; 4, 4; and 1½, 4, 2½. If the specifications require a minimum spacing of ¾ inch between glued edge joints in adjacent laminations, laminations can be assembled in the sequence indicated. In other cases, the spacing of edge joints in the finished product may not be critical, and miscellaneous mixed widths may be acceptable for edge gluing. It is advantageous to have all laminations that are to be glued into an assembly of the same width at any given section in order to permit easier alinement of the laminations and to distribute gluing pressure more uniformly. Any method of cutting to width is satisfactory, as long as uniform width is obtained.

It is often necessary in laminating operations to produce full-length laminations by end-jointing short boards for the purpose of obtaining better utilization of raw material, for building into the assembly the required grade, quality, and strength properties, or sometimes merely to enable handling each full-length lamination in one piece. Various kinds of glued end joints are used for this purpose (fig. 15 and page 97). The plain scarf, hooked scarf, finger, and serrated scarf are among those commonly used. All these joints require a relatively long slope to develop a high proportion of the strength of an unjointed piece. A well-glued, plain scarf joint in oak, for example, might require a slope of 1:15 to produce such strength, while in Douglas-fir and southern yellow pine a slope of 1:12 would be equally sufficient.

It is desirable to have the slope of a scarf with, rather than against, the grain of the wood. There is also no strength advantage in having the slope of a scarf less steep than that of the grain of the wood. Steep slopes have an advantage in that they result in less wood waste, but they also are weaker and may contribute little or nothing to the final strength of the laminated member. There is also the risk that they will break when long laminations are handled in assembling and when bent to curved form. Glued scarf joints introduce an added stiffness to the board at the scarf area that somewhat increases the difficulty of drawing such areas of the lamination to the form in fabricating curved assemblies.

The preparation of gluing surfaces for making end joints requires accurate and uniform machining. End-grain wood is involved in such surfaces, and the fibers must be cleanly cut, not crushed or torn, in order to develop glue bonds of maximum strength. Surfaces can be prepared on planers, shapers, single-end tenoners, special scarfing machines, or saws. Surfaces prepared on machines equipped with cutter heads fitted with sharp knives are generally superior to sawed surfaces, especially with lumber of dense hardwood species. There are no high-speed machines on the market suitable for a low-cost, high-volume production of glued end joints.

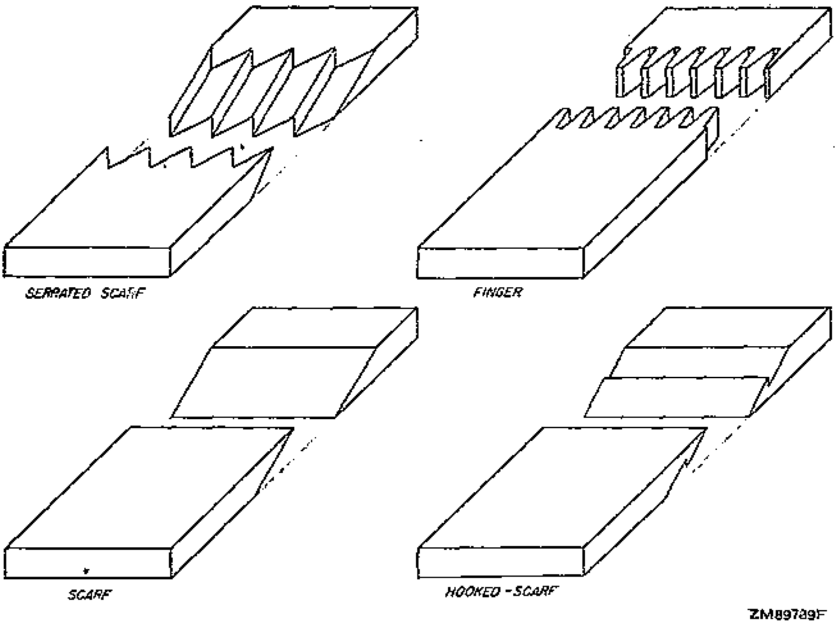

FIGURE 15.—Typical end joints that are glued and used in laminating.

There is some advantage in cutting end joints of the plain- or serrated-scarf type so that the sloping surfaces of all joints in any lamination are in parallel planes. This practice will permit successive boards to be fitted together as they come from the machine without turning them over, and will permit cross-cutting any board and bringing the machined ends together without turning either piece. It is not advisable, however, to permit this practice to interfere with the recommended practice of cutting the scarf with, rather than against, the grain of the wood.

Sometimes lumber is resawed to obtain thinner laminations needed in laminating curved members, or for some other reason. The resawed lumber will develop some degree of cupping if case-hardened or not uniformly dry. Cupping is a disadvantage later in applying glue with the glue spreader, and also in applying gluing pressure with clamps. Cupping of resawed lumber can be minimized by using uniformly dry stock, relatively free from case-hardening (*6*). In planing lumber that has been resawn from case-hardened stock, cupping can be reduced by taking the heaviest planing cut from the original outer surface. In case-hardened lumber it is also very difficult to produce well-fitted scarf joints.

FINAL SURFACING

The final surfacing of the stock preparatory to spreading the glue, assembling, and clamping is one of the most important operations in the fabrication of laminated wood products. The quality of the final product is determined to a large degree by the accuracy and care with which this part of the work is done. In order to develop glue joints of maximum strength, the wood surfaces to be glued must be cleanly machined and must fit accurately.

Finish surfacing can best be done on cabinet-type surfacers equipped with well-fitted cutter heads mounted in ball bearings. The final surfacing should be a light cut, in general not more than one-sixteenth inch. Knives should be kept well sharpened to prevent compressing or otherwise damaging the wood fibers. Glazed or burnt areas indicate damaged fiber.

Double surfacers are probably best suited for machining lumber to be glued. Single surfacers have the disadvantage of giving greater difficulty in maintaining uniform pressures against the bed, particularly with stock having a tendency to cup. Matchers and molders are less adaptable to the surfacing of laminations for gluing. It is recommended that when a lamination consists of a single board or piece (either solid, edge-glued, or end-glued and smoothly planed), the differences in thickness throughout the board should not exceed 0.016 (approximately 1/64) inch. When a lamination consists of two or more pieces laid side by side or end to end, the differences in thickness throughout the entire lamination (made up of two or more pieces but not edge-glued) should not exceed 0.010 inch in order to produce consistently good and dependable glue joints. It is entirely practical to surface lumber to these requirements in single or double surfacers in which heads and bearings are accurately fitted and set up.

Rates of feeding the planer that result in 20 to 30 knife marks per inch on the stock have been satisfactory for the final surfacing of laminations for gluing. The surfacing should be of such quality that knife marks are hardly perceptible. During the surfacing operation, stock should be tested frequently with slip-on gages on both edges throughout the length of the piece. Such gages are inexpensive and will not be forced out of shape if at least three-fourths inch wide. Micrometers are best suited for tolerance measurements, but usually require too much time for routine checking. They should be of such construction as to permit measurements at both edges and centers of boards. Clipping at the ends of boards usually indicates improper adjustment of pressure bars, knives ground below the normal cutting circle of the head, or improper setting of the feed rolls.

When lumber containing edge- or end-glued joints is surfaced, the surplus glue should first be removed in order to prevent skips in dressing and irregularities in surfacing.

Experience has indicated that cup in boards after the final surfacing probably should not exceed one ninety-sixth of the ratio of width to thickness of boards. For laminations 6 inches wide, this will allow ¼-inch cup in a board one-fourth inch thick, ⅛-inch cup in a board one-half inch thick, and $^{1}\!/_{16}$-inch cup in a board 1 inch thick.

The uniformity and quality of surfacing recommended for final machining of lumber must be retained until the time of gluing in order to produce strong and durable glue bonds. Lumber stored too long after final surfacing may have a change in moisture content that will result in nonuniform dimensional changes and make it less satisfactory for gluing into laminated assemblies. Therefore, final surfacing should be done just prior to gluing, or at most within 2 or 3 days before gluing, and the dressed lumber should be protected from significant moisture changes during this interval. Lumber surfaced at the mill before shipment to the laminating plant should be resurfaced just before gluing.

Sawed lumber surfaces have not been used to any great extent in glued laminated wood products. Although resawing dry lumber into thin laminations might afford an opportunity to use sawed surfaces for gluing, present sawing equipment is at a disadvantage for preparing gluing surfaces because it does not produce boards sufficiently uniform in thickness. Saws also tend to compress and damage the wood fibers. The rougher surface would also require more glue.

Sometimes wood surfaces are intentionally roughened by tooth planing, scratching, or sanding with coarse sandpaper, but tests made with such surfaces under good gluing conditions show this practice to be of no benefit to the glue bond. Sanding operations generally remove more wood at edges and soft areas than at denser areas, and thus result in greater inequality in the thickness of the sanded board than in well-planed lumber. Sanding is not recommended for surfacing laminations preparatory to gluing.

LAYOUT OF LAMINATED ASSEMBLY

A plan for the position of laminations in the glued assembly is necessary for each gluing operation, particularly where the laminations are of different grades or contain edge- and end-glued joints and where the member is curved or bent. The strength of the laminated member is influenced by the position of such joints. In many cases the purchase specification will establish the minimum spacing of edge and end joints and the grades of inner and outer laminations.

Location of Edge and End Joints

Edge joints, when properly made, can develop the full strength of the wood, so that the lamination will act as a single full-width board. In members subjected to bending stresses resulting from loads normal to the edge of the laminations, it is necessary that the edge-glued joints provide such strength. Beams with vertical laminations and stems and keels in boats illustrate such requirements.

When beams are made of laminations containing imperfect edge-glued joints, coincidence of edge joints in adjacent laminations increases the possibility of cleavage under alternating wet and dry exposures. For members to be exposed to the weather or equally severe service, laminations should be laid up with the edge joints in adjacent laminations offset as much as possible, and never by less than the thickness of the laminations.

Well-glued scarf joints in lumber do not develop maximum strength unless they have long slopes, and even with relatively long slopes 95 percent of the strength of clear wood in tension is about the maximum obtainable. The more abrupt the slope, the weaker the joint. Furthermore, scarf joints should also be spaced so that the tip of a scarf joint in one lamination does not directly meet the tip of a scarf in an adjacent lamination (fig. 16). Whenever practical, all scarf joints in the surface lamination should slope in one direction; this gives best results in machining the finished product. Butt joints do not furnish reliable strength and are not considered a load-bearing type of end-glued joint.

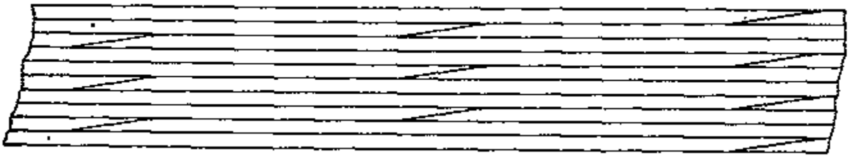

FIGURE 16.—Spacing of scarf joints in a laminated assembly.

STRAIGHT MEMBERS

In assembly lay-up, consideration should be given to the species and grade of lumber, thickness of laminations, and grain of wood, as well as to the position of edge and end joints. Generally, all laminations in a glued timber will be of the same species. The lumber may be of the same grade throughout, or of mixed grades as permitted by the specifications covering the order. Mixing species in the same glued assembly is practical where special strength properties are desired in members that are to be subjected to uniform moisture-content conditions in service. However, where there are wide variations of moisture content in service, unequal shrinking and swelling of adjacent laminations will occur. The higher stresses induced by the stronger species are likely to cause the wood of the weaker species to rupture, which will reduce the strength and usefulness of the member even though the glue joint is durable.

Laminations up to approximately 2 or 3 inches thick may be used in straight members, provided suitably dry stock is available. Sometimes it may be desirable to use more than one thickness of stock in order to attain maximum utility of the lumber supply or to fabricate a laminated member to exact dimension. Arrangement of laminations by thickness is governed largely by the intended use of the member and by the character of the machining operations to be performed upon it. The thinner laminations ordinarily are placed in the position entailing the least subsequent face machining.

Because of the superior weathering resistance, with a minimum of loosened grain, shown by that surface of a flat-grain board toward which the growth rings are convex, it is preferable that the top and bottom laminations (if flat-grain lumber) be placed with the sap side out in members that are to be exposed to the weather. This practice has the additional advantage of facilitating penetration of a preservative.

CURVED MEMBERS

The assembly layup for curved members is governed by the same considerations of species of wood, grade of lumber, and position of edge and scarf joints that apply to straight members, but the maximum thickness of the laminations is governed by the curvature to which the laminations are to be bent.

Lumber that is to become part of a curved laminated member must be bent, unheated and dry, after glue has been applied to its faces. The practice of steaming thick lumber to permit bending to sharp curvature has no application in a gluing operation. The minimum radius to which dry, clear, straight-grained lumber can be bent without breaking is approximately 40 to 60 times its thickness, and varies with the species of wood. In general, hardwoods can be bent more severely than softwoods of the same thickness. Lumber containing knots and other defects cannot be bent to so sharp a curvature as clear lumber. In high-strength curved members, the laminations should be bent to a radius not less than 1.6 times their breaking radius.

Table 2 shows the minimum bending radii recommended for different thicknesses of clear, straight-grained white oak, Douglas-fir, or southern yellow pine lumber at a moisture content of about 10 percent. The table applies to both flat- and vertical-grained lumber at a moisture content of about 10 percent. For drier lumber, and especially for fast-grown material, somewhat longer radii may be required. In any curved laminated member, the radius of curvature of the inner or concave face is shorter than the radius for the outer lamination. In thick curved assemblies this difference may make desirable the use of thinner stock at the inner face of the member.

TABLE 2.—*Minimum bending radii recommended for different thicknesses of clear straight-grained lumber of white oak, Douglas-fir, or southern yellow pine*

Thickness of lamination (inches)	Recommended minimum radius of curvature: White oak	Recommended minimum radius of curvature: Douglas-fir or southern yellow pine
	Inches	*Inches*
1/4	18	31
5/16	24	41
3/8	30	51
7/16	36	63
1/2	43	74
5/8	58	98
3/4	73	125
13/16	79	137
1	105	173
1 1/4	140	227
1 1/2	178	283
1 3/4	217	323
2	256	400

GLUING JIGS AND FORMS

The purpose of gluing jigs and forms is to permit assembling the laminations after glue has been applied to them and then to draw them to the shape desired in the final product and to hold them in that shape under gluing pressure until the glue is set and cured.

For gluing straight members, the jig or form generally consists of a flat bed on which the laminations, spread with glue, are laid consecutively. Often the jig is designed to glue two or more members of the same size, placed one on top of the other. Suitable caul boards are placed on top and bottom of the assembly to assist in distributing the gluing pressure. Sometimes an arrangement whereby the jig, laminations, and cauls are placed in a vertical position is also satisfactory. The jig may be designed to glue a single laminated assembly, or two or more assemblies of the same thickness, placed side by side.

When gluing curved laminated members, the cured assembly essentially retains, upon release from the retaining clamps, the curved shape in which it was glued. When members are cured in the jig, which must be strong enough to hold the desired shape of laminations when they are drawn into position and clamped, less spring-back is likely to develop than when it is necessary to remove the clamped assembly from the jig before curing it. In general, a curved glued laminated member made of many thin laminations is less likely to develop spring-back when released from the form than one of equal depth made of a few thick laminations. Use of high temperatures, such as 200° F., maintained for 15 to 20 hours for the purpose of curing the glue, has been found to minimize spring-back. The amount of spring-back for a specific item must be determined by trial, and the proper compensation made by decreasing the radius of the jig.

The gluing of curved assemblies may be done on either a male or a female type of jig or form. The jig may be constructed for a single curvature or may be adjustable to various curvatures (fig. 17). The general laminating procedure with such jigs is to lay the individual laminations in approximately bent position and hold them by a series

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FIGURE 17.—Adjustable jig for laminating curved timbers.

of stops, or to draw the entire assembly into bent position at one time by block and tackle, winch, or the like. The next step is to use draw-up clamps to pull the assembly into final shape and to hold it there while gluing pressure is applied (fig. 18).

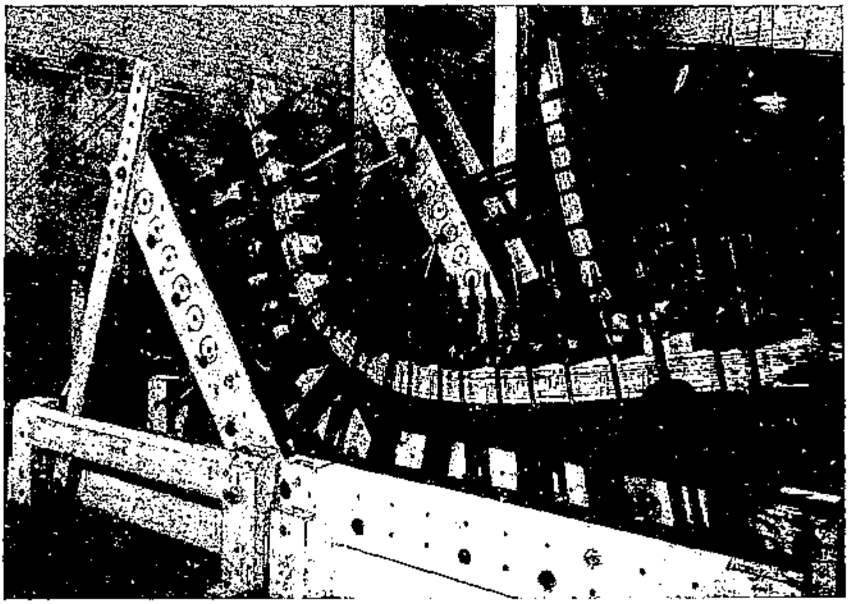

FIGURE 18.—Curved laminated timbers in adjustable jigs.

Adjustable jigs must be set to the shape desired for the curved glued product. Light but rigid patterns that will not bend or become deformed with use or changes in moisture and temperature should be used for setting adjustable jigs. Plywood patterns often serve this purpose very satisfactorily.

The spacing and setting of adjustable arms on the bed of a bending jig necessarily must be such that the laminations will follow the line of the pattern when clamped to the jig. Any irregularity in the alinement of the arms or any departure of the arms from the line of the pattern will be carried into the laminated product. Jigs, therefore, should be designed to prevent movement or twisting of the arms while stock is being bent and gluing pressure applied. The jig must also be durable under conditions used in treating the laminated member while curing the glue, a factor that is particularly important when heat is used for this purpose.

In setting up jigs to be used for curved assemblies, it is usually advisable to carry the line of the curve well beyond the net length of the finished member. This practice is particularly desirable in patterns having a sharp curve near the end of the assembly. Failure to set at least one arm on the bed of the jig beyond this length is a frequent cause of distortion.

In setting jigs for curved laminated assemblies that permit little tolerance in the shape of the finished product, it is necessary to add the thickness of the caul to the width of the pattern on the jig side. Otherwise, the radius of the finished member will be in error by the thickness of the caul.

Spacing between jig arms may be varied with the degree of curvature. In flat assemblies, a spacing of 4 feet is not excessive if the cauls and stock are thick enough to prevent sagging or bending of the package during the clamping and curing process. In curved members, the spacing of the jig arms must be decreased as the bending radius is shortened. Required spacing may be as close as 9 inches on sharp bends of 30-inch radius or less. Proper spacing can best be judged by observing the fit of the pattern and the behavior of the laminations as they are clamped into position.

Sometimes it is desirable to laminate members of single curvature but bent in two directions. This can be accomplished by the use of relatively thin and narrow laminations, and by permitting the laminations to bend and slip over each other in two planes. The gluing may be done in 1 operation requiring gluing pressure to be applied simultaneously in 2 planes, or in 2 operations requiring gluing pressure in 1 plane only in each operation.

It is also possible to laminate assemblies of slight compound curvature, such as bilge stringers of a boat, in one operation. The edge joints must have the pattern of the arc of a circle to permit the lamination to twist freely when bent to form. Special jigs are needed to provide the compound curvature desired, and special clamping arrangements are necessary (fig. 19).

GLUING OF EDGE AND END JOINTS

It is highly important in the production of laminated material to plan the sequence of operations carefully and to carry out the various steps in the proper order. Edge gluing is sometimes necessary to obtain laminations of the proper width, and end gluing to obtain the desired lengths. It is usually necessary to preglue edge and end joints prior to laminating if maximum-strength members are required. Whether edge gluing should precede end gluing or vice versa, depends on the sizes of lumber available and the type of assembly. In general, it is more convenient to place the end joints at the desired locations if the edge joints are made prior to the end joints.

Edge Joints

As pointed out previously, edge gluing is ordinarily not necessary in laminations used in members intended for normally dry interior use. Where edge gluing is required, properly fitted planed or sawed joints may be used. Results of exposure tests have indicated, however, that greater durability is obtained in dense hardwood species with joints prepared by planing than by sawing.

The glue used for edge gluing should generally develop as great joint strength and durability as the glue used in bonding the laminations. In certain cases, however, edge gluing is necessary merely to permit handling full-width laminations during the laminating process,

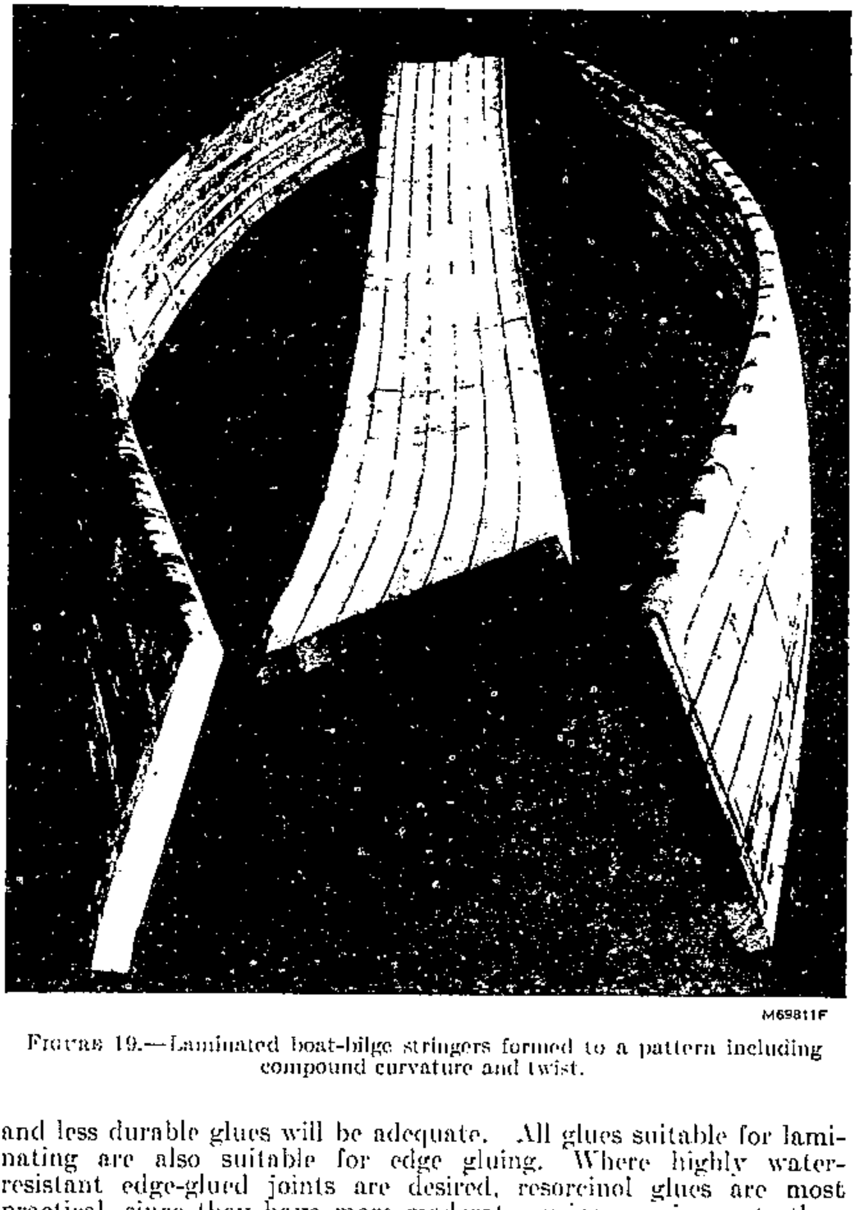

FIGURE 19.—Laminated boat-bilge stringers formed to a pattern including compound curvature and twist.

and less durable glues will be adequate. All glues suitable for laminating are also suitable for edge gluing. Where highly water-resistant edge-glued joints are desired, resorcinol glues are most practical, since they have more moderate curing requirements than phenol-resorcinol or melamine glues.

A single-roll spreader is probably the most convenient means for applying glue to the edges of lumber. Application by brush may be equally satisfactory, but is slower and often less practical. The assembly time is usually rather short in edge-gluing operations, and single spreading (application of glue to only one of the mating surfaces) is satisfactory.

Various types of clamping equipment may be used to apply pressure when edge gluing. The conventional rotary type of clamp carrier is satisfactory for use with short stock, provided the material is held under pressure for a period sufficient to develop joint strength that will permit handling the edge-glued stock without damaging the glue bond. The carrier should be properly alined to assure straight glued boards. This type of clamp can be enclosed and heat can be supplied to hasten the setting of the glue. Complete cure of the glue is not usually required in the edge-gluing operation, but sufficient set to permit handling and machining the material is necessary. The final cure may be effected in the curing of the laminated assembly, although this should not be depended upon where maximum edge-joint strength is required.

Edge-glued stock can also be clamped with piling clamps (fig. 20), which will permit the assembly of such stock on trucks for ready removal to a heated chamber for initial curing. When room-temperature-setting glues are used, a clamping period of 3 hours or more is usually long enough for adequate curing.

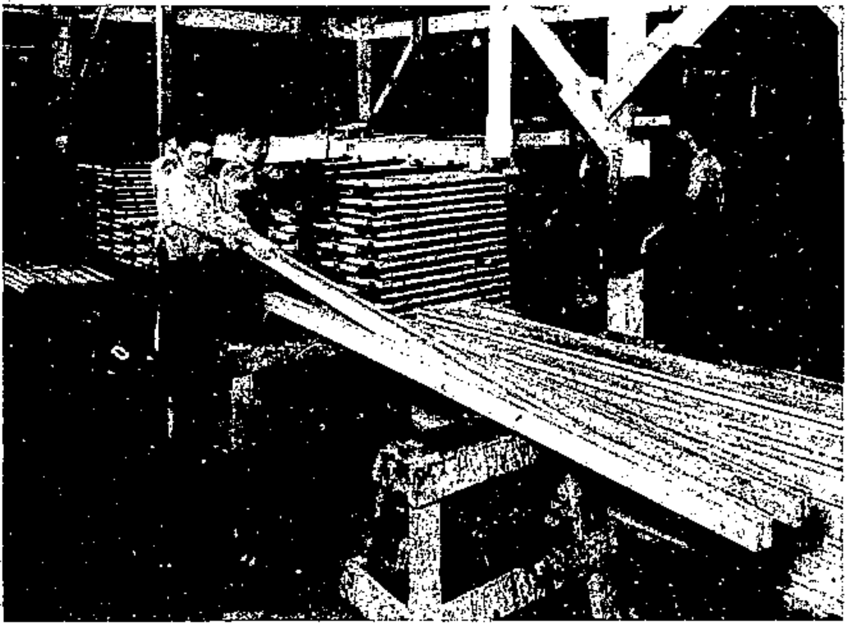

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FIGURE 20.—Edge-glued lumber laminations in piling clamps.

A number of edge-gluing machines using high-frequency dielectric heating for quick setting of the glue have been developed in recent years. Most of these are designed for short stock of the type suitable for furniture panels, but equipment could be designed for edge gluing the longer stock usually used to laminate structural members. The main advantage of the high-frequency process for edge gluing is that the glue can usually be set in a period of about 1 minute or less.

If edge-glued boards are planed too soon after removal from clamps or other means of pressing, sunken joints will probably result. This can be avoided by conditioning the boards for a period sufficient to permit the water added with the glue to diffuse away from the joints.

End Joints

The choice of glues for end joints involves the same considerations as that for edge joints. Where durable end-glued joints are required in the laminated member, the glue used for end jointing should be as strong and durable as that used for bonding the laminations. Since rapid setting is often important in the gluing of end joints, it might sometimes be of advantage to use a type of glue for the end joints different from that for the laminating. Resorcinol glues, which have moderate curing requirements and set comparatively fast, have been found practical for end-joint gluing where highly durable bonds are required.

End joints may be glued separately or in the same operation in which the laminated member is assembled. However, it is extremely difficult to produce end joints of uniformly high quality during final assembly. Consequently, for exterior use or service where maximum strength is required, pregluing of end joints is recommended. Where design requires maximum end-joint strength in laminations, the end-joint gluing should be done in advance of the final surfacing. This procedure permits the application of adequate gluing pressure, enables the development of a strong glue bond over the entire area of the glue joint, and makes it easier to plan in advance of the laminating operation the location of joints and defects in order to meet the specification covering the completed members. It also affords opportunity to match the grain and the location of edge joints in adjacent laminations and thus to minimize the development of stress in the final product. Assembly time in the final gluing operation can also usually be minimized when the end joints are glued beforehand. Advance gluing of end joints, with subsequent final surfacing, also helps to insure uniform thickness of stock for the full length of each lamination and avoids the occurrence of open joints adjacent to butt joints in curved assemblies.

Plain scarf and serrated end joints, which require a slight overlap to insure adequate gluing pressure on the joint (fig. 21), must be glued in a separate operation to insure consistently high-strength joints. Serrated, double-bevel, or pegged scarfs facilitate alinement of the end joints but do not provide definite assurance that proper pressure will be applied on the scarf-joint surfaces or adjacent gluing surfaces.

End joints should be cut to a perfect fit and properly alined when gluing pressure is applied. A rigid bed with rigid uprights (fig. 22) to which the boards can be firmly clamped and held flat and straight during the setting of the glue, is usually desirable. Several end joints can then be clamped in a single package. Wax paper may be placed between the laminations at places where glue squeeze-out occurs, to prevent them from sticking together. When gluing scarf joints in this manner, provision should be made to prevent end slippage.

High-frequency curing is also well adapted for quick setting of the glue in scarf joints, particularly where narrow boards are jointed and parallel heating is practical. Where wider boards (about 4 inches or

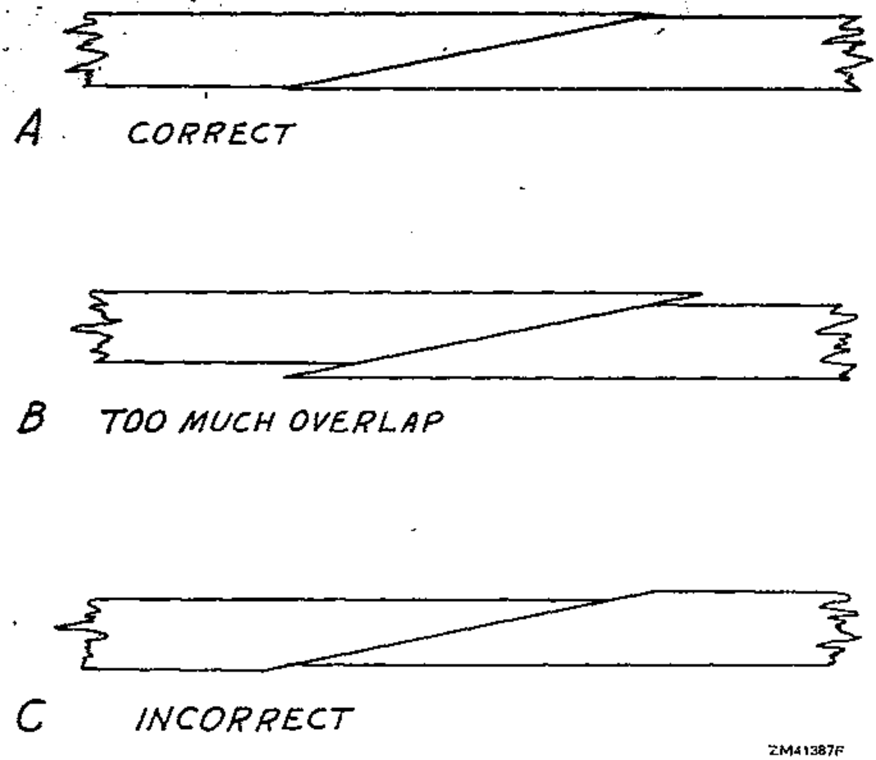

FIGURE 21.—Alining scarf joints for gluing. *A*, Correct with slight overlap; *B*, incorrect, too much overlap; *C*, incorrect.

more) are end-jointed, stray-field or perpendicular heating is probably more applicable. The requirement for overlap, as mentioned above, is equally important regardless of the curing method employed in setting the glue.

Hot presses have been used occasionally for curing the glue in end joints, but high-frequency heating is gaining in use for this purpose.

To obtain uniform wetting of all end-joint areas, it is recommended that glue be applied to both contacting surfaces, and because glue penetrates readily in end grain, a fairly heavy spread should be used. It is usually also desirable to allow a few minutes of open assembly to permit the glue to become tacky before the surfaces are brought into contact and pressure is applied. Ordinarily it is advantageous to use somewhat higher gluing pressure for end joints than for laminating. If several joints are pressed in one package by means of retaining clamps, fairly heavy cauls must be used on the top and bottom of the package.

GLUING LAMINATED ASSEMBLIES

Much of the success in fabricating satisfactory laminated members depends on following a correct procedure when gluing the assembly. Good practice requires that attention be given to arranging the lami-

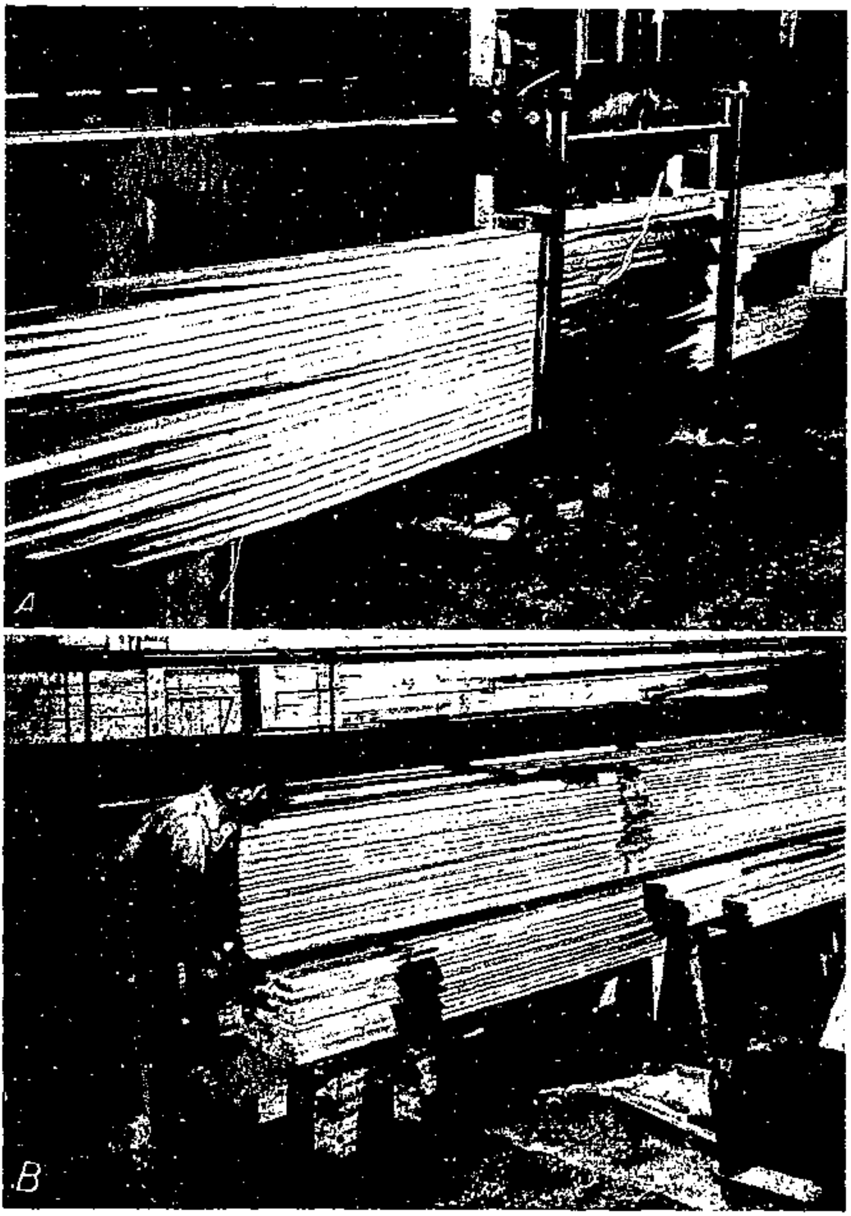

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FIGURE 22.—Method of applying pressure in gluing. *A*, Screw press used with plain or serrated scarf joints; *B*, long bar clamp used with finger-type end joints.

nations in the proper order in a convenient place for feeding them to the glue spreader. Mixing and spreading the glue properly, and placing the laminations on the jig or gluing bed and applying adequate pressure uniformly and quickly to avoid initial set of the glue before application of pressure is completed, are necessary (fig. 23). A well-planned and rapidly executed procedure is especially important when glues having short assembly times, such as casein and urea resins, are used.

In the normal laminating procedure, the laminations are first edge glued (when edge gluing is necessary), then end jointed (when necessary), and finally surface finished just prior to gluing.

Mixing and Preparing Glue

The choice of glue must be governed by the conditions under which the laminated product will be used. Extreme care should be exercised in the mixing and preparation of any glue. Directions for mixing (furnished by the manufacturer) give the weight of each ingredient to be used. These directions should be carefully followed. Scales of the proper sensitivity must be available and in good working condition. All containers used for weighing the different ingredients should be kept clean, and it is usually desirable to use a separate container for each ingredient.

Small amounts of glue may be mixed by hand, but larger batches require a mechanical mixer for best results. Various types of mixers have been used successfully. The dough-type mixer (fig. 24), equipped with a mechanism for turning the paddle in a double rotary motion at 2 or 3 different speeds, has been used with excellent results for both casein and resin glues. The proper paddle speed of a mixer is important, as too rapid stirring may introduce air into the the glue and thus develop foam, and too slow stirring will require excessive mixing time and thus shorten the pot life of the glue. For the type of mixer shown in figure 24, a maximum paddle speed of 60 revolutions per minute is usually satisfactory. Mixing bowls made of steel, zinc, copper, brass, or aluminum are suitable for use with approximately neutral glues. Metals other than steel should not be used with highly acid or alkaline glues, since acids or bases attack these metals. In warm weather a water-jacketed pot may be used to cool the glue mixture and maintain a long working life.

Since some resins tend to develop heat when mixed with the hardener, the manufacturer's instructions for keeping the materials cool during mixing should be followed. Precooling of the resin in refrigerated storage just before mixing is helpful in avoiding undesirable heating.

For the mixing of most prepared casein glues, the proper amount of water is placed in the bowl of the mixer and the glue powder sprinkled or sifted in gradually, with the paddle in slow motion. Care should be used that large lumps do not form. The dry powder is mixed thoroughly with the water and stirred until it has dissolved. It is usually recommended that initial mixing be continued only for 3 to 5 minutes. The glue is then allowed to rest without agitation for 15 to 20 minutes, and again mixed for 3 to 5 minutes before using. Many casein glues thicken and set to stiff pastes during or shortly after the original mixing, but return to workable consistencies during the rest period. This original thickening is normal for these glues and not an indication that additional water is needed.

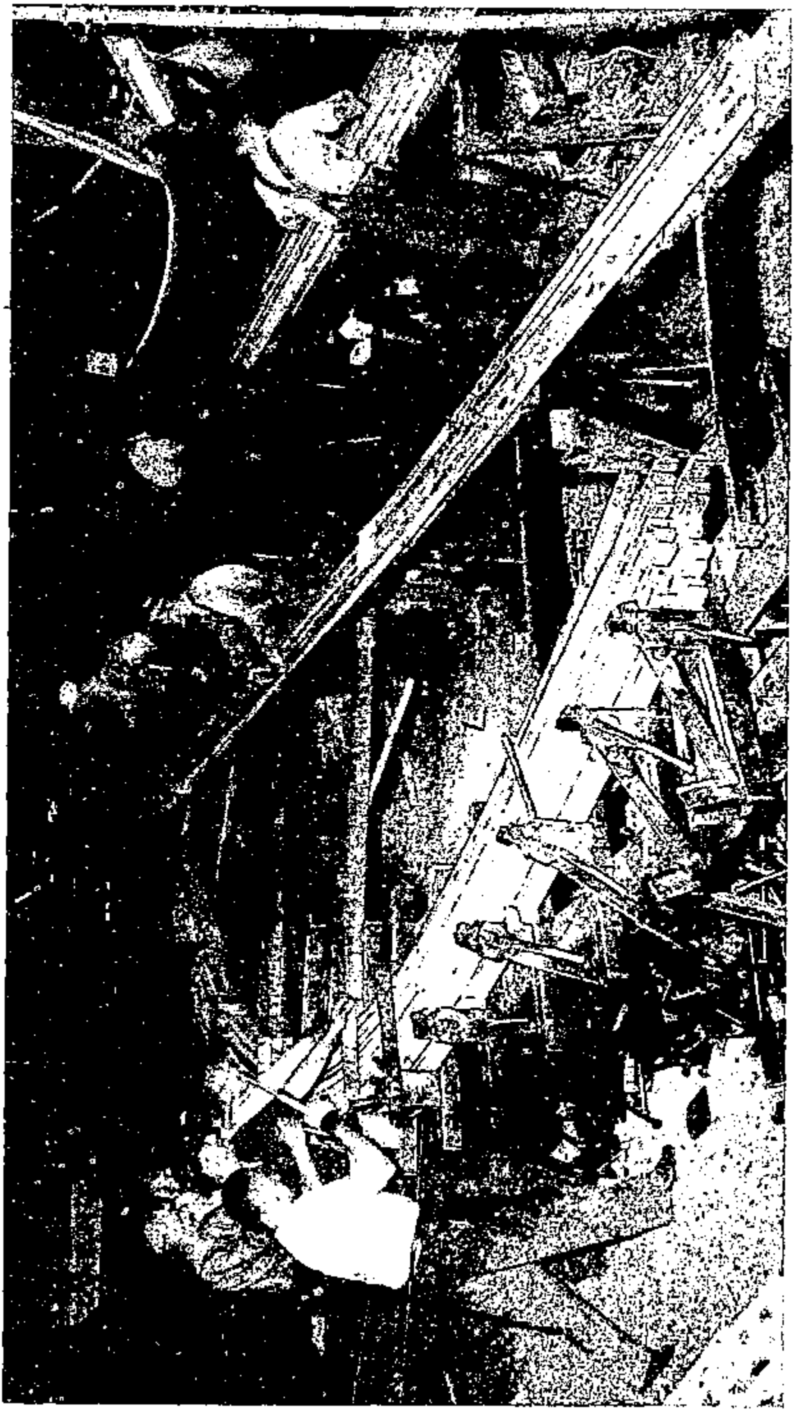

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FIGURE 23.—Laminating barn rafters with phenol-resorcinol resin glue.

M48436F

FIGURE 24.—Three-speed electric mixer with 3- and 8-quart bowls and two sizes of paddles for mixing glue.

For urea resins supplied in powder form, probably the most generally applicable mixing procedure is to place about two-thirds of the required water in the mixing bowl, add the powder gradually with slow stirring, allow the mass to mix until smooth and free from lumps, and then add the remainder of the water. Stirring is continued for a few minutes until the mixture is of uniform consistency throughout.

In mixing intermediate-temperature-setting phenol-resorcinols or resorcinols, it is usually most convenient to place the liquid resin in the mixing bowl and add the powdered hardener with slow stirring. After the hardener is completely submerged in the resin, stirring may be more rapid. Rapid stirring at the start is likely to cause loss of hardener. A total mixing time of 3 to 10 minutes is usually sufficient for these types of glues.

The procedure in mixing melamine glues is similar to that for urea-resin glues.

Many glues, especially of the synthetic-resin types, contain ingredients that are injurious to the skin and other body tissues. Great care should be exercised in their use. Workers may need rubber gloves, aprons, and goggles. If toxic fumes are evolved, good ventilation should be provided and suitable exhaust fans may be desirable. Information on precautionary measures with any particular glue should be obtained from the glue manufacturer.

SPREADING GLUE

To make satisfactory glue joints, it is necessary to apply the correct amount of glue and to spread it evenly. With certain glues this should be done within as short a time as possible. These requirements can usually be most easily met by using a double-roll machine spreader with rubber-covered rolls and fitted with doctor rolls to control the glue spread (fig. 25). Application of glue to only one of the mating surfaces of a joint (usually referred to as single spreading) is satisfactory for many types of work, but in laminating lumber that involves spreading of long laminations and sometimes relatively long assembly periods, double spreading (coating both of the mating surfaces of a joint with glue) is recommended. This will insure even wetting of all the joint surfaces to be glued and, with most adhesives, will also allow considerably longer assembly periods than single spreading. In double spreading, one-half of the glue required should be applied on each face of each lamination. This may be conveniently done by passing all, rather than alternate, laminations through a double-roll spreader. Application of glue on the outer faces of the outer laminations can be avoided by adjusting the spreader rolls to apply glue on one surface only; in any case, the outer faces of the surface laminations should be covered with wax paper to prevent adhesion to the cauls.

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FIGURE 25.—Double-roll glue spreader equipped with doctor rolls and rubber-covered spreader rolls.

The required amount of glue spread varies somewhat with the gluing condition and with the species of wood used. Porous woods usually require a heavier spread than do dense, nonporous woods. For most lumber laminating, the following spreads of wet glue mixture are recommended per 1,000 square feet of joint area: Casein, single spread, 60 to 90 pounds; double spread, 75 to 110. Resin, single spread, 40 to 60 pounds; double spread, 50 to 75.

The higher range of spread should be used with long assembly periods, excessively sloping or end-grain surfaces, scarf-joint surfaces, or imperfectly planed surfaces. Slightly lower spreads than those shown in the tabulation may also be satisfactory when the assembly period is short and the wood used is not too absorbent.

In general, the glue spread can be checked by weighing a board of convenient size before and after spreading and dividing the weight of the glue by the area of the board. Provision should be made to permit glue spreads to be checked quickly and frequently. For this purpose, test pieces of the same thickness as the material being laminated should be used. If a test piece 6 inches wide and 26½ inches long (total area of both faces 2.2 square feet) is used and glue is applied on both faces of the test piece, the weight of glue in grams is numerically equivalent to the number of pounds per 1,000 square feet of surface area spread. If, for example, a test piece of the size described increased 30 grams in weight by the application of glue to both faces when passed through the spreader, the rate of spreading would be equivalent to 30 pounds per 1,000 square feet of spread area. When both contact areas of a joint are spread with glue (double spreading), the number of grams on the test piece must be multiplied by 2 to obtain the rate in pounds per 1,000 square feet of joint area.

The glue spreader should be adjusted and the glue spread checked before the first lamination is passed through the spreader, in order that there be no undue delay after spreading has started. For this reason, it is desirable to have the test samples of the same thickness as the laminations that are to be glued. When adequate gluing pressure is applied at the proper time, the appearance of a thin bead of squeezed-out glue along the edges of the joint is usually a fair indication that sufficient glue has been applied.

Moisture Added to Wood in Gluing

The moisture content of wood is increased in the gluing process by the absorption of water contained in the mixed glue. Glues of high water content add more water than those of low water content, and heavy spreads add more water than do light spreads. More glue is used per unit volume of wood, and consequently, more water is added when laminating with thin laminations than with thick ones. The percentage of increase in moisture content from a given amount of glue will be greater with species of low specific gravity than with those of high specific gravity.

The percentage of moisture content added to the wood when laminations of equal thickness are used, may be calculated by using the following formula:

Increase in moisture content (percent)

$$=\left(\frac{W/100\times G\times(L-1)}{\frac{T\times L}{12}\times 1{,}000\times S\times 62.5}\right)100=\frac{0.000192WG}{TS}\frac{L-1}{L}$$

where W=pounds of water in 100 pounds of mixed glue
G=pounds of mixed glue used per thousand square feet of glue-joint area
L=number of laminations
$L-1$=number of glue lines in glued assembly
T=average lamination thickness (in inches)
S=specific gravity of wood (dry)

Table 3 shows the increase in moisture content of the wood resulting from the addition of water contained in the glue used in typical constructions.

TABLE 3.—*Calculated*[1] *percentages of moisture added to wood in gluing (five-ply construction)*

Kind of glue	Glue spread	Lamination thickness	Hard maple	White oak	Mahogany	Douglas-fir	Southern yellow pine
	Pounds per 1,000 square inch	*Inch*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Casein	65	¾	1.4	1.3	1.8	1.9	1.8
Do	95	¾	2.1	2.0	2.7	2.7	2.6
Do	65	⅜	2.8	2.7	3.6	3.7	3.5
Do	95	⅜	4.2	3.9	5.3	5.5	5.1
Urea resin	45	¾	.6	.6	.8	.8	.7
Do	65	¾	.9	.8	1.1	1.1	1.0
Do	45	⅜	1.2	1.1	1.5	1.5	1.4
Do	65	⅜	1.7	1.6	2.2	2.2	2.1
Resorcinol or intermediate-temperature-setting phenol	45	¾	.4	.4	.6	.6	.5
Do	65	¾	.6	.6	.8	.8	.8
Do	45	⅜	.9	.8	1.1	1.2	1.1
Do	65	⅜	1.3	1.2	1.6	1.7	1.6

[1] Moisture calculated on the basis of average specific gravity values as follows: hard maple, 0.63; white oak, 0.67; mahogany, 0.49; Douglas-fir 0.48; southern yellow pine, 0.51. Glue mixtures used were: Casein, 1 part solids to 2 parts water; urea resin, 1 part solids to 0.65 part water; resorcinol and intermediate-temperature-setting phenol, 70 percent solids.

ASSEMBLING LAMINATIONS

Normally, the lumber should be at room temperature before the glue is spread, especially when glues not requiring elevated curing temperatures are used. Since sizable assemblies heat rather slowly, minimum pressing periods are obtained if the lumber is at the desired glue-curing temperature when the assembly is laid up and clamped. Cold lumber will permit the use of longer assembly periods, such as may be required for large members, but longer pressing or heating of the clamped assembly then becomes necessary.

Wood surfaces to be glued should be clean and free from crayon marks, grease, oil, or other materials that might interfere with good bonding.

Prior to the start of gluing, the laminations should be stacked in the order desired in the glued member. They should then be passed through the spreader and assembled in the same order. This procedure will minimize the chance of interchanging laminations during the gluing, which might upset the predetermined pattern for end-joint spacing. If workmen are assigned to definite stations, confusion and delay in laying up long assemblies are avoided. The use of roller conveyors at the glue spreader may save manpower, but the rollers used to carry glue-coated laminations should be V-shaped to avoid appreciable disturbance of the glue film. Placing the spread laminations together promptly, so that the glue surfaces are not exposed to the atmosphere, reduces evaporation of solvent and permits longer assembly periods.

Assembly Period

The interval between the spreading of glue on the first lamination and the application of full gluing pressure is called assembly time. If pieces of wood are coated with glue and exposed freely to the air, a much more rapid change in consistency of the glue occurs than if the pieces are laid together as soon as the glue has been spread. The condition of free exposure is conveniently referred to as open assembly, and the other as closed assembly. Assembly and pressing must be completed before the glue has developed an initial set, which is the result both of chemical reaction and of loss of solvent to the wood and to the air.

Since the setting action of the glue and the evaporation of solvent are accelerated by heat, the permissible assembly time will vary with the gluing temperature. At low temperatures, a considerably longer assembly time may be allowed than under hot, dry conditions. Proper regulation of the assembly period is very important, since application of pressure either too soon or too late may result in unsatisfactory bonds. Permissible assembly times are discussed in general in connection with the various types of glues, but for any specific glue formulation the manufacturer usually furnishes instructions covering permissible assembly periods at different temperatures.

Gluing Pressure

The application of adequate and uniformly distributed gluing pressure is essential to the production of consistently good joints. Pressure on the joint during the early stages of setting is required for best results in practically all types and forms of gluing. The functions of pressure include smoothing the glue to form a continuous, uniformly thin film between the wood layers, bringing the wood surfaces into intimate contact with the glue and holding them in this position while the glue sets. Insufficient pressure often results in thick glue lines that are undesirable regardless of the type of glue used.

The amount of pressure required to produce a strong joint varies within a wide range. Species of high crushing strength require and withstand higher gluing pressures than do woods of lower strength. For dense woods, such as oak, satisfactory results may be obtained with pressures within the range of 150 to 250 pounds per square inch. For softwood species, pressures of 100 to 200 pounds per square inch are usually satisfactory. The successful use of light pressure presupposes that the wood surfaces are true and accurate as to fit, or that they deform readily under small loads. The minimum pressure permissible for any assembly is one that will insure close contact of the wood surfaces and hold such contact until the glue has set.

EQUIPMENT FOR APPLYING GLUING PRESSURE

There are various means of applying gluing pressure to laminated assemblies. If room-temperature-setting glues are used, hydraulic presses or screw presses may be used in making straight members. In gluing curved members, retaining clamps serve to best advantage since pressure must be applied progressively along the assembly to permit slippage of laminations. If heat is required to set the glue, it is important that the assemblies under pressure be readily movable to a curing chamber, and under such conditions heavy presses would not be practical for applying gluing pressure. The deteriorating effects of high temperature and humidity, where such conditions are required for curing, also render the use of expensive presses unsuitable.

Large members that are difficult to move while clamped are often pressed in jigs equipped with portable covers and heating facilities.

Use of screws or nails for applying gluing pressure has not been thoroughly investigated. In general, however, such fastenings provide low and inadequate pressures for most gluing operations, particularly where dense hardwoods are involved. On lower-density softwoods, reasonably good bonds have been obtained with nail pressure when glues of the resorcinol type are used on rather small members, such as light rafters. Hence, on the basis of existing knowledge, nailing as a means of applying pressure in gluing is not recommended for high-strength laminated members of substantial size.

A frame type of retaining clamp with rocker head (fig. 26, *A*) and a C-type of retaining clamp with rocker head (fig. 26, *B*) for equal distribution of pressure across the width of the assembly have been used successfully for producing laminated members. Tops and bases of such clamps have been made of cast iron, steel, or aluminum alloy. The initial cost is considerably higher when clamps of steel or aluminum alloy are used, but they deteriorate much less under conditions of high temperature and humidity, and there is less breakage. For narrow members, a yoke-type, single-bolt clamp (fig. 27) has been found effective for simultaneous application of pressure to two assemblies. Retaining-clamp bolts may be procured with V-threads or square threads. The initial cost of V-threaded bolts is usually less than for the square-threaded ones, but V-threads are easily damaged and do not give so satisfactory service over long periods of use.

Air-operated or electric nut runners will speed production and have been used to advantage for tightening nuts on retaining clamps (fig. 28).

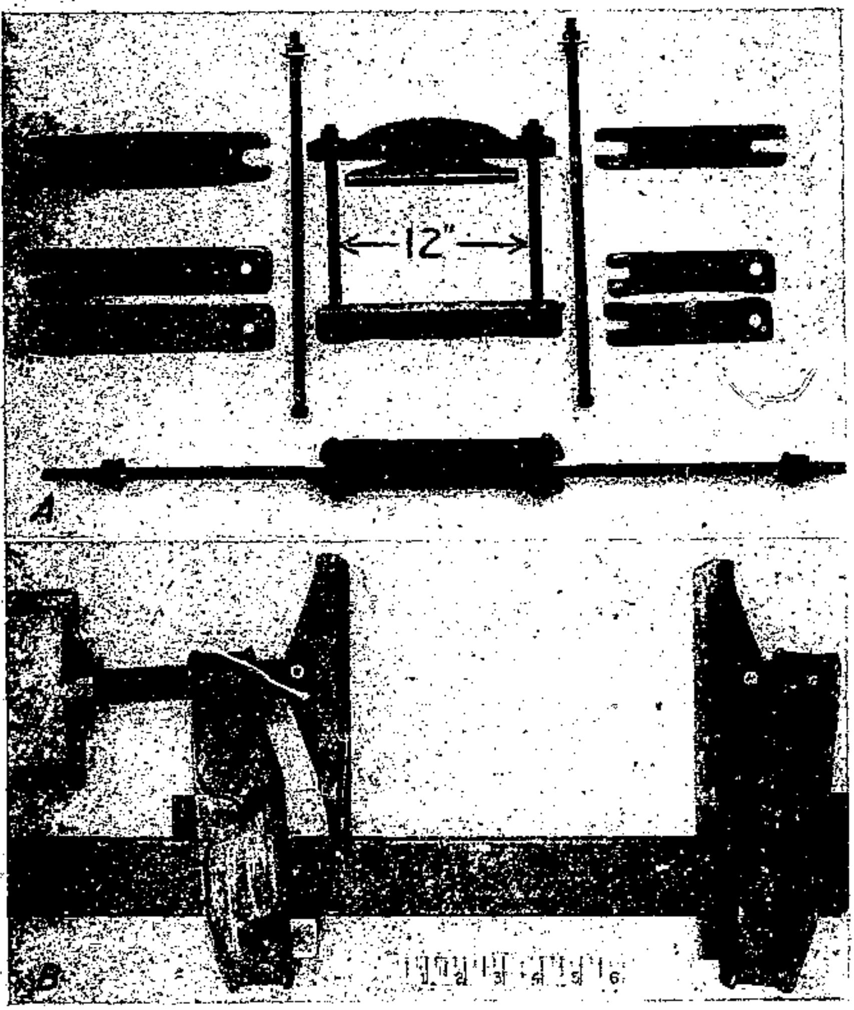

FIGURE 26.—*A*, Rocker-head type of two-bolt retaining clamp used to apply pressure to a laminated assembly; *B*, rocker-head C-type of clamp adjustable to different depths of assembly.

Fire hose inflated by air, water, or steam is frequently used to supply gluing pressure. In most operations of this type, the hose is placed between a rigid support and a movable rigid caul, and the pressure developed by the inflation of the hose is transmitted to the caul (fig. 29). The pressure in the hose may be read by means of a hydraulic pressure gage, and the total load computed from the following relationship:

Total load equals the gage pressure multiplied by the area of contact between hose and caul.

If, for example, for each hose shown in figure 29 it is assumed that 2 inches of the circumference of the inflated hose bear on the caul,

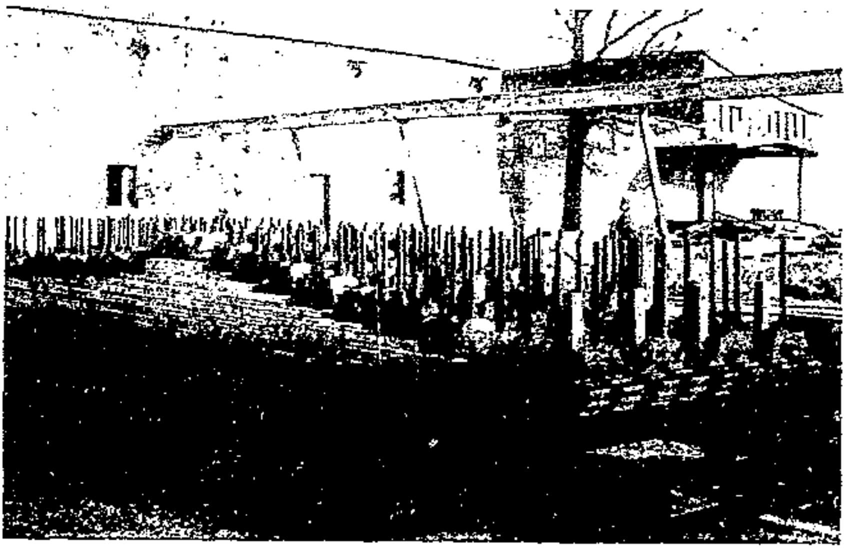

FIGURE 27.—Yoke-type, single-bolt clamp used to apply pressure to two narrow assemblies.

and the gage shows 100 pounds of pressure in the hose, then the load delivered per 12 inches of length of a single hose will be 100 x 2 x 12, or 2,400 pounds. The 4 hoses shown in figure 29 would accordingly deliver 4 x 2,400, or 9,600 pounds per foot of length in contact with the caul. If the width of block to be laminated is 5 inches, this load per foot of length must be distributed over 60 square inches (5 x 12) of glue joint.

Gluing pressure $= \frac{9,600}{60} = 160$ pounds per square inch. A heavy, rigid caul is required to prevent undesirable deflections in this type of pressure application.

CAULS AND CLAMP SPACING

With the retaining clamps generally used in making laminated members, pressure is applied by drawing up a nut on a threaded bolt. Since it is usually impractical to place retaining clamps on the assembly so close together as to apply suitable gluing pressure directly to all parts of the glue-joint area, cauls are placed between the laminated assembly and the retaining clamps to distribute the pressure over the area between clamps. These cauls may be wood or metal and are placed on both faces of the work. When a wide assembly is clamped, it is usually necessary to use short clamp spacings to obtain the required average pressure. In such a case, there is no particular need to use heavy cauls. For a narrow assembly, however, the clamps may be spaced relatively far apart and still furnish the required pressure if heavy cauls are used to distribute the pressure uniformly. The use of heavy cauls with narrow assemblies permits the use of longer clamp spacings and appreciably reduces the time required for clamping.

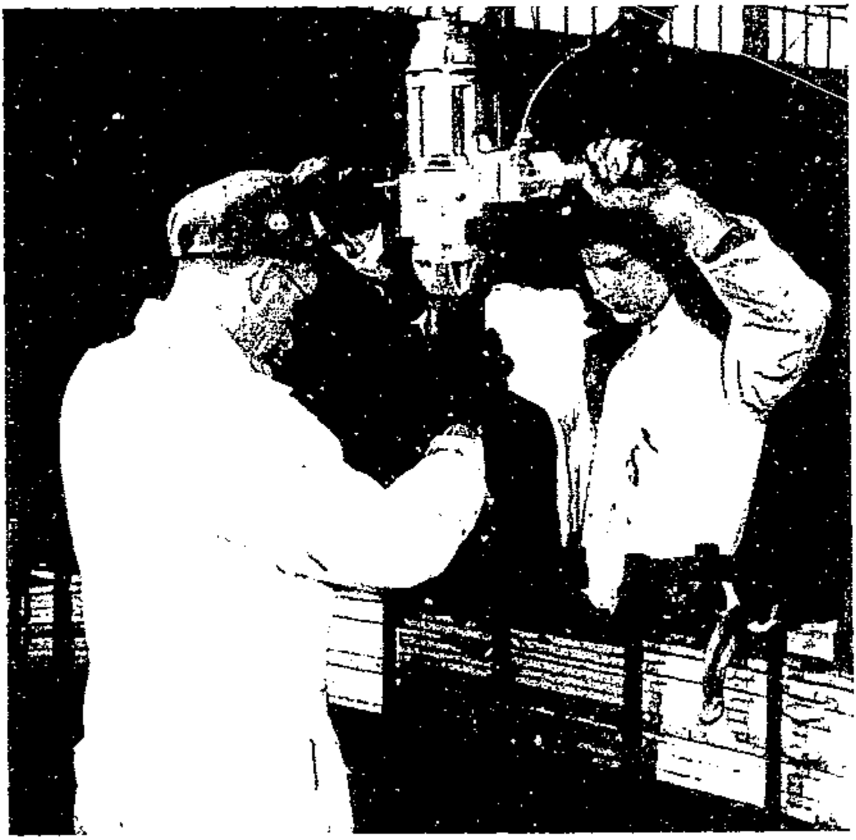

FIGURE 28.—Applying gluing pressure to a laminated assembly with an electric torque wrench. The motor may be adjusted to produce proper torque to exert adequate clamping pressure.

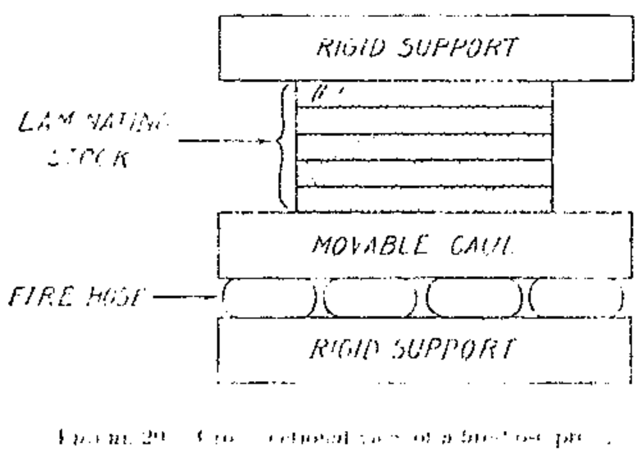

FIGURE 29.—Cross-sectional view of a fire-hose press.

In general, it is advantageous to use thick cauls except when curved members of short radius are made. In this case, the use of 2 or more thin cauls on each face of the assembly will distribute the pressure more evenly than if only 1 caul is used on each face.

Thick cauls, such as 2-inch planks, are commonly used on flat laminated work and will permit spacing the clamps as much as 15 inches apart, while the use of ¾-inch wood cauls may permit a clamp spacing of as much as 9 inches with some woods, although spacing them 7 inches apart is, in general, safer practice.

In gluing curved laminated members, the caul thickness is governed to a certain extent by the sharpness of curvature. With members of short radius, thin cauls must be used and short clamp spacings are necessary. A space not greater than 4 inches between clamps is recommended when the wood caul is about ⅜ inch thick.

Measuring Gluing Pressure

In using retaining clamps, control of the amount of pressure involves a determination of the force applied when tightening the nuts. This will vary with individual operators, and therefore the use of a torque-indicating wrench or a lever arm that shows the force applied is recommended (fig. 30, *A*). Some torque wrenches are equipped with a light that flashes when the required force is applied; in others, a clicking sound informs the operator when the necessary torque is exerted. The load exerted by a clamp when a known torque is applied on the nut may be measured by a hydraulic device, known as a compressometer, illustrated in use and plan in figures 30, *B*, and 31. Torque wrenches are generally calibrated in foot-pounds. When the compressometer is placed within the clamp and the clamp nuts are tightened with a torque wrench, the load on the compressometer developed by the clamp can be plotted against the number of foot-pounds applied to the clamp nut by the wrench. A chart of this type can later be conveniently used to determine the number of foot-pounds required on the torque wrench to develop tha desired pressure on an assembly by a clamp.

If no compressometer is available, the approximate loads applied by screws of square threads may be calculated from the formula:

$$FL=WR\frac{(\pi fD+K)}{(\pi D-fK)}=\frac{WD}{2}\frac{(\pi fD+K)}{(\pi D-fK)}$$

where F=force applied to the lever, in pounds
L=length of the lever arm, in inches
W=total load, in pounds
R=mean radius of the screw, in inches
D=mean diameter of the screw, in inches $=1/2$ (diameter at root $+$outside diameter)
K=pitch of thread, in inches
f=coefficient of friction (may be assumed as 0.20)
$\pi=3.1416=22/7$, approximately.

The torque required to develop a certain load in a clamp will vary from time to time, depending upon the wear and condition of the threads. Therefore, a check of the load should be made at reasonable

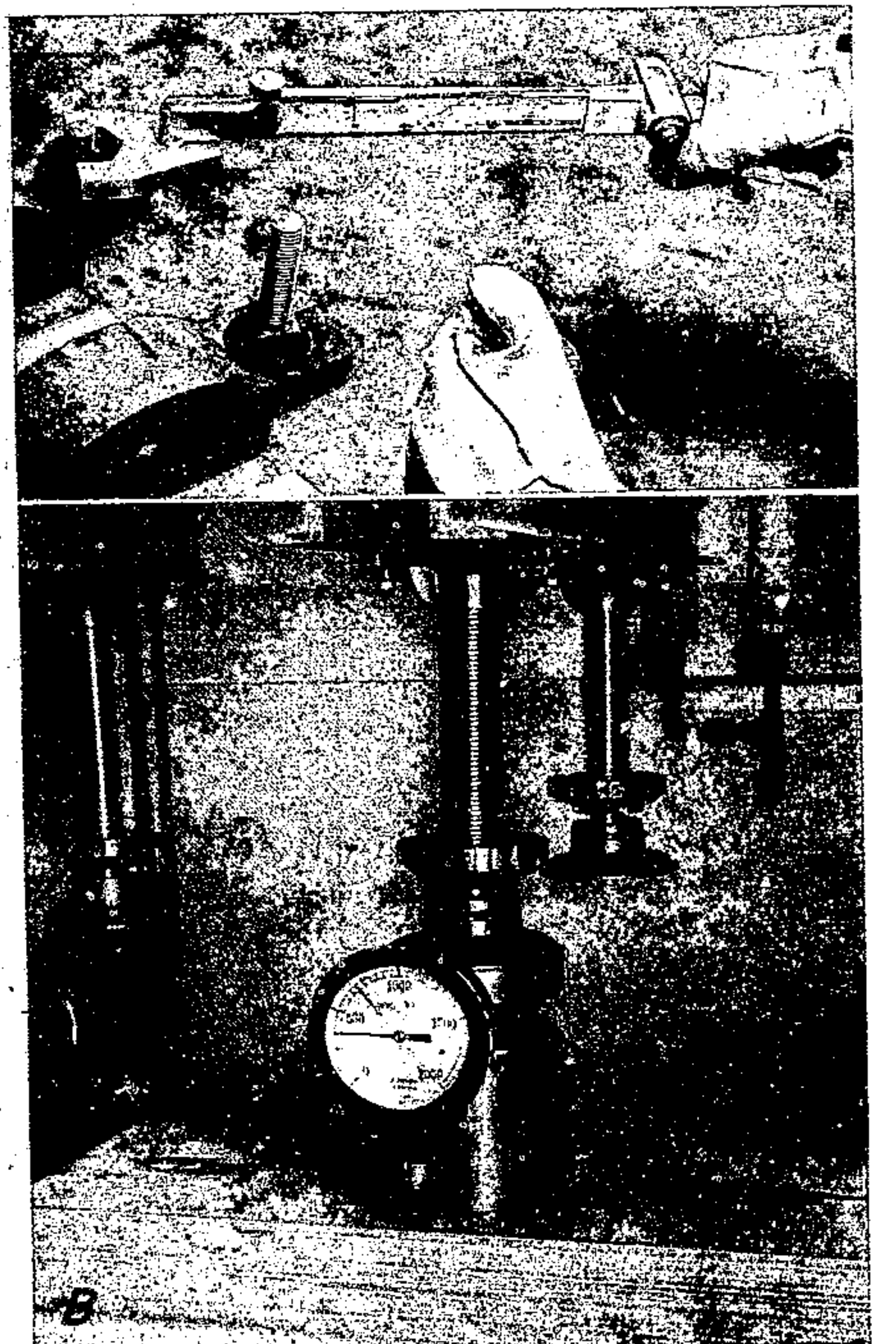

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FIGURE 30.—Devices for measuring pressure applied to retaining clamps: *A*, Torque wrench; and *B*, compressometer.

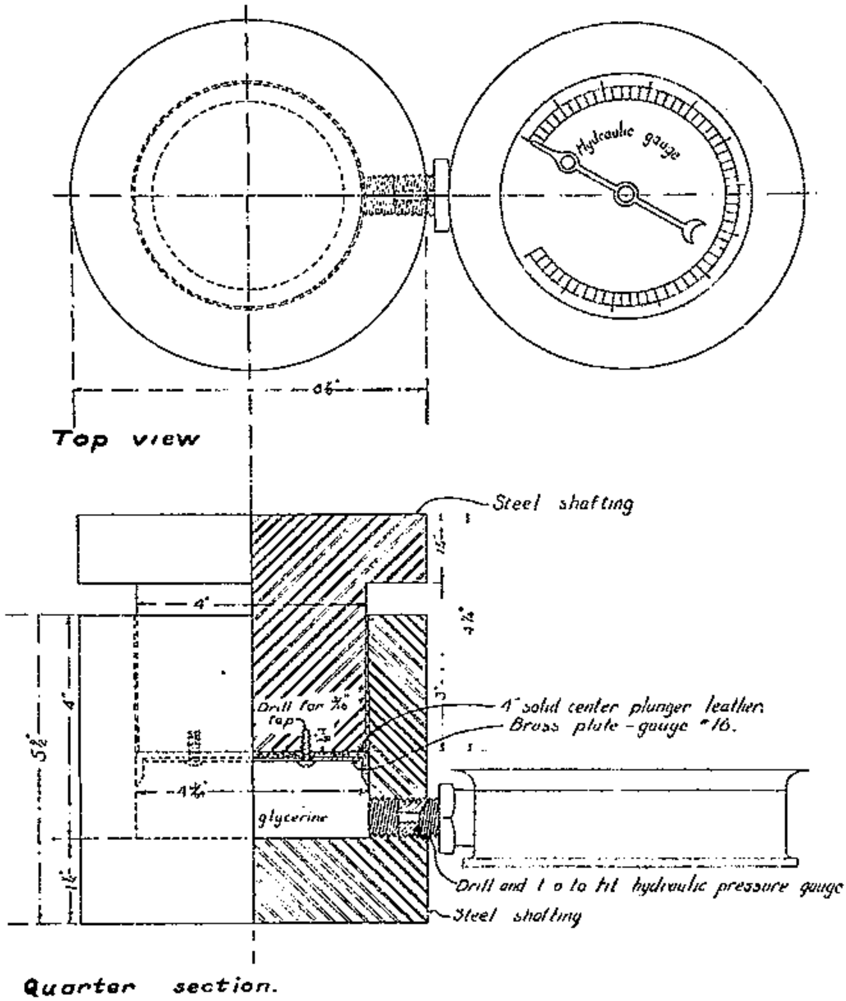

FIGURE 31.—Detailed drawing of a compressometer used to measure gluing pressure.

intervals. The threads on clamp bolts should be kept clean and well oiled at all times; otherwise, wide variations will occur in the torque-load relation.

CLAMPING TECHNIQUE FOR STRAIGHT AND CURVED MEMBERS

Clamp pressure should be applied to a straight assembly by tightening the clamps progressively from one end to the other (fig. 32), or from the center outward in both directions. It is usually the best practice first to apply moderate pressure to all clamps and then, in a second step, to apply full pressure progressively along the assembly.

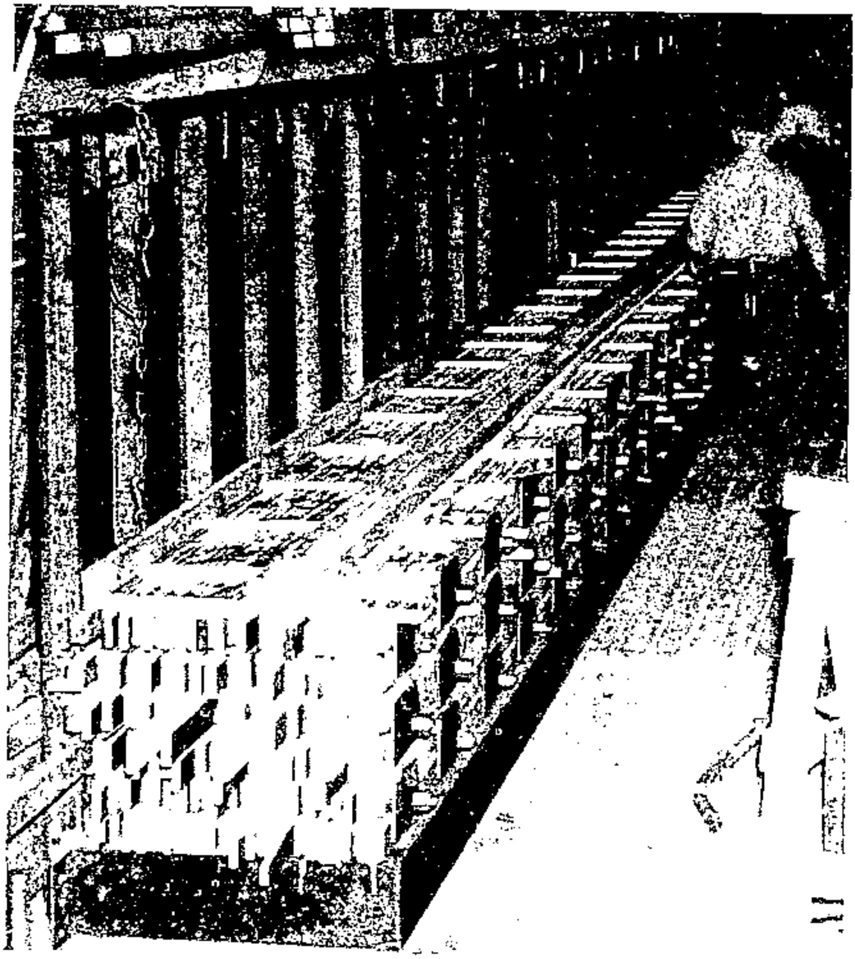

FIGURE 32.—Laminating of straight members by use of retaining clamps.

If the clamps are tightened to full pressure in the first application, a slight bend in the member is likely to be produced. When the assembly is clamped on a solid bed (fig. 33) and pull-down clamps are used to insure straightness in the member, the foregoing precautions become less important.

When laminations are glued into a curved member, it is necessary to use pull-down clamps or other means to pull the laminations to the shape of the jig (fig. 34), and retaining clamps to furnish pressure on the glue joints. In drawing an assembly into bent form, free endwise slippage of the laminations must be permitted to provide intimate wood-to-wood contact at all glue-joint areas. When a female form is used, this can be accomplished by drawing the assembly snugly to the form at some central point in the curve and drawing other positions of the assembly approximately, but not too tightly, to the form.

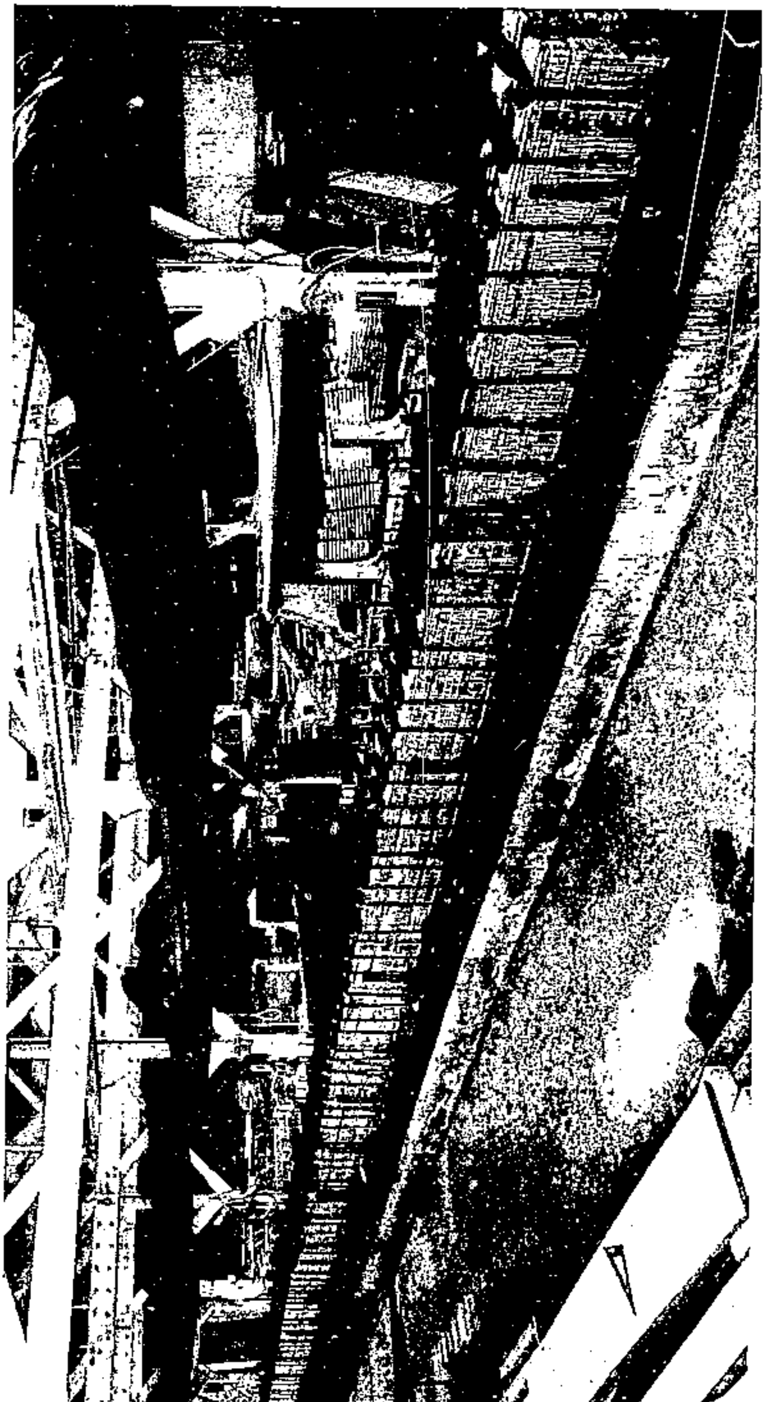

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FIGURE 33.—Laminating straight member, showing pull-down and retaining clamps. Clamped assembly of eight 65-foot-long laminated ship-keel members (in two packages) glued from nominal 1-inch white oak lumber with intermediate-temperature-setting phenol-resorcinol resin.

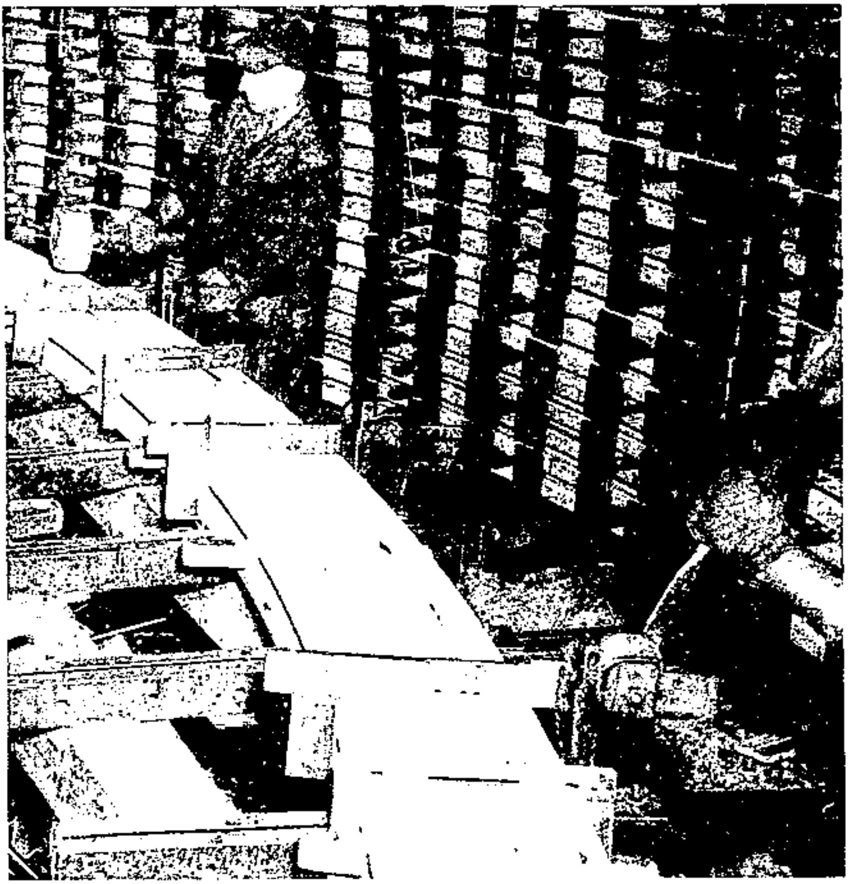

FIGURE 31.—Special type of pull-down clamps used in laminating curved barn rafters.

Then, on each side of the central point, retaining clamps are progressively applied toward each end, and each pull-down clamp is tightly drawn to the form just before a retaining clamp is applied at that point. This procedure enables the bent laminations to slip endwise where necessary to produce uniformly tight joints. If male forms are used, the same technique generally applies, except that application of pressure may begin at either end or at a central point of the assembly. The procedure of progressive use of pull-down clamps, closely followed by tightening of retaining clamps, also applies when male forms are used.

CURING THE GLUE IN LAMINATED ASSEMBLIES

In general, the glues used in laminating set as a result of chemical reaction and loss of solvent. Although some glues, such as casein, resorcinol, and urea resins, may cure adequately at ordinary shop temperatures (ureas should not be used at temperatures below 70° F., and resorcinols require heating to 140° for certain purposes), others require application of considerable heat for adequate curing. When room-temperature-setting glues are used, the joints should be retained under pressure at least until they have sufficient strength to withstand the internal stresses tending to separate the laminations. The length of the pressing period varies somewhat with the lamination thickness, the size of the laminated assembly, the amount of curvature in the glued members, and the water-absorptive power of the wood.

For glues that will cure adequately when held under pressure for a sufficient period at room temperature, setting is sometimes appreciably accelerated when heat is employed. For large timbers, however, it is usually more practical with such glues to allow longer periods under pressure than to furnish heat, because wood is a poor conductor of heat and consequently heats very slowly.

The curing requirements for assemblies made with various types of glues are discussed in the following paragraphs.

Members Glued With Casein

Assemblies laminated with casein glue develop strong joints at ordinary room temperatures. Within the temperature range of 70° to 90° F., a pressure period of 4 to 6 hours is sufficient, although this should be followed by a conditioning period of about a week for development of maximum joint strength. Strong bonds may be obtained with casein glues at temperatures almost as low as the freezing point of water, but under these conditions the clamping period must be increased to several days, or even to several weeks, and depends upon the species glued. Glued members with severe curvature exert more initial stress on the glue bond, so that longer pressing time is recommended.

There is little advantage in heating casein-glued laminated assemblies of considerable size in order to hasten the curing of the glue, but the curing will take place in a minimum time if the lumber at the time of gluing is thoroughly warmed to the highest practical permissible assembly temperature about 90° F. Although warm lumber will accelerate the setting of glue, it will also appreciably shorten the permissible assembly period.

Members Glued With Urea Resin

Urea-resin glues, in general, produce joints of inferior strength and water resistance when cured at temperatures below 70° F. Therefore, the lumber should be heated to at least 70° before gluing, or enough heat should be applied to the glued member to bring all parts of the glue line to this temperature. Straight members glued with urea resins at 70° should be kept under pressure for at least 4 hours to develop enough joint strength to permit releasing the pressure. For heavy, curved members glued at 70°, a pressing period of 6 to 8 hours is recommended. Members laminated with urea resins and cured at room temperature require a conditioning period of about a week at room temperature for the development of maximum joint strength and water resistance.

The application of heat to assemblies glued with room-temperature-setting urea resins has been found beneficial in speeding the cure of the glue when it is possible for heat to reach the glue lines within practical time limits. However, prolonged heating and temperatures above 212° F. are not recommended for curing these glues. Moderate heating of urea-resin-glued assemblies results in somewhat better initial bonds, but the durability of urea-resin glue bonds under exposure to moisture and heat is not appreciably improved by curing under heated conditions.

Members Glued With Intermediate-Temperature-Setting Phenol-Resorcinol, Resorcinol, and Melamine Resins

Intermediate-temperature-setting phenol-resorcinols will cure to a certain extent and develop appreciable joint strength at room temperatures, but it has been found that at these temperatures the glues generally are not completely cured. Room-temperature curing, however, may be adequate for bonding certain low-density species with these glues. These glues are capable of providing durable joints when exposed to moisture, weather, and the like, and the minimum temperature and minimum time requirement for curing them for such service will vary with the glues, the species of wood, and probably with the type of construction.

When gluing white oak with intermediate-temperature-setting phenol-resorcinols for exterior use, a curing temperature as high as 190° F. maintained for as long as 10 hours at the innermost glue line has sometimes been found necessary to develop adequate resistance to delamination. To meet this requirement, the clamped assembly should be heated until all parts of the glue joints have reached this minimum temperature, and it should then be held at or above that temperature for at least 10 hours. Extension of the curing period beyond the 10-hour minimum requirement or at a higher temperature is not detrimental to the glue bond, but such heating should not be carried to a point where it will seriously affect the strength of the wood.

Partial curing in clamps followed by further heating without clamps to complete the cure of the glue may result in defective glue joints because of the temporary softening that often occurs when heating an incompletely cured resin. With less dense species, lower curing temperatures produce adequate bonds. It has been found that with Douglas-fir several intermediate-temperature-setting phenol-resorcinols develop satisfactory bonds in straight members when cured at a glue-line temperature of 110° F. for 10 hours. Curing at 80° (glue-line temperature) and increasing the pressing period to 20 hours have been found equally satisfactory. The assemblies may also be heated to temperatures above 110° in order to hasten the curing of the glue. Southern yellow pine members require heating to 110° (glue-line temperature) or higher for 10 or more hours to produce durable joints. For Central American mahogany, curing at 140° for 10 hours has been found adequate.

Melamine glues also require considerable heating to develop high strength and water resistance. A curing period of 10 hours at 190° F. (glue-line temperature) is recommended for gluing white oak and a similar period at 140° for southern yellow pine and Douglas-fir intended for severe exposure. When a curing period of 10 hours or more is used, it appears inadvisable to employ curing temperatures above 210° with some of these glues.

Members laminated with straight resorcinol-resin glues will develop joint strength adequate for many purposes when cured at temperatures from 70° to 80° F. When softwood species, such as Douglas-fir and southern yellow pine, were being glued, glue bonds cured at these temperatures for 10 hours were found to be durable when exposed outdoors. It is also possible to produce durable joints in laminated members of Douglas-fir, spruce, and similar species with resorcinol-resin glues cured at lower temperatures, if the pressing period is extended. Tests have shown that when pressure is maintained for 14 days, glue joints cured at 50° F. are adequate for some softwood species, such as Douglas-fir and Sitka spruce. With denser and stronger woods, such as white oak, heating of the glue joints to 140° or higher for 10 hours has been found necessary to provide similar durability with some of these glues.

With some glues of the foregoing types, curing may be delayed as much as a week after spreading and clamping have been completed, but others may not perform so well if curing is delayed for several days. The manufacturer's recommendation for the particular glue should be followed.

METHODS OF HEATING CLAMPED ASSEMBLIES

Various means have been devised for applying heat to laminated assemblies to facilitate curing the glue. Each has advantages and disadvantages, and some have distinct limitations. Moderate heating to temperatures of about 120° to 150° F. with proper humidification may be accomplished in a warm room in the plant. A canvas or synthetic-rubber canopy, dropped over the assembly to enclose automatically controlled heating and humidification equipment, involves a relatively low expenditure and may serve satisfactorily. Portable plywood enclosures are also being used for this purpose. Among other means of heating are high-frequency generators and radiant heating. Where temperatures appreciably higher than 150° are required, it is desirable to provide a heated chamber built on the same principles as modern conventional forced-circulation dry kilns, in which the chamber walls, roof, and doors are well insulated against heat and vapor losses. In all cases, the heated room or space must be large enough to accommodate the laminated assembly in clamps and sometimes in the jig.

Heated Curing Chambers

Heated chambers used for curing laminated assemblies at relatively high temperatures should be vaportight and, for the purpose of conserving heat, should be made of materials having good insulating characteristics. Steam coils are usually the most convenient means for supplying heat, and should be of sufficient capacity to enable raising the temperature of the chamber to the desired level in a reasonably short time, usually from 1 to 2 hours. The curing chamber should be equipped with steam or water sprays for maintaining the proper humidity during the heating cycle and with cold-water sprays for supplying humidification during the cooling period.

In a curing operation where an actual glue-line temperature of 190° F. is required, it is most practical to operate the chamber at 210° to 215°. At temperatures much above 215°, it is difficult to maintain the proper relative humidity, and the use of such temperatures is not recommended. Whenever assemblies of a considerable size are to be heated in a curing chamber, it is usually most practical to maintain the chamber temperature at about 20° above the required glue-line temperature. If a smaller differential is used, longer curing cycles that may be impractical will be required.

Radiant Heating

Radiant heat supplied by infrared lamps or electric heaters has been tried for curing the glue in laminated assemblies, but these means are usually less satisfactory than heated chambers because of the difficulty of properly controlling humidity at the surface of the wood. Infrared lamps and strip heaters might be useful, however, for laminating small members in constructions in which relatively little checking will occur when appreciable changes in moisture content are encountered. Radiant heat does not penetrate beyond the surface of the wood and the interior heating is substantially by conduction.

High-Frequency Heating

By the use of high-frequency dielectric heating equipment, all parts of the glue lines in a large assembly can be heated in a relatively short period. This is a distinct advantage over the slow process of transferring heat by conduction from an external source.

If wood is placed in an electric field that oscillates at the frequencies used in the short-wave broadcasting range or higher, heating occurs throughout the mass, and thus it is possible to introduce heat at a rate dependent on the material to be heated and on the power capacity of the equipment. Moreover, if the electric field is applied parallel to a glue line containing water, the glue line can be heated selectively without materially increasing the temperature of the wood adjacent to it.

Although the use of high-frequency circuits in gluing is a comparatively recent development, it is gaining favor for the rapid setting of the class of adhesives that sets at room temperatures or slightly higher. It is currently most applicable whenever a large quantity of a single item is required or when the object to be heated is thick and cannot be heated readily by conduction.

High-frequency dielectric heating equipment is similar to that used in short-wave broadcasting except that, instead of radiating the energy into space, the equipment is so designed that the energy is converted into heat within the mass of wood occupying the space traversed by the high-frequency field. The function of the high-frequency generator is to convert commercial electric power at low frequencies to power at frequencies varying from about 1 to 40 million cycles per second and employing much higher voltages.

The amount of power converted to heat in the dielectric can be increased by raising the voltage. The higher the frequency, the lower the voltage necessary to obtain a given power input to a load. When the working voltage is kept low, there is less tendency toward arcing, which is especially troublesome in parallel heating. Standing waves are most likely to occur at high frequencies, and since these result in uneven heating they must be avoided as much as possible. The effect of standing waves can be reduced by means of tuning stubs or induction coils applied between the eletrodes. It is often necessary to use such coils when gluing long beams.

It is important that the equipment be properly constructed and shielded, otherwise an objectionable amount of high-frequency energy may be radiated and cause interference with radio communication. The Federal Communications Commission has assigned certain frequency bands for industrial induction and dielectric heating equipment, and within these bands there is no limit on the amount of energy that may be radiated. In dielectric heating applications such as curing of glues, however, the electrical characteristics of the material or load are changed while it is being heated, so that with the type of generator commonly used for this purpose the frequency changes and it is difficult to keep it within the assigned band. An alternative means, then, is to shield the equipment so that the amount of radiation comes within the limit permitted by the Federal Communications Commission. Shielding to cut down radiation is considered more practical and less costly than building equipment that will maintain constant frequency under varying load (*20*).

Several methods of utilizing high-frequency energy for the gluing of wood are in use (fig. 35). The most common are those known as parallel heating, perpendicular heating, and stray-field heating. In parallel heating, the field is parallel with the glue lines, and, since these are more conductive than the wood, the wood is not appreciably heated unless the heating period is prolonged. This method is the most economical of the three, but it is generally not considered satisfactory if the length of the glue lines between the faces of the electrodes is more than 3 inches. In perpendicular heating, the field is perpendicular to the plane of the glue joints and the entire assembly is heated. Consequently, more power is required in this method. In stray-field heating, the glue lines are not in direct line with the electrodes, but as in parallel heating, the field is largely concentrated in the glue line. This method is applicable to the gluing of scarf joints in boards that are too wide to make parallel heating practical.

High-frequency heating has been used to a limited extent in commercial production of flat and curved plywood, and to a much greater extent for gluing edge and end joints (fig. 36), furniture panels, and similar products. Recently it has also been used for large-scale production of laminated curved rafters. The resorcinol type of glue is used, and the field is applied parallel to the glue line.

Urea-, resorcinol-, and melamine-resin glues have been used successfully with high-frequency curing. This process is less applicable to hot-press phenol resins because of the high temperatures required to set them. Acid-catalyzed phenols, on the other hand, appear to cure satisfactorily with high-frequency heating, although experience with them is limited. The choice of glue is much more critical in parallel

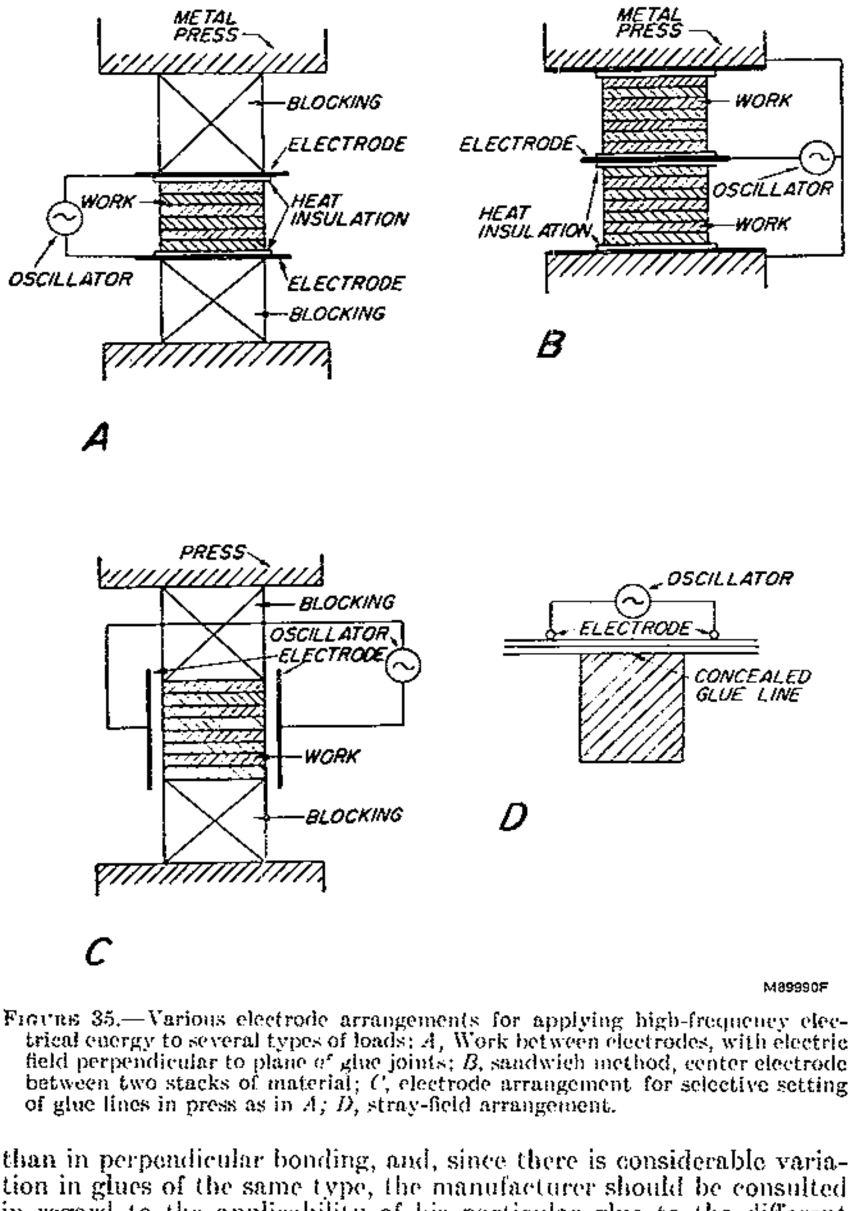

FIGURE 35.—Various electrode arrangements for applying high-frequency electrical energy to several types of loads: *A*, Work between electrodes, with electric field perpendicular to plane of glue joints; *B*, sandwich method, center electrode between two stacks of material; *C*, electrode arrangement for selective setting of glue lines in press as in *A*; *D*, stray-field arrangement.

than in perpendicular bonding, and, since there is considerable variation in glues of the same type, the manufacturer should be consulted in regard to the applicability of his particular glue to the different methods of high-frequency bonding.

The moisture content of the wood affects its conductivity, and the length of time required for curing the glue increases with higher moisture content. Because of the difference in conductivity of wet and dry wood, it is important that the moisture content be uniform throughout the assembly; otherwise the glue might cure nonuniformly.

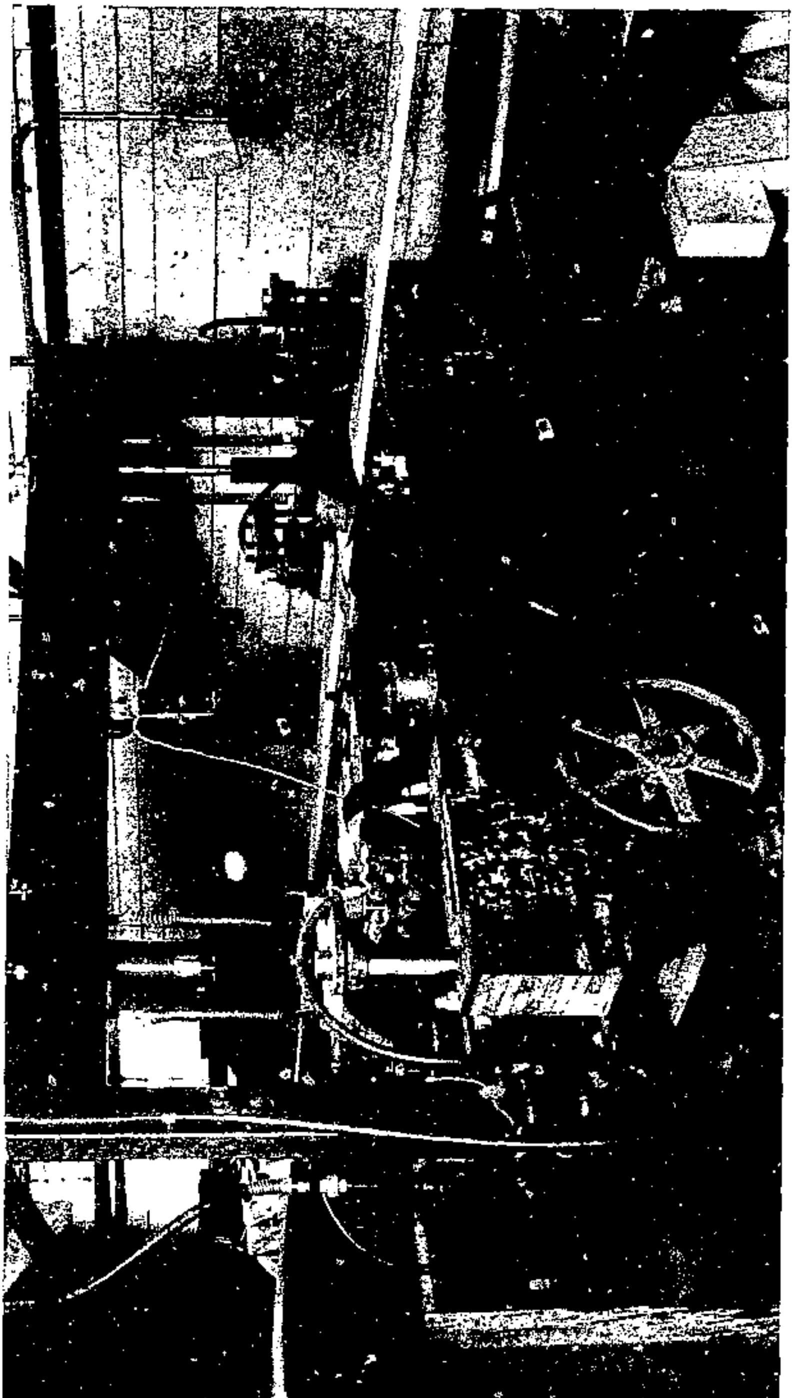

FIGURE 36. High-frequency generator and pressing equipment for scarf gluing.

It is well known that more careful technique is required for successful gluing of the denser species than for less dense ones. This holds true also when high-frequency curing is employed. Longer curing cycles are also required for the denser species.

The application of high-frequency heating to members glued with room-temperature-setting adhesives should be continued until the bond strength is sufficient to prevent separation of joints after the pressure has been released. Several days must then be allowed for conditioning and for completing the cure at room temperature.

RATE OF HEATING IN LARGE ASSEMBLIES

The rate at which heat is transferred from the surface to the center of a laminated assembly varies somewhat with the species and the moisture content of the wood and depends a great deal upon the dimensions of the assembly. Figures 37, 38, and 39 show the rate at which members of white oak and Douglas-fir assembled with cauls and clamps heat in curing chambers maintained at the temperatures indicated. Heating periods required for other sizes can be calculated by the use of formulas (*13*). When several assemblies are clamped in one package, the rate of heat transfer to the interior of the package may be considerably increased by inserting sheets of aluminum between the assemblies. This procedure is especially advantageous when several wide assemblies are clamped in one package.

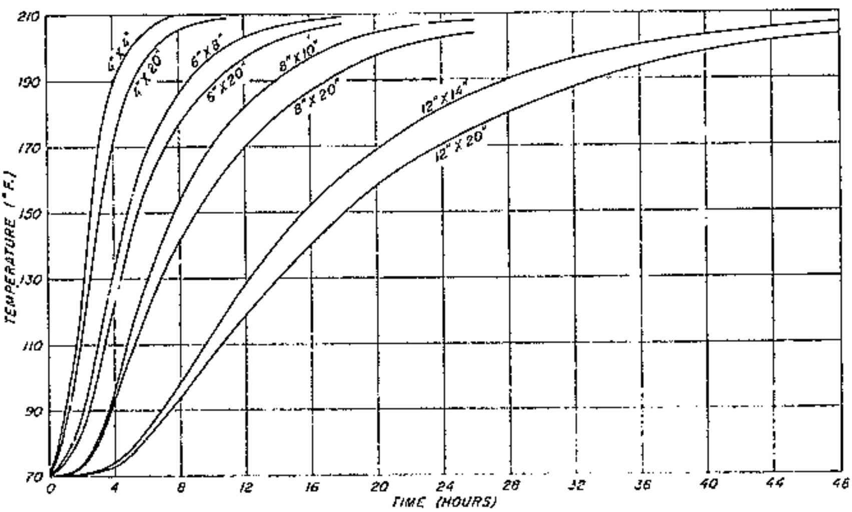

FIGURE 37.—Glue-line temperatures at center of laminated members. Curing temperature, 210° F. Relative humidity, 80 percent.

The total curing cycle may be considered as consisting of three parts:

(*a*) Heating the assembly to bring all parts of the glue lines to the minimum temperature required for curing the glue.

(*b*) Maintaining this minimum temperature or a higher temperature at all glue lines for the required curing period.

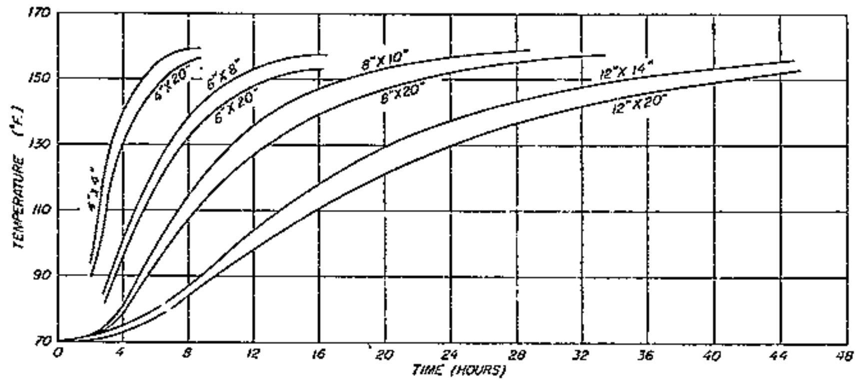

FIGURE 38.—Glue-line temperatures at center of laminated members. Curing temperature, 160° F. Relative humidity, 80 percent.

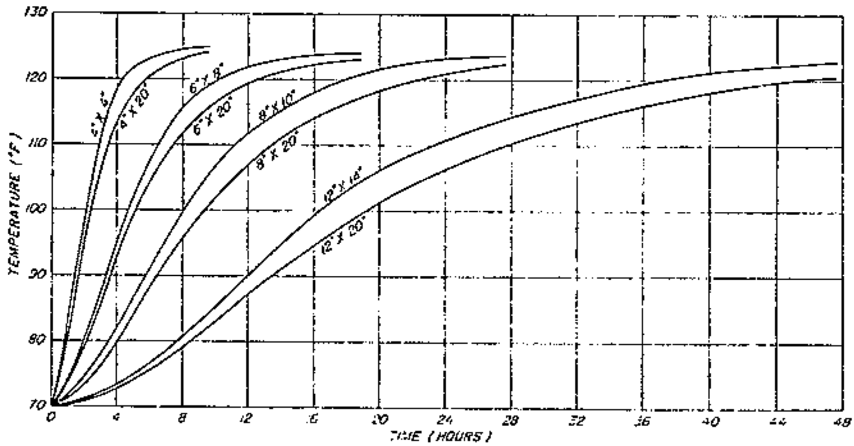

FIGURE 39.—Glue-line temperatures at center of laminated members. Curing temperature, 125° F. Relative humidity, 75 percent.

(*c*) Cooling the laminated assembly. The length of time that the glue joints are at or above the minimum curing temperature during this period may be considered as a part of the required curing period.

Although the outer area of a laminated assembly may be expected to heat rapidly as the atmosphere of the curing chamber is raised in temperature, hours may be required before the glue line at the center of the assembly will reach the temperature required to cure the glue. During the cooling period, however, the outer area cools first, and hours may again elapse while the center remains at or above the minimum curing temperature. Consequently, cooling can be started before the required curing time for the innermost glue line has elapsed.

The use of thermocouples and a potentiometer is recommended to check the interior temperatures during curing, particularly when laminating the first few members of a particular size and shape.

In addition to placing thermocouples at various points within a member, it is also desirable to place some on the outside surfaces.

During the heating-up period, the wet-bulb temperature should be kept slightly lower than the surface temperature of the member. If this is done, condensation on the timbers will be avoided.

After the heating has been carried on for the required period, it is necessary to cool the member to room temperature without appreciable drying, in order to avoid surface checking. Ordinarily, cooling is accomplished by shutting off the steam supply to the heating coils and to the steam spray. Water vapor will usually escape from the chamber so rapidly during the cooling period, however, that the relative humidity will become very low and the surface of the wood will dry and check. It is important, therefore, to control the relative humidity also during the entire cooling period. A satisfactory method of rapid cooling is to inject a fine water spfay or mist into the circulating air of the curing chamber during the cooling period. This is conveniently done by means of spray nozzles attached to the cold-water supply. Use of compressed air in the water-spray line helps to avoid clogging of the spray nozzles. The introduction of water spray or mist, however, should be controlled to avoid wetting glued members.

HUMIDIFICATION OF HEATED CHAMBERS

When wood is heated in an atmosphere of low relative humidity for a number of hours, the wood dries and tends to shrink. This shrinkage may cause checking of the wood or opening of the glue joints along the edges before the glue has cured sufficiently to withstand the drying stresses. If a high relative humidity is maintained in the curing chamber, however, the wood will not dry and thus will not shrink or check, and the glue joints will remain tight. It is desirable to provide a relative humidity that will maintain the moisture content of the wood in the laminated assembly. Figure 40 indicates, for example, that to maintain a moisture content of 10 to 12 percent in wood heated to 210° F., a relative humidity of 80 to 85 percent is required. At a curing-chamber temperature of 210°, such a relative humidity requires a wet-bulb temperature of 199° to 202°.

Humidity refers to the amount of water vapor in the atmosphere. Absolute humidity is expressed in terms of the weight of water vapor per unit volume of air. For example, at ordinary shop conditions the amount of moisture in the air may amount to 5 grains of water vapor per cubic foot. Relative humidity is the ratio of the amount of moisture present to the amount of moisture required to saturate the atmosphere at the same temperature. For example, if the air in a shop operating at a temperature of 70° F. contains 5 grains of water vapor per cubic foot, its relative humidity is 62.5 percent, because it will contain 8 grains of water vapor per cubic foot when saturated (100 percent relative humidity) at 70°.

The moisture-holding capacity of the atmosphere is greatly increased with increase in temperature (almost doubled for each 20° F. rise in temperature). At 210° the capacity of the atmosphere rises to 255 grains of water vapor per cubic foot, and a relative humidity of 80 percent requires about 204 grains per cubic foot. Obviously, in order to provide sufficient moisture in a curing chamber to avoid drying of the glued assembly, it is necessary to add a considerable amount of water vapor to the atmosphere. The vapor can be most

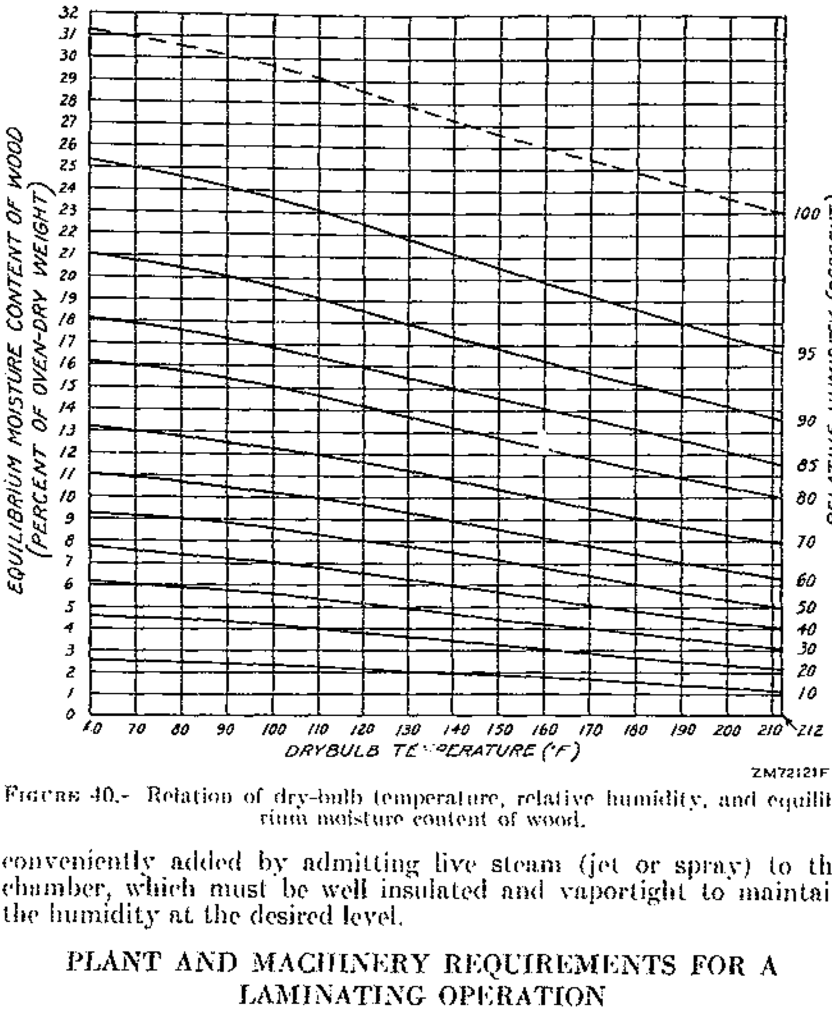

FIGURE 40.—Relation of dry-bulb temperature, relative humidity, and equilibrium moisture content of wood.

conveniently added by admitting live steam (jet or spray) to the chamber, which must be well insulated and vaportight to maintain the humidity at the desired level.

PLANT AND MACHINERY REQUIREMENTS FOR A LAMINATING OPERATION

The fabrication of strong and dependable glued laminated wood products requires careful and accurate preparation of the lumber. Plant facilities and machinery should be capable of turning out a product exhibiting a high quality of workmanship. Accurate machining of the lumber to obtain well-fitted joints, controlled glue spreading, adequate clamping of the assembly, and sufficient curing of the glue are necessary to produce dependable joints. Average woodworking machinery and hand-fitting of joints do not generally lend themselves to production of high-strength and uniformly consistent glue bonds.

The equipment and facilities required for the different laminating operations may vary considerably according to the type and size of members to be produced. All of the equipment described in this section may not be necessary for satisfactory laminating, but it is included for the convenience of anyone entering the laminating field.

PLANT SPACE

The amount of floor space required for a plant for laminating lumber products depends on three major factors: (*a*) The source of dry lumber or the facilities for kiln drying and storing lumber, (*b*) the anticipated daily production, and (*c*) the size and shape of the laminated material.

By assuming that a plant intended for fabrication of laminated members already has facilities for drying and storing lumber and that its expected daily output has been decided, the amount of floor space required for that output will then depend upon the type of members to be manufactured.

If the material is to be fabricated into lengths greater than those obtainable from the standard lengths of lumber, space must be provided for scarfing operations involved in producing these lengths. The required space must be long, but may be comparatively narrow. It is not essential that scarfing, gluing of scarfs, and their curing prior to final surfacing be done in the same space or department in which the final assembly is undertaken.

Space should be provided for the inspection of lumber and for dry assembly of laminations to their final package size before they are glued. Such provision will permit placing the laminations in the correct position for the required spacing of scarfs and for assembling the proper number of pieces for each package.

The space required for spreading glue is slightly more than twice the length of the longest member to be fabricated. Some space can be saved by mounting the spreader on casters, so that it can be moved easily, but ample space is nevertheless highly desirable.

The space requirements for fixed clamping beds or jigs are somewhat greater than those for mobile equipment, but such a plant layout is advantageous if the material is to be cured on the bed. The beds may be in rows, and the finished material may be removed from the beds by hoist or other mechanical means. The total space requirements for a fixed-bed type of operation will depend upon the size and number of fixtures needed for the required curing cycles and upon the desired production capacity.

DRY KILNS

In general, it is desirable that the fabricator have at his plant, or have access to, kilns of such design that lumber for laminating can be dried uniformly and stress-free to meet the requirements of good laminating procedure. A source of well-dried lumber is satisfactory if the fabricator does not dry the lumber himself. Equipment for determining the moisture content of lumber must be available.

STORAGE BUILDINGS

It is often necessary for the fabricator to have facilities for the dry storage of kiln-dried lumber in enclosed and sometimes in heated buildings.

Sawing and Jointing Equipment

The fabricator will generally require the following sawing machinery to prepare lumber properly for gluing:

(*a*) Chain-fed ripsaws capable of ripping a true straight edge suitable for the edge gluing of lumber.

(*b*) Crosscut saws for trimming boards and removing defects.

(*c*) A band resaw, usually required when thin laminations are needed for laminating sharply bent items, and also advantageous for resawing items that can be glued in multiple widths.

Edge- and Scarf-Joint Gluing Equipment

Clamping equipment for edge gluing may consist of hand clamps, clamp carriers, piling clamps, or other devices to apply and hold pressure satisfactorily on the edges of boards during the edge-gluing operations.

Equipment for end jointing of lumber may be a planer, shaper, tenoner, milling head, or any other device to produce the fingered, plain, or serrated surfaces of the shape and uniformity required.

Scarf-gluing pressure equipment may be hydraulic or screw presses, C-clamps, or any suitable device to apply and hold pressure during the gluing and curing of scarf joints.

Surfacing Equipment

The rough planer is used for the initial surfacing of both sides of kiln-dried rough lumber. Either a single or double planer is satisfactory.

The cabinet surfacer is an essential piece of equipment. It may be a single- or double-cylinder, ball-bearing machine, capable of being set to surface lumber accurately within close limits. Preferably, it should be not less than a six-roll machine.

Glue Storage, Mixing, and Spreading Equipment

Adequate storage facilities that will enable storage of glue under cool and dry conditions are often advantageous. For intermediate-temperature-setting phenol-resorcinol resins some means of refrigeration may be desired in order that temperatures as low as 30° to 40° F. may be maintained in the storage room.

Equipment for mixing glue must be designed to produce a homogeneous mixture of the various glue ingredients with the least amount of agitation. Equipment made of materials easily attacked by acids or bases should not be used with glues that are highly alkaline or highly acid. Mixers made of steel are suitable for most laminating glues.

Casein glue may be applied with glue spreaders equipped with properly corrugated metal rolls or corrugated rubber-covered rolls. The equipment for applying resin glues should be a double-rubber-roll spreader, with adjustable doctor rolls to control the amount of spread. The rate of feed should be about 50 to 100 feet per minute. A single-roll spreader is suitable for edge gluing. Suitable scales are essential for checking glue spread.

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Gluing Jigs, Forms, Clamps, and Handling Equipment

The type of jigs, beds, and fixtures necessary will depend largely on the type of laminating to be done. It is desirable that the jigs for curved work be readily adjustable. The use of fixtures that are rigid and nonadjustable is likely to be costly unless large quantities of material of a given size and curvature are required. All jigs and fixtures should permit the finished package to be readily removed from the form, but must be sufficiently strong and rigid to withstand the pressures of bending curved work to the contour of the jigs without being deformed. Flat beds for clamping straight members should be of such construction as will prevent the material from slipping out of place during the clamping operation.

Provision should be made for the mechanical handling of heavy members by overhead hoists, floor cranes, or other lifting equipment. The weight of the finished laminated material with the clamps added may sometimes be several thousand pounds, and then special consideration must be given to the handling problem. Overhead hoists may be most effective, but floor cranes can also be used to advantage if they are designed and sized to span the gluing beds. If trucks or dollies are used, a flat and preferably level floor is necessary. Otherwise the bed of the dolly might follow the warping and slope of the floor. The package would then be cured in a distorted position, and the distortion would be permanent. This danger is most pronounced in thin packages. Precautions should be taken at all times to see that the laminated packages in retaining clamps are evenly and well supported and in proper alinement.

Retaining clamps should be sturdy and readily adjustable for different sizes of packages It is desirable that the clamps have some compensating device by which the pressure will be applied uniformly across the assembly. I-beam retaining clamps or other types of frame clamps can be used. Their heads and bases should be sufficiently rigid to prevent distortion during clamping and should be capable of maintaining required loads.

Curing Chambers

Separate curing chambers are desirable for some types of gluing. With certain types of large members that are difficult to handle, it may be necessary, however, to precure or fully cure the glue while the members remain in the jigs in which they are formed, because of the danger of distortion when they are moved to a separate curing chamber. If provision is made for curing in a separate chamber, it will be desirable to glue and clamp the assembly on movable trucks or dollies. The glued material, thus clamped, is stored until a sufficient quantity has been assembled to charge the curing chamber.

Laminated products glued with adhesives that cure at room temperatures can be cured adequately in the room in which the gluing is done. If the adhesives require elevated temperatures for adequate curing, however, heated chambers provided with accurate control of temperature and humidity are necessary. The closest approach in a woodworking plant to the kind of control required is the internal-fan dry kiln, which seldom, however, has been designed or constructed to maintain the highest (210° F.) temperatures and relative humidities required for this purpose. Curing chambers should be provided with:

(a) Heating coils of ample capacity to heat the chamber to the required temperature (sometimes as high as 210° F.) in a period of about 2 hours. A heating unit installed as a return-bend system in a chamber not more than 50 feet long will ordinarily, under thermostatic control, be able to provide a uniform temperature distribution. It is desirable to have the heating system subdivided into several sections, so that only part of the heating coils need be used after the chamber is heated to the desired temperature. In longer chambers, it is desirable to have a separate heating system for each half-chamber length, each separately controlled by a thermostat, to maintain uniform temperatures.

(b) Highly vaportight and well-insulated building construction. The inner face of the chamber structure should prevent the ready passage of water vapor. (The vapor pressure within the curing chamber at 210° F. and 80 percent relative humidity is approximately 12 pounds per square inch, which will cause considerable vapor leakage through structural openings, cracks, or permeable wall materials.) Painting the inside faces with a good grade of asphaltic kiln paint is very helpful. Outdoor surfaces should not be vaportight. In addition to being vaportight, the chamber should be well insulated against heat loss to avoid condensation on the interior faces of the chamber.

The wall construction of a dry-kiln type of curing chamber may be of conventional hollow tile, brick, or similar material. In small units, vaportight cement-asbestos-board interior lining, applied over insulating board, and interior joints sealed with asphaltic plastic are satisfactory for use inside enclosed buildings. Requirements for heating, humidifying, circulation of air, cooling, and automatic instrument control in such a small chamber are the same as those for large installations.

(c) Forced-air circulation system. The uniform control of temperature and relative humidity is much easier if there is mechanical equipment for producing definite circulation of the air in all parts of the curing chamber. The circulation of air in the curing chamber may be readily observed by releasing chemical smoke (titanium tetrachloride) into the chamber with the circulation system in operation. It is most practical to do this while the chamber is cool.

A curing chamber for certain applications can be provided by enclosing the glued assembly, heating coils, and steam spray, with or without mechanical equipment for circulating the air, within a rubber-treated canvas that is highly vaportight. The useful life of the canvas covering is relatively short, but it may be practical in certain instances. Synthetic-rubber or portable plywood enclosures are also used for this purpose.

It is desirable to have the curing chambers located where escaping vapor will not interfere with moisture conditions in the plant.

(d) Equipment to provide high humidity. During heating and curing a live-steam spray system controlled by a wet-bulb thermostat is satisfactory for supplying the required humidity. Steam sprays are undesirable during cooling, however, since they will admit heat also. The use of a water mist or fog injected into the circulating air by spray heads or by an air-operated spray gun is very effective.

Equipment for Surfacing Glued Products

Most cured glues tend to dull the knives of surfacing equipment, so that it is undesirable to use finishing planers or jointers for the surfacing of glued products. A portable planer of the type shown in figure 41 is convenient for rough surfacing of either straight or curved members. Timber sizers or shapers may also be used to advantage if the dulling effect of the glue squeeze-out is not too objectionable. Removing the squeeze-out by use of scrapers prior to surfacing will reduce the wear on planer knives.

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Figure 41.—Portable planer used for surfacing straight or curved timbers.

CONTROL INSTRUMENTS

Certain control instruments may be considered essential to the fabricator of laminated material. They include:

(*a*) Equipment for determining the moisture content of lumber—drying oven, scales, and moisture meter.

An oven that can be operated at 210° to 220° F. with temperature control is suitable.

An accurate triple-beam balance or its equivalent, capable of weighing to 0.01 gram, is suitable for weighing samples for moisture determinations.

A resistance-type moisture meter is suitable for rough checking of the moisture content of untreated lumber.

(*b*) A screw type of micrometer (or its equivalent) measuring to 0.001 inch, which is suitable for measuring the thickness of lumber when setting up the finishing planer and for checking stock thickness. Slip-on gages are convenient for checking the thickness of the surfaced laminations.

(*c*) A balance capable of weighing accurately to 1 gram, which is suitable for determination of glue spread.

Equipment not always necessary, but useful in a laminating operation, includes the following:

(*a*) A compressometer with gage, which is suitable for checking the pressures developed with different types of clamps when various amounts of torque are applied to the nuts.

(*b*) Torque wrenches, which are suitable for measuring torque when applying and checking gluing clamp pressure.

(*c*) A potentiometer (electric thermometer) and thermocouples, which, when assemblies are heated in a curing chamber, are desirable for determining temperatures within the package during heating and cooling. These determinations can be made accurately by the use of thermocouples of the proper type for the particular potentiometer.

(*d*) Equipment for making glue-joint shear tests. If the fabricator does not have it, he should have available to him the services of some laboratory to make such tests.

(*e*) Equipment for making accelerated delamination test. (ASTM Designation D1101–50T.)

METHODS OF EVALUATION OF PRODUCT

The usefulness of a laminated member is determined by the lumber used and by the glue joints produced. These cannot be fully evaluated merely by a visual inspection of the finished product. Adequate control of the entire laminating process is extremely important, and standardized inspection of the materials and processes, as well as glue-joint tests on sample material, is very helpful in assuring the production of dependable glued members. Since in many types of tests for the quality of glue bond in laminated material the test specimens are loaded to destruction, such methods are consequently not applicable to whole members intended for use. To obtain samples for testing, however, the members may be made somewhat longer than required in use and the extra length can be cut off for test specimens, or short sample beams may be laminated, glued, and cured under conditions identical to the production run. The quality of the glue bonds in these test specimens and in the members intended for structural purposes should be comparable.

Quality of Materials

The type of glue required is usually specified in a contract, and whether it is being used or not can be readily verified at the time of fabrication. Determination of the type of glue in a finished product, however, may require performance tests and chemical analysis. Even so, the quality of the glue cannot be differentiated from the quality of the technique with which it was used. The grade of the lumber in the laminations making up a member may be readily checked immediately after final surfacing but before gluing. The finished member can be inspected for defects appearing on the surface, for proper spacing of end joints, and for open glue joints that may occur along the sides of the member.

Testing Glue-Joint Strength and Quality

The adequacy of the gluing procedure and the initial strength of the glue joint can to a large extent be determined by the dry block-shear test. Standard block-shear specimens can be cut from the laminated product or from a separate sample laminated beam. The types of shear specimens used in this test are shown in figure 42. Either the stairstep or the standard block type of shear specimen may be used. The former is somewhat more convenient to cut from laminated members. It is recommended that for each 6-inch width of laminated member (measured across the width of the laminations) at least 1 shear test be made upon each glue line, and that the total number of tests per member tested be not less than 5.

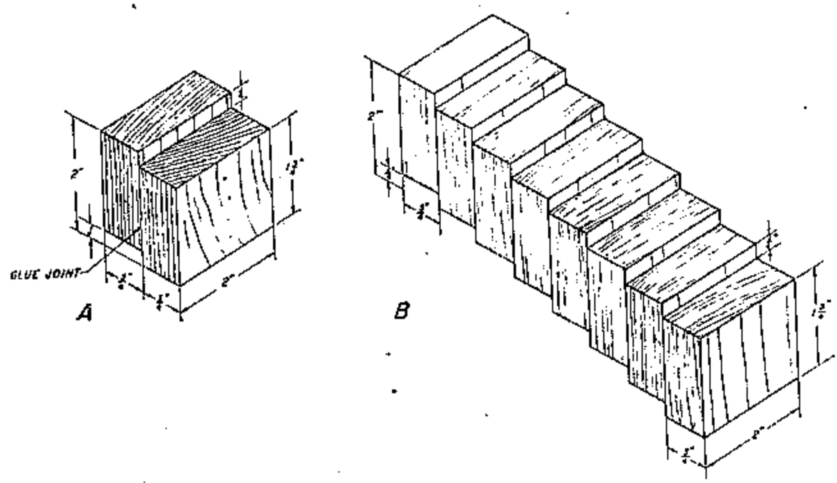

FIGURE 42.—Standard block (*A*) and stair-step type (*B*) shear specimens for testing glue-joint strength.

A storage and conditioning period of at least 5 days at a temperature from 70° to 100° F. should be allowed between gluing and testing for members glued and cured at room temperature. When assemblies have been heated fully to cure the glue bond, specimens may be tested immediately upon being cooled to room temperature.

Shear blocks should be tested in a machine equipped with the shear tool illustrated in figure 43. The load should be applied to the specimen at a rate of 0.015 inch per minute plus or minus 25 percent.

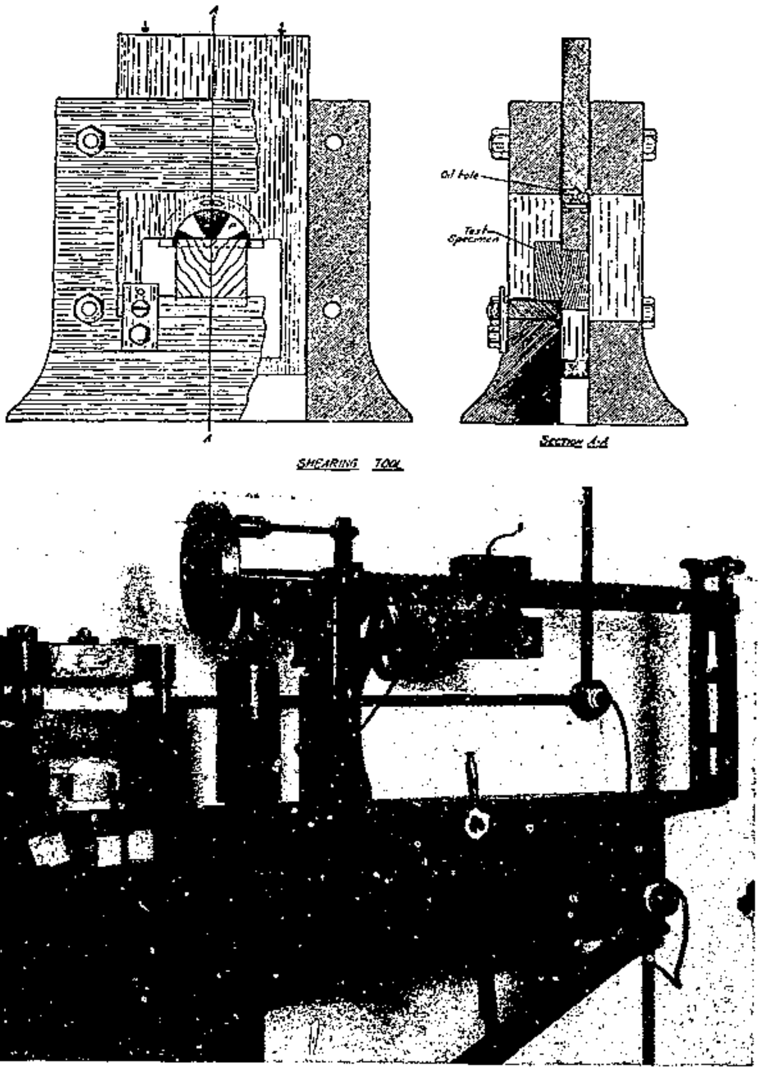

FIGURE 43.—Shearing tool and testing machine used in glue-joint testing.

The breaking load should be expressed for each specimen in pounds per square inch of glue-joint area, and the percentage of wood failure occurring over the glue-joint area should be estimated. Shear-strength values may be adjusted for variations in the moisture content of the wood by the use of table 4.

The shear-strength values given in the column for 12 percent moisture content in table 4 are computed as 90 percent of the value for clear wood. Adjusted strength values for other moisture content values below the fiber saturation point may be calculated by use of the values given in the last column of table 4.

TABLE 4.—*Shear strength of glue joints in laminated construction of different species at various moisture content values*

Species	Moisture content: 8 percent	Moisture content: 12 percent	Moisture content: 16 percent	Moisture content: At fiber saturation point or higher	Increase in shear strength for each 1 percent decrease in moisture content
	P. s. i.	*P. s. i.*	*P. s. i.*	*P. s. i.*	*Percent*
Redwood	910	850	790	720	1.7
Douglas-fir	1,100	1,030	960	840	1.7
Western hemlock	1,160	1,050	950	730	2.5
Pine, southern (shortleaf)	1,360	1,180	1,020	760	3.7
White oak	1,940	1,700	1,490	1,140	3.4
Sugar maple	2,450	2,100	1,800	1,310	3.9

Specimens that show strength values below the required average for the species and wood-failure values of 75 percent or more should be excluded in calculating the average of the test results. Specimens with knots, pitch pockets, or other defects in contact with the glue line should also be excluded in forming the average.

MEMBERS FOR CONTINUOUSLY DRY USE

Laminated wood products intended for continuously dry use (moisture content not more than 20 percent) should have glue joints that consistently meet the average strength requirements shown in table 4 when tested dry by the block-shear method, and, in addition, should develop average wood-failure values of not less than 50 percent. With good control of the gluing process, wood-failure values considerably higher than 50 percent can be obtained with most species.

MEMBERS FOR EXTERIOR USE

Laminated members intended for exterior exposure are expected to perform satisfactorily under conditions as severe as continuous soaking in water, alternate soaking and drying, or exposure to steam without serious delamination of the glue joints. Tests have shown that glue joints sufficiently durable for such exposures must develop high shear-strength and wood-failure values and, in addition, must be highly resistant to delamination in cyclic soaking and drying tests. The glue joints in such timbers should meet consistently all the following requirements:

1. Satisfy the shear-strength values shown in table 4, and, in addition, show average wood-failure values of not less than 50 percent.

The dry block-shear test can be carried out quickly and might be used as a continuous check on the production. For greater assurance of the adequacy of the glue joints for exterior service, the delamination test should be applied.

2. Show a shear-strength value equal to 90 percent of the value at the fiber saturation point (table 4), and an average wood-failure value of not less than 75 percent on standard shear blocks that have been boiled in water for not less than 12 hours, thoroughly cooled by immersion in cold water, and tested wet. This test is recommended for checking whether the glue is of a type suitable for exterior use. It is not recommended as a daily control test, but would be useful for checking each shipment of glue.

3. Show openings in the glue joints averaging not more than 10 percent when tested according to either Procedure A or Procedure B, which follow. For either test, cut 3 cross sections, each with a length (along the grain) of 3 inches, from the laminated member or sample beam, or preferably 1 section from each of three different beams. The end-grain surfaces of the sections should be cut or sanded to a smooth condition.

Procedure A. Place the test specimens in an autoclave or other type of pressure vessel and immerse them in water at room temperature of 65° to 80° F. The specimens should be weighted down to keep them submerged, and separated by stickers or other means in such a manner that all end-grain surfaces have free access to the water. Draw a vacuum of at least 25 inches of mercury (at sea level) and maintain it for 2 hours. Then release the vacuum and apply a pressure of 75 ± 5 pounds per square inch for 2 hours. Repeat this vacuum-pressure cycle with the specimens still immersed, making a 2-cycle impregnating period requiring a total of 8 hours.

Dry the specimens for a period of 88 hours (3⅔ days) in air at 80° to 85° F. and 25 to 30 percent relative humidity and circulating at a rate of at least 200 feet per minute. During drying, the specimens should be placed at least 2 inches apart and with the end-grain surfaces parallel to the stream of air. Repeat the entire soaking-drying cycle twice to comprise a total test period of 12 days. At the end of the final drying period measure the total length of open glue joints (delamination) on the end-grain surfaces of the specimens to the nearest 1/16 inch (0.05 inch). Failure in the wood due to checking or other causes should not be regarded as delamination.

Procedure B. Soak the specimens by immersing them in water at room temperature for not less than 15 days, and then dry them as in Procedure A. After three soaking-drying cycles, measure delamination as in Procedure A.

The total length of open glue joints on the two end-grain surfaces of each specimen is expressed as a percentage of the entire length of the glue joints exposed on these surfaces (except that glue lines at knot areas are omitted), and this value is referred to as the percentage delamination of the specimen.

As a substitute for an autoclave or other suitable pressure vessel, the type of equipment shown in figure 44 has been used successfully at the Forest Products Laboratory in carrying out the test described under Procedure A.

This equipment consists of two water-softener tanks bolted in a vertical position to a welded angle-iron frame. A welded iron-wire cage with slots large enough to hold the test sections fits into each tank and keeps the specimens separated and submerged. Water

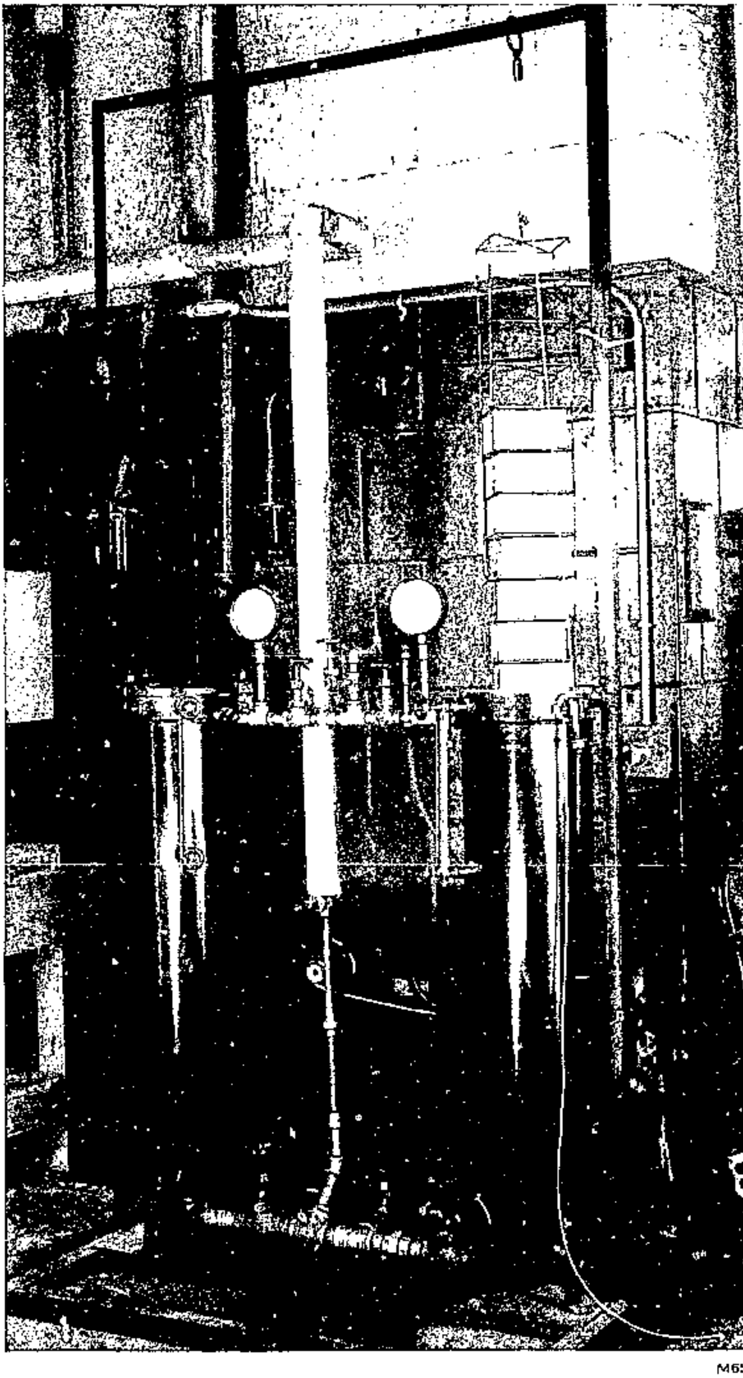

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FIGURE 45.—Pressure tanks suitable for use in accelerated soaking-and-drying test of laminated sections.

pressure is supplied from the city water line, and vacuum is obtained by use of a small suction pump. Each tank can be operated separately and is fitted with a vacuum-pressure gage and a glass gage to indicate the water level.

The frequency of application of the various tests recommended depends upon the type and size of members produced. Systematic checking of the quality of the product, however, would undoubtedly be valuable in any operation. The dry block-shear test is the least time consuming of the tests given and might be applied daily to a certain number of specimens. As previously mentioned, the boiling test would probably be required only once for each shipment of glue. The cyclic test might be required occasionally, but probably not nearly so frequently as the dry shear test.

PRESERVATIVE TREATMENTS OF LAMINATED WOOD AND GLUING OF TREATED WOOD

Glued laminated members used under continuously dry conditions are not subject to decay of the wood or deterioration of the glue by micro-organisms, and both wood and glue can normally be expected to give long service. Fire, however, can destroy both, and it is sometimes desirable to protect the member by treating it with fire-retardant chemicals. These treatments may be given in the form of external paint coatings before or after ultimate installation, with little possibility of damage to the glue joints. Pressure-impregnation treatments, however, with fire-retardant chemicals in water solution will likely damage casein and urea-resin glue joints because of the action of the water and subsequent drying. If pressure impregnation with water-borne chemicals is required, it is recommended that exterior-type resins be used.

Certain fire-retardant chemicals will raise the equilibrium moisture content of wood. Because of the higher equilibrium moisture content of wood treated with chemicals, some reduction in strength of the wood can be expected and may need to be taken into account in structural design.

The wood in members used under wet or humid conditions in either interior or exterior exposure is subject to decay, and its useful life may be appreciably prolonged by the application of preservatives (*10*). The ability of the phenol, resorcinol, and melamine glues in well-cured joints to maintain their strength and resistance to delamination beyond the useful life of untreated wood often makes it desirable to apply preservatives to the laminated member. Glue joints in laminated members bonded with these glues are not appreciably affected by cold or hot water, oils, or most chemicals that do not damage wood. Results of tests indicate that such glued members may be treated with any present-day commercially used wood-preserving or fire-retardant chemical without appreciable damage to the glue joint. Information on the performance of glue joints in laminated members treated with wood-preserving and fire-retardant chemicals is limited to weather-exposure tests and service tests extending over a period of 5 to 6 years, so that the conclusions just stated are subject to revision after further study and tests.

Less information is available concerning the ability of laminating glues to develop adequate bonds on lumber that has been treated with wood-preserving chemicals prior to gluing. Gluing of preservative-treated lumber may often be advantageous, since treatment of laminated members may be inconvenient, and sometimes impossible, owing to their size or shape. Casein glues do not perform satisfactorily under conditions where the use of preservative-treated wood is required, and only exterior-type resin glues are adequate for this purpose.

In the case of oil-borne preservatives, such as creosote, results of tests have indicated that resorcinols and resorcinol-modified phenols will adequately bond southern yellow pine when the treatment is not sufficiently heavy to cause appreciable bleeding in subsequent surfacing and gluing operations. Results of tests have indicated that red oak and maple also can be glued satisfactorily under similar conditions of treatment. Where bleeding of creosote occurs, removal of the exuded preservative by wiping with clean rags was beneficial, and wiping with rags dipped in acetone was particularly helpful. To remove as much as possible of the excess creosote, it is advisable to stand the lumber on end to facilitate drainage. Lumber that was permitted to drain for several weeks to several months was more easily glued than freshly treated lumber.

Surfacing is necessary after treatment and before gluing, because the treatment often leaves a deposit on the surface of the lumber that is likely to interfere with good bonding. The necessity for surfacing after treatment is, in one way, a disadvantage, because of removal of part of the lumber that has the highest preservative retention. Surfacing of the lumber before treatment is therefore desirable, since it facilitates the use of a lighter cut in the final surfacing of the lumber.

When the treatment is with water-borne chemicals, the moisture content of the wood is increased appreciably. Upon redrying, the lumber generally is too variable in thickness to be suitable for good gluing, and resurfacing becomes necessary. Some water-borne preservative and fire-retardant chemicals used on wood appear to be compatible with certain laminating glues, and adequate bond can be obtained if the lumber is surfaced after treatment. The data available are limited, however, and the glue manufacturer should be consulted to ascertain the compatibility of glue and treatment.

In general, test results have indicated that satisfactory bonds can be obtained with many species-preservative-glue combinations, but that procedures used when gluing untreated lumber may have to be varied for treated lumber. For instance, higher curing temperatures are often required when gluing treated wood.

Part II. DESIGN

BASIC FEATURES OF GLUED LAMINATED WOOD CONSTRUCTION

Glued laminated wood can be used in a wide variety of structures, such as buildings, bridges, aircraft, and boats. Its versatility is enhanced by the fact that it can be made to required forms and sizes without regard to standard sizes and shapes and is free of the limitations commonly imposed on timber structures by the sizes and lengths of available solid material. Although large structures are usually laminated from material in lumber thicknesses, it has been found (see appendix) that laminating with veneer gives comparable results.

Some designers of glued laminated members have proposed that, in addition to the glue, mechanical fastenings be used for joining the laminations. It should be noted, if such a procedure is contemplated, that mechanical fastenings of all types can be expected to carry but little load until some relative movement of the joined parts has occurred. Glued joints will not permit the relative movement necessary to enable the mechanical fastenings to become fully effective, so that the use of mechanical fastenings to supplement the strength of the glued joints is impractical—they cannot be fully effective until the glue joint has failed, and even then cannot be expected to provide shear strength equivalent to that provided by the glue.

Beams of glued laminated wood may be either horizontally or vertically laminated. A horizontally laminated beam (fig. 45, *A*) is one in which the loads on the beam act in a plane normal to the plane of the laminations, and is probably the most commonly used form. A vertically laminated beam (fig. 45, *B*) is one in which the loads on the beam act in a plane parallel to the plane of the laminations. In the horizontally laminated type, edge joints in laminations that must be wider than the boards available need not necessarily be glued, since their strength normally will not affect that of the beam. In the vertically laminated type, however, the strength of edge joints in laminations is of considerable importance, since their strength will affect the shear strength of the beam.

Glued laminated construction is particularly adapted to use in arches or in curved beams, since laminations can be used that are thin enough to permit bending them to the required curvature. Laminated arches are commonly designed as 2-hinged (fig. 46, *A*) or 3-hinged (fig. 46, *B* and *C*). Arch designs involving fixed ends should give consideration to the fact that, over a period of time, the fixity may be reduced by working of the connections that results from deformations due to load and from shrinking and swelling due to changes in moisture content.

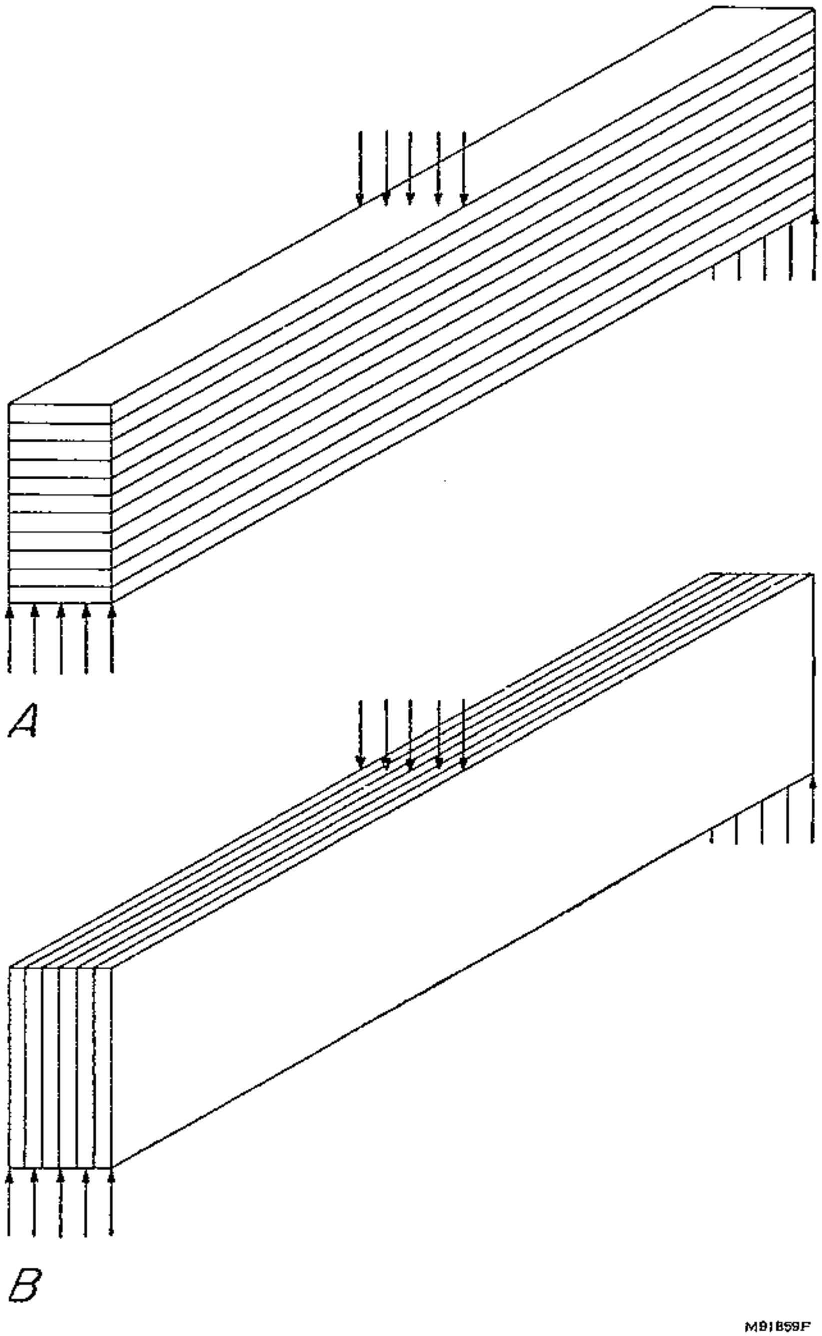

FIGURE 45.—Laminated beams: *A*, Horizontally laminated; *B*, vertically laminated.

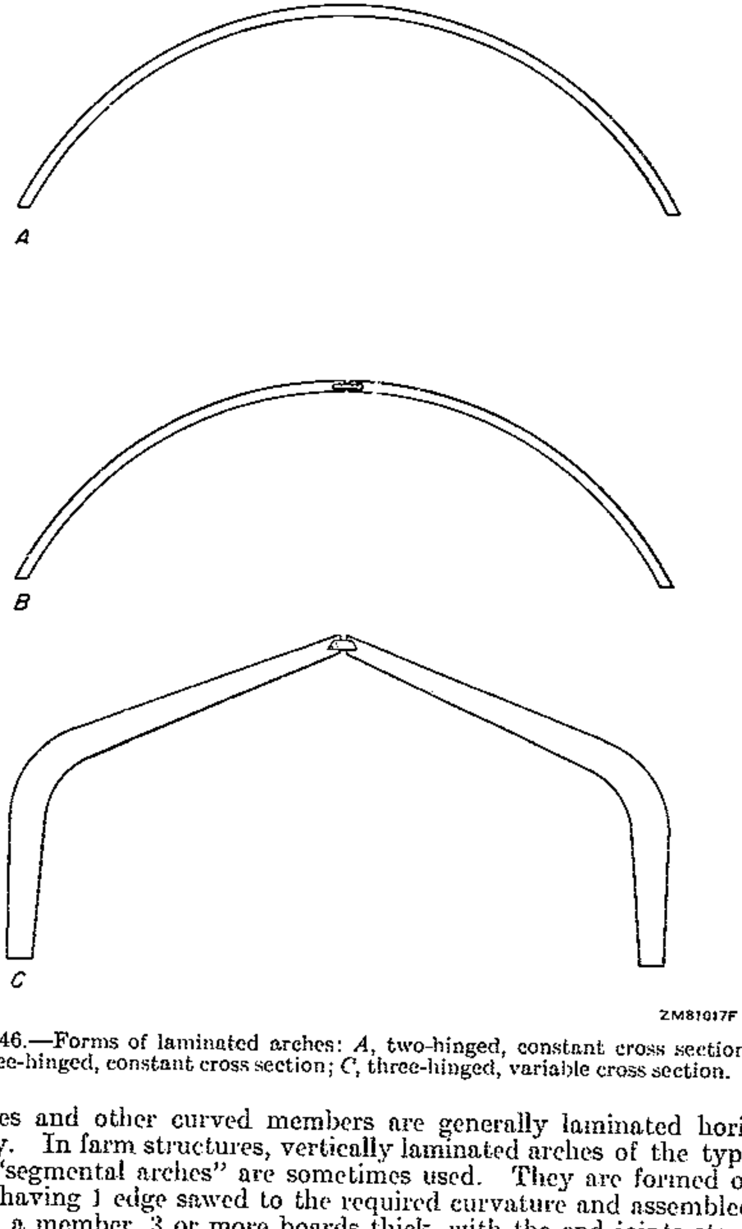

FIGURE 46.—Forms of laminated arches: *A*, two-hinged, constant cross section; *B*, three-hinged, constant cross section; *C*, three-hinged, variable cross section.

Arches and other curved members are generally laminated horizontally. In farm structures, vertically laminated arches of the type called "segmental arches" are sometimes used. They are formed of boards having 1 edge sawed to the required curvature and assembled to form a member, 3 or more boards thick, with the end joints staggered or alternated in adjacent layers (fig. 47). This type of arch, while it has been used in farm structures, is wasteful of material in that one or more of the laminations of a cross section including a joint is ineffective because of the butt joints commonly used. The arches are usually nailed, and the lack of shear resistance between layers tends to permit them to buckle. Even if the end joints were glued scarf joints and the layers were bonded with an adhesive, this type would be open to objection because of the large number of end joints required and because of the fact that, at most cross sections, the direction of grain of one or more layers would not coincide with the direction of principal stress.

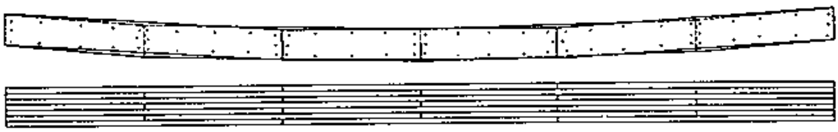

FIGURE 47.—Sketch of segmental curved member.

Glued laminated construction may be combined with plywood to form members having I, box, or other cross sections for use in beams, arches, or columns (fig. 48). Such constructions offer economy through the use of laminated material in the areas of high tension and compression stresses and of plywood to resist shear stress. The amount of strength that can be gained by such a distribution of material is limited to some extent by the influence of the form and the height of the cross section on the bending strength. Such designs do, however, promote efficient use of material by utilizing plywood, which is of relatively light weight and high shear strength, to resist shear in the beam.

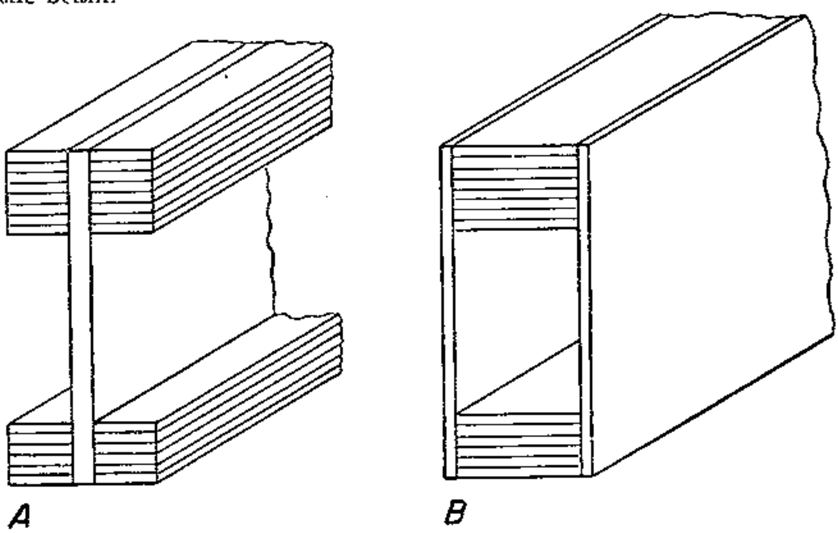

FIGURE 48.—Laminated construction combined with plywood: *A*, I section; *B*, box section.

The depth of cross section at various points may be varied to suit the stress requirements by varying the number of laminations and tapering them to a smooth outline (fig. 46, *C*). This is commonly done by building up the member to approximately the desired depth and cutting to the desired shape on the convex surface. By this procedure, the grain direction of the outer laminations near the convex surface will not coincide with the direction of principal stress. If the slope of grain with respect to the direction of stress becomes so steep by this procedure as to reduce the strength below that used in design, a modification of the procedure becomes desirable. In this modified procedure, the arch is built up to all but a few inches of its final depth, is surfaced to a smooth outline, and sufficient continuous or end-jointed laminations are added to produce the required depth.

Edge Joints

If available material is not wide enough, laminations may be made of two or more edge-joined pieces. Edge gluing of the two pieces is sometimes unnecessary. For example, edge joints in horizontally laminated beams do not, from the standpoint of strength requirements, need to be glued. From the standpoint of fabrication, however, there are definite advantages to edge gluing, even though strength requirements may be such as to permit an unglued joint. An edge-glued joint facilitates handling of the material in assembly, inasmuch as only 1 rather than 2 or more boards need be handled. In vertically laminated beams, however, edge joints in those laminations required for shear resistance need to be glued to have adequate strength in longitudinal shear. Edge gluing may be desirable in outer laminations from the standpoint of appearance. Glued edge joints, where required for reasons of strength, should be of high quality and as durable as the glue joints between laminations. Joints made only to facilitate handling in assembly may be of lower quality.

A plain edge joint (fig. 49, *A*) offers an advantage over tongue-and-groove and other types of edge joints in the ease with which good joints may be made with most species. Although the machined joints facilitate alinement and possess the theoretical advantage of added gluing area, they are more wasteful of material, require special equipment, and, because of difficulties in machining, may actually afford less effective gluing area than does a plain joint.

End Joints

End joints are frequently required between pieces in order to provide laminations of sufficient length. Those most commonly used are the plain scarf joint (fig. 50, *A*), the stepped or hooked scarf joint (fig. 50, *B*), and the butt joint (fig. 50, *C*).

Glued butt joints are not only extremely weak but quite variable in strength. For this reason, generally, no dependence is placed on the strength of the joint, and butt joints, when used, are not glued. Thus butt joints, while simple to make, possess a serious disadvantage in that they cannot transmit any tensile stress and can transmit compression stress only after considerable deformation or when a metal bearing plate is tightly fitted between the two pieces. Extreme care in assembly would be required to make the latter procedure effective. Normally, however, they are not considered to transmit any stress, even in compression, so that all stress must pass around them through adjacent laminations. Butt joints are, therefore, serious sources of stress concentration. They are, in addition, undesirable in curved

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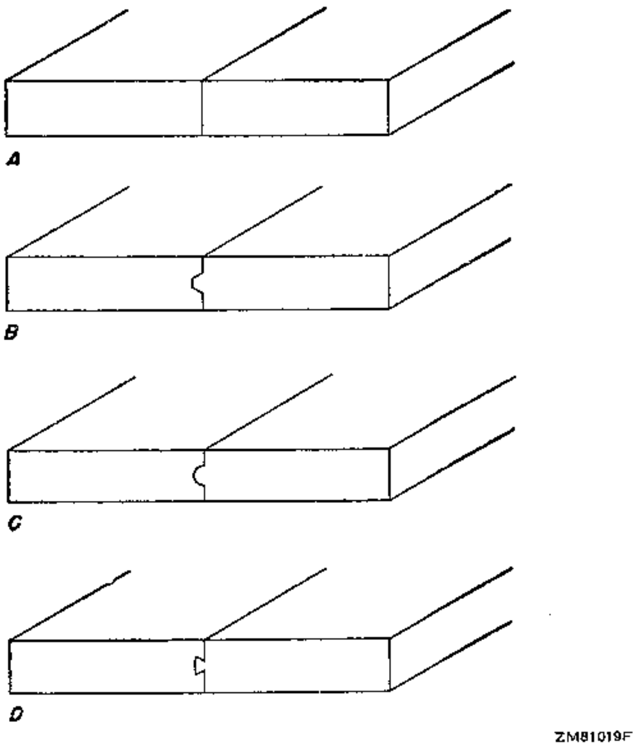

FIGURE 49.—Some types of edge joints: *A*, Plain; *B*, tongue-and-groove; *C*, circular tongue-and-groove; *D*, dovetail.

laminations because of their effect on interlamination contact in their vicinity. It is impossible to produce uniform curvature right to the end of a square-end piece; hence, in the vicinity of butt joints, contact between adjacent laminations can result only from pressure sufficient to crush the wood and that is likely to expel too much of the glue, thus making the joints between laminations locally deficient in resistance to shear. This condition is illustrated by figure 51.

Scarf joints, on the other hand, may be made to have considerable proportions of the strength of uncut boards, both in tension and in compression. Scarf joints are designated by the slope of the plane of the scarf with respect to the axis of the piece; this slope is computed from the ratio of thickness to length of scarf (*b/c*, fig. 50, *A*), as 1 in 20, 1 in 15, or 1 in 10. Well-made scarf joints of flat slope have high percentages of the strength of the uncut boards; their strength in tension decreases percentagewise with increasing steepness of the scarf, with the rate of decrease increasing rapidly for the steeper slopes. Plain and stepped scarfs having the same slope of the plane portion may be expected to have the same strength except for the portion of the area occupied by the step, which is ineffective in transmitting stress. The stepped scarf offers some advantage in ease of positioning the parts of the joint and—although some strength is lost because of the step—it is markedly superior to the butt joint both in

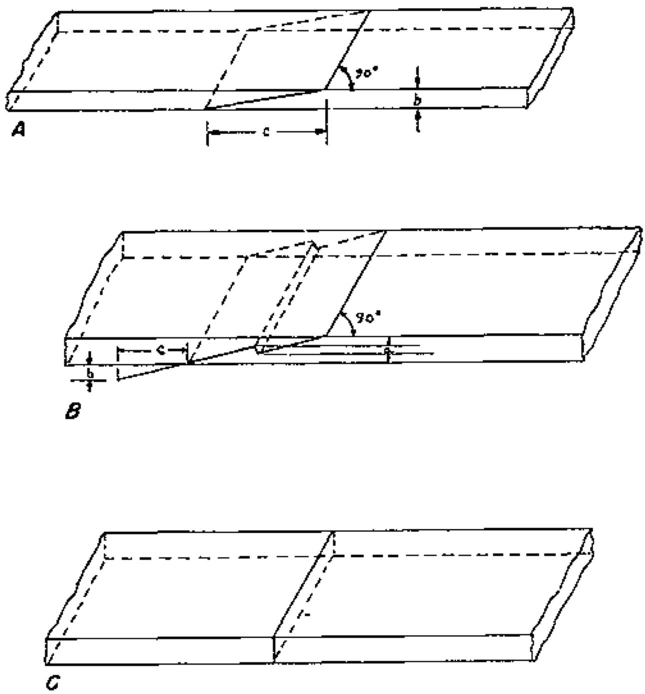

FIGURE 50.—End joints: *A*, Plain scarf: *B*, stepped scarf; C, butt.

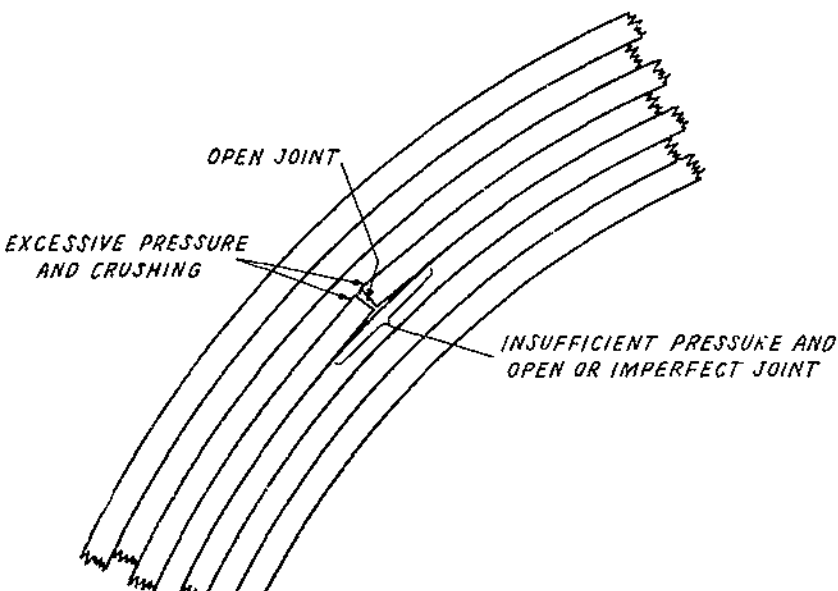

FIGURE 51.—Conditions at a butt joint in a lamination of a curved assembly.

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FABRICATION AND DESIGN OF GLUED LAMINATED WOOD STRUCTURAL MEMBERS
FREAS, A D ; SELBO, M L 2 OF 3

strength and in the fact that each piece can be bent all the way to its end to obtain intimate contact between adjacent laminations.

Since scarf joints that are not well glued cannot be expected to develop the strength intended for them, and, since there is no way of evaluating the loss in strength resulting from poor gluing, special care should be taken to make sure that the procedures used in the manufacture of scarf joints for structural members are such as to produce dependable results. As indicated under Gluing of Edge and End Joints, p. 42, pregluing of end joints is recommended for exterior use or service where maximum strength is required.

A modification of the plain scarf joint (patent pending) is in use by at least one laminator. This joint, illustrated in figure 52, consists of a number of oppositely sloping scarf cuts across the width of the lamination. With proper technique in the preparation of the scarfed surfaces and in the gluing of the joint, this type of joint should be essentially equivalent in strength to a plain scarf joint of the same slope. This equivalence would be limited to some extent by the fact that, if cross grain through the thickness and across the width of the lamination is present, some portion of the width must necessarily have the scarf slope "across" rather than "with" the grain.

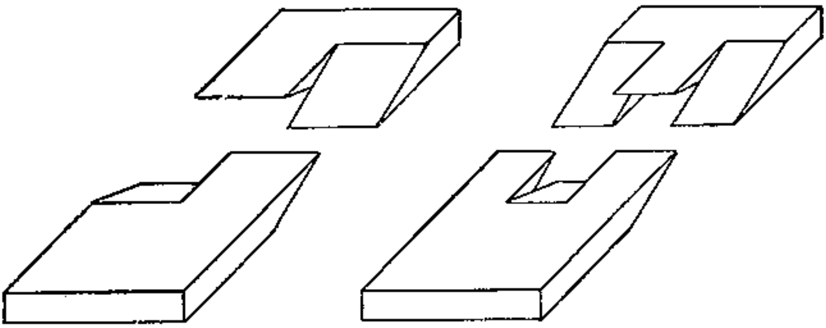

FIGURE 52.—Two versions of a modification of the plain scarf joint. Patent pending on this joint.

The durability of scarf joints in laminated members is not well established. The indications are, however, that scarf joints of steep slope are less durable than those of flat slope. It would appear, then, that the steepest permissible slope of scarf joint for exterior or other severe exposure should be less steep than would be permitted for interior use. While the data are not adequate to permit exact recommendations, it is suggested that, for exterior or other severe exposure, scarf joints no steeper than 1 in 10 be used.

Several other types of end joints (fig. 53) have been used. Generally, they are designed to facilitate alinement of the parts and provide added gluing area. As with edge joints, however, accuracy of fit is an important factor in producing strong end joints, and inaccuracies may actually cause a reduction in effective gluing area and result in reduced strength. Presently, the plain scarf joint possesses a distinct advantage in that it combines relative ease of manufacture with high strength if it has a sufficiently flat slope.

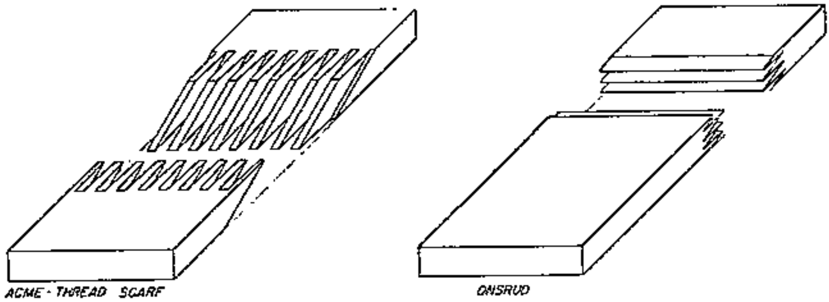

FIGURE 53.—Two types of patented glued end joints used in laminating.

End joints of all types are most efficient when they have flat slopes that expose as little end grain and as much side grain as possible in the surfaces to be glued.

FACTORS TO BE CONSIDERED IN DESIGN

The design of a structure made of laminated material involves consideration of more factors than does that of a structure made of one-piece members. On the other hand, it permits better utilization of material because material can be placed where its strength may be best utilized and constant-strength members can be designed where such a procedure is expedient.

The number and thickness of laminations to be used depends, in general, only upon the thickness of available material and the size of the cross section required. As indicated earlier, however, for curved members, the individual laminations must be thin enough to permit bending them to the required curvature without damage.

Knots, of course, affect the strength of laminated members to an extent that is dependent on their size, number, and location in the lamination. In beams, their effect on strength depends also on their longitudinal position in the beam and upon the location of the lamination in the cross section of the member. Since a knot of a given size has a greater effect on strength when in the outer laminations of a beam, most efficient use of material can be obtained by using material of the higher grades in the outer laminations and that of lower grades in the inner laminations. Knots in curved laminations, furthermore, may interfere with bending the laminations to a smooth curve and thus prevent the intimate contact between laminations that is needed for the production of good glue joints. Other defects, such as cross grain, also affect strength, but may be taken into account by imposing limitations that make their effects similar in magnitude to those of knots of permitted size.

Checks lying in a horizontal plane, as in a beam horizontally laminated with edge-grain boards or in one vertically laminated with flat-grain boards, will affect shear strength to the same extent as in a solid beam. Since material for glued laminated construction is generally dried in relatively small thicknesses, checks do not occur frequently; certainly, the large checks that are common in one-piece sawn timbers are not to be expected.

Shakes, if present in flat-grained laminations of a horizontally laminated beam, will also affect shear strength to the same extent as in a solid beam. They should be excluded or placed in areas of low shear.

End joints play a large part in determining the strength of laminated members. The indiscriminate use of butt joints, especially in beams or tension members, can result in a member of exceedingly low strength as compared to one made from continuous laminations. On the other hand, the use of well-spaced scarf joints of flat slope will result in a member that has a high percentage of the strength of one with continuous laminations. Other types of end joints may be used, but such use should be based on data permitting the sound design of members in which they are used. In some cases, tests have shown them to be only slightly more efficient than butt joints, so that the added expense involved in their manufacture is not adequately compensated for by a gain in strength.

The form and height of wood beams affect stresses at both proportional limit and ultimate as computed by conventional methods. Thus, stresses at proportional limit and ultimate, when computed by conventional methods, have lower values for I and box sections than for rectangular sections, and lower values for deep than for shallow rectangular sections. These effects, therefore, must be taken into account in the design of beams.

The bending of laminations for curved members induces stresses in such laminations. Such stresses are, of course, greater for the sharper curvatures. A large part of the stress so induced is relieved by plastic flow, but tests indicate that there is some residual stress. Design stresses must be lowered to compensate for these residual stresses.

In general, the problems of analysis may be treated by the same methods as are employed with other wood structures. The same engineering formulas are generally applicable, and the same supplementary problems of elastic stability and fastening design must be met. Certain additional factors must be considered; these are discussed later under Design Considerations for Laminated Wood, p. 130.

CALCULATION OF WORKING STRESSES

Working stresses are the stresses appropriate for use in design. Those that are appropriate in any given instance depend on a number of features of construction, such as type and location of end joints, size and location of permitted knots, size of member, and, in some instances, the number of laminations. It is convenient to state the allowable working stress in each such instance as a percentage of a fixed basic stress, and thereby continue the practice in use for solid timbers.

Basic Stresses

Basic stresses for one-piece sawn structural timbers (derived from tests of small clear specimens), as recommended by the Forest Products Laboratory, are published by the American Society for Testing Materials under designation D245–49T (*1*). It has long been recognized that the numerous factors affecting the strength of wood and the design of wood structures involve a degree of engineering judgment that precludes the determination of basic stresses by any simple mathematical analysis.

Because the same factors are considered to be involved in both, the basic stresses for laminated timbers are related to those for solid timbers, taking into account the beneficial moisture-strength effect for laminated construction used in dry locations.

The basic stresses for laminated construction used in damp or wet locations have therefore been taken to be the same as the basic stresses for solid timber. The basic stresses for laminated construction used in dry locations have been obtained from those for solid construction by increasing them by an amount reflecting the increase for drying appropriate to each property. Because the various properties are differently affected by a reduction in moisture content, the increase varies from 10 to 37½ percent.

The basic stresses of table 5 apply when laminated material is used under conditions continuously dry, as in most covered structures. Those of table 6 apply when laminated material is used under moist or wet conditions. The choice of values to be used as a basis for design is left to the engineer who has knowledge of the conditions under which the structure is expected to serve. It is not possible to set up any general rules to serve in making the choice. However, most exterior structures, such as bridges or towers, should be designed on the basis of table 6. Care must be exercised in choosing values for design of buildings. For example, it may be necessary to design a completely enclosed, heated building on the basis of table 6 because of the presence of persistent high humidity or the probability of condensation. Examples of such a case are concrete-pipe-manufacturing plants or dye rooms in textile factories.

The values of both tables 5 and 6 are applicable to glued laminated construction only when all laminations are straight-grained and free from significant defects. The flexural-stress values apply directly only to members of rectangular cross section and 12-inch depth; values for other properties are applicable regardless of form or size of member. The basic stress values given are applicable regardless of number or thickness of laminations. That is, the same basic stress in bending would be applicable to a member 12 inches deep whether it were made from 8 laminations 1½ inches thick or from 16 laminations three-fourths inch thick. Since the basic stresses correspond with long-time loading, they are directly applicable where the maximum design load is continuous or cumulative for periods of 25 to 50 years. They should be modified for other durations of load.

As indicated in tables 5 and 6, an increase of one-sixth in the basic stress for certain properties is permitted for Douglas-fir and southern yellow pine conforming to certain rules for density *(19)*. A similar increase of one-fifteenth is permitted for Douglas-fir and redwood conforming to certain rules for rate of growth. These increases are applicable to laminations conforming to those requirements. Certain cautions to be observed in the application of these increases are discussed later.

TABLE 5.—*Basic stresses for structural members laminated from clear material and under long-time service at maximum design load and under dry conditions, as in most covered structures, for use in determining working stresses according to grade of laminations and other applicable factors*

SOFTWOODS

Species [1] (1)	Extreme fiber in bending or tension parallel to grain (2)	Maximum longitudinal shear (3)	Compression perpendicular to grain (4)	Compression parallel to grain (5)	Modulus of elasticity in bending (6)
	P. s. i.	*P. s. i.*	*P. s. i.*	*P. s. i.*	*1,000 p. s. i.*
Baldcypress (southern cypress)	2, 400	170	330	2, 000	1, 300
Cedars:					
Redcedar, western	1, 600	135	220	1, 300	1, 100
White-cedar, Atlantic (southern white cedar; and northern	1, 400	115	195	1, 050	900
White-cedar, Port Orford	2, 000	150	275	1, 650	1, 600
Yellow-cedar, Alaska (Alaska cedar)	2, 000	150	275	1, 450	1, 300
Douglas-fir, coast type	2, 750	150	350	2, 000	1, 800
Douglas-fir, coast type, close-grained	2, 950	150	375	2, 150	1, 800
Douglas-fir, Rocky Mountain type	2, 000	135	310	1, 450	1, 300
Douglas-fir, all regions, dense	3, 200	150	410	2, 350	1, 800
Fir, balsam	1, 600	115	165	1, 300	1, 100
Fir, California red, grand, noble, and white	2, 000	115	330	1, 300	1, 200
Hemlock, eastern	2, 000	115	330	1, 300	1, 200
Hemlock, western (west coast hemlock)	2, 400	125	330	1, 650	1, 500
Larch, western	2, 750	150	350	2, 000	1, 600
Pine, eastern white (northern white), ponderosa, sugar, and western white (Idaho white)	1, 600	135	275	1, 400	1, 100
Pine, jack	2, 000	135	240	1, 450	1, 200
Pine, lodgepole	1, 600	100	240	1, 300	1, 100
Pine, red (Norway pine)	2, 000	135	240	1, 450	1, 300
Pine, southern yellow	2, 750	180	350	2, 000	1, 800
Pine, southern yellow, dense	3, 200	180	410	2, 350	1, 800

Redwood	2,200	115	275	1,850	1,300
Redwood, close-grained	2,400	115	295	2,000	1,300
Spruce, Engelmann	1,400	115	195	1,100	900
Spruce, red, white, and Sitka	2,000	135	275	1,450	1,300
Tamarack	2,200	160	330	1,850	1,400
HARDWOODS					
Ash, black	1,800	150	330	1,150	1,200
Ash, white	2,550	210	550	2,000	1,600
Beech, American	2,750	210	550	2,200	1,800
Birch, sweet and yellow	2,750	210	550	2,200	1,800
Cottonwood, eastern	1,400	100	165	1,100	1,100
Elm, American and slippery (white or soft elm)	2,000	170	275	1,450	1,300
Elm, rock	2,750	210	550	2,200	1,400
Hickory, true and pecan	3,500	235	660	2,750	2,000
Maple, black and sugar (hard maple)	2,750	210	550	2,200	1,800
Oak, red and white	2,550	210	550	1,850	1,600
Sweetgum (red or sap gum)	2,000	170	330	1,450	1,300
Tupelo, black (blackgum)	2,000	170	330	1,450	1,300
Tupelo, water	2,000	170	330	1,450	1,300
Yellow-poplar	1,800	150	240	1,450	1,300

[1] Species names from approved check list, U. S. Forest Service, 1944. Commercial designations are shown in parentheses.

TABLE 6.—*Basic stresses for structural members, laminated from clear material and under long-time service at maximum design load and under wet conditions, for use in determining working stresses according to grade of laminations and other applicable factors*

SOFTWOODS

Species [1] (1)	Extreme fiber in bending or tension parallel to grain (2)	Maximum horizontal shear (3)	Compression perpendicular to grain (4)	Compression parallel to grain L/d=11 or less (5)	Modulus of elasticity in bending (6)
	P. s. i.	*P. s. i.*	*P. s. i.*	*P. s. i.*	*1,000 p. s. i.*
Baldcypress (southern cypress)	1, 900	150	220	1, 450	1, 200
Cedars:					
Redcedar, western	1, 300	120	145	950	1, 000
White-cedar, Atlantic (southern white cedar) and northern	1, 100	100	130	750	800
White-cedar, Port Orford	1, 600	130	185	1, 200	1, 500
Yellow-cedar, Alaska (Alaska cedar)	1, 600	130	185	1, 050	1, 200
Douglas-fir, coast type	2, 200	130	235	1, 450	1, 600
Douglas-fir, coast type, close-grained	2, 350	130	250	1, 550	1, 600
Douglas-fir, Rocky Mountain type	1, 600	120	205	1, 050	1, 200
Douglas-fir, all regions, dense	2, 550	130	275	1, 700	1, 600
Fir, balsam	1, 300	100	110	950	1, 000
Fir, California red, grand, noble, and white	1, 600	100	220	950	1, 100
Hemlock, eastern	1, 600	100	220	950	1, 100
Hemlock, western (West Coast hemlock)	1, 900	110	220	1, 200	1, 400
Larch, western	2, 200	130	235	1, 450	1, 500
Pine, eastern white (northern white), ponderosa, sugar, and western white (Idaho white)	1, 300	120	185	1, 000	1, 000
Pine, jack	1, 600	120	160	1, 050	1, 100
Pine, lodgepole	1, 300	90	160	950	1, 000
Pine, red (Norway pine)	1, 600	120	160	1, 050	1, 200
Pine, southern yellow	2, 200	160	235	1, 450	1, 600

Pine, southern yellow, dense	2, 550	160	275	1, 700	1, 600
Redwood	1, 750	100	185	1, 350	1, 200
Redwood, close-grained	1, 900	100	195	1, 450	1, 200
Spruce, Engelmann	1, 100	100	130	800	800
Spruce, red, white, and Sitka	1, 600	120	185	1, 050	1, 200
Tamarack	1, 750	140	220	1, 350	1, 300
HARDWOODS					
Ash, black	1, 450	130	220	850	1, 100
Ash, white	2, 050	185	365	1, 450	1, 500
Beech, American	2, 200	185	365	1, 600	1, 600
Birch, sweet and yellow	2, 200	185	365	1, 600	1, 600
Cottonwood, eastern	1, 100	90	110	800	1, 000
Elm, American and slippery (white or soft elm)	1, 600	150	185	1, 050	1, 200
Elm, rock	2, 200	185	365	1, 600	1, 300
Hickory, true and pecan	2, 800	205	440	2, 000	1, 800
Maple, black and sugar (hard maple)	2, 200	185	365	1, 600	1, 600
Oak, red and white	2, 050	185	365	1, 350	1, 500
Sweetgum (red or sap gum)	1, 600	150	220	1, 050	1, 200
Tupelo, black (blackgum)	1, 600	150	220	1, 050	1, 200
Tupelo, water	1, 600	150	220	1, 050	1, 200
Yellow-poplar	1, 450	130	160	1, 050	1, 200

[1] Species names from approved check list, U. S. Forest Service, 1944. Commercial designations are shown in parentheses.

MEMBERS SUBJECT TO FLEXURE

In members subject to flexure, moment of inertia is to be computed about the gravity axis of the full cross section.

A number of factors must be considered in computing working stresses based on the features involved in the member. These include end joints, knots, cross grain, depth or form of member, and curvature of laminations. The first four of these are not accumulative. That is, the one of these that gives the lowest factor by which to multiply the basic stress is the one determining the strength ratio of the member. For curved members, however, the effect of curvature of the laminations must be considered in addition to the other effects. For example, if knots were controlling in a member, and gave a factor of 0.80, and the curvature factor were found to be 0.90, the strength ratio by which to multiply the basic stress would be 0.72.

Since tests have indicated that the effect of various factors influencing strength is different for horizontally than for vertically laminated members, they are treated separately.

HORIZONTALLY LAMINATED MEMBERS

Provisions applicable to both straight and curved members.—The provisions with respect to end joints, knots, and cross grain are applicable regardless of whether the member is straight or curved. These, being most important, are treated first and separately from those provisions that relate only to curved members and consequently have more limited application.

End joints.—Numerous more or less intricate shapings of the ends of pieces to be joined are in common use in woodworking, but no general rules have been established for the strength of the resulting joints. Consequently, provision is made herein only for butt joints and for glued plain or stepped scarf joints. Data from tests of several other types are included in the appendix.

When adequate data are lacking on which to base limitations of slope, spacing, and placement, and on which to calculate allowable design stresses, it is recommended that types other than those discussed herein be used only if they are placed and treated, in the calculation of design stresses, as if they were butt joints.

End joints in compression portion of cross section.—Butt joints or nonglued joints of other types may be used in the compression portion of the cross section, provided that all laminations at a single cross section having such joints are disregarded in computing the moment of inertia. It is suggested that butt joints in adjacent laminations be spaced apart at least 10 times the lamination thickness.

No modification of moment of inertia or of working stress need be made for glued plain scarf joints having a slope not steeper than 1 in 5. There are no requirements for spacing of scarf joints of 1 in 5 slope or flatter when located in the compression portion of the cross section.

End joints in tension portion of cross section.—Accurately fitted and well-glued plain scarf joints (fig. 50, *A*) are permitted provided the maximum stress at the joint does not exceed the following percentages of the basic flexural stress:

Effective slope of scarf:	Scarf-joint factor (percent)
1 in 12 or flatter	90
1 in 10	85
1 in 8	80
1 in 5	65

Accurately fitted and well-glued stepped scarf joints (fig. 50, *B*) may be used at the stress ratings specified above, but the portion of the thickness of the lamination occupied by the step (dimension *a*, fig. 50, *B*) should be disregarded in computing the moment of inertia. In applying the stress ratings to stepped scarf joints, the slope of scarf to be considered is that of the plane part of the joint—that is, the ratio of *b* to *c*, as shown in figure 50, *B*; the slope is not to be taken as the thickness divided by the distance between the tips of the joint.

The proportion of end grain appearing on a scarfed surface will be greatly increased if the material to be spliced is somewhat cross-grained and the scarf is made across rather than in the general direction of the grain. Since end-grain gluing is more difficult than side-grain gluing and results in weaker joints, it follows that, where cross grain within the specified acceptable limits is present, all scarf cuts should be made in the general direction of the grain slope. From the standpoint of simplicity of manufacturing procedure, it is desirable to cut the scarf slopes without regard to the direction of grain slope. If this is done, it is suggested that it be assumed that scarf cuts are always made opposed to grain slope and that the steepest grain slope permitted in the grade is always present. Design would then be based on the effective scarf slope rather than on the actual or apparent scarf slope. The effective scarf slope corresponding to a combination of actual scarf slope and slope of grain may be found from figure 54.

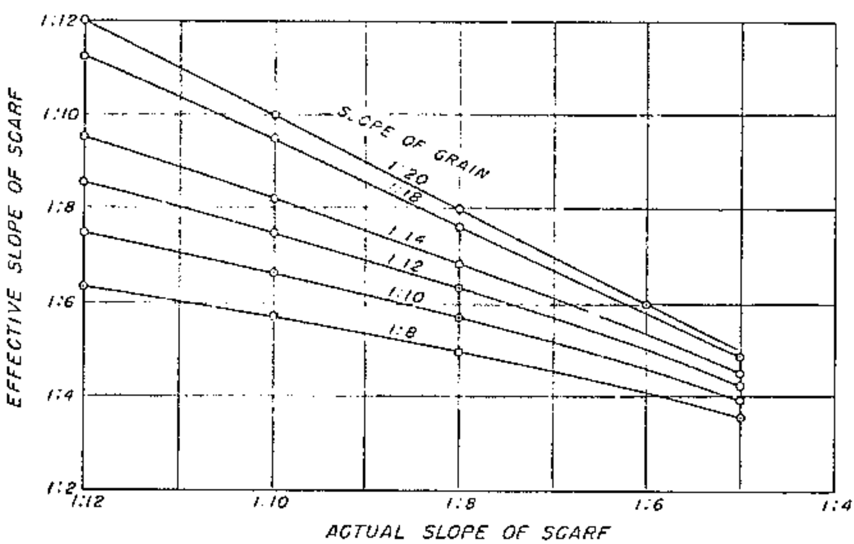

FIGURE 54.—Curves relating effective slope of scarf joint to actual slope of scarf joint when scarf cut is made opposed to grain slope.

Test results show that, where scarf joints in adjacent laminations are closely spaced, failure progresses more or less instantaneously from the joint in the outer lamination through the others. Adequate longitudinal separation of scarf joints in areas of high stress is, therefore, desirable to prevent weakening of the member beyond that which would result from the outermost joint alone. It is suggested, therefore, that a center-to-center spacing of scarf joints of at least 24 times the lamination thickness be maintained in areas of the member where the stress is at or near the maximum allowable value.

The nature of the failures in test is such as to indicate that, with closely spaced joints, failure in the outermost joint results in partial separation, from the rest of the member, of the lamination containing the joint. Sufficient separation of this lamination results in a beam of reduced depth at the location of the adjacent joint; stress at this joint is immediately excessive, and the joint fails. The amount of joint separation required appears, then, to depend on the ability of the interlamination joint to resist the suddenly applied "peeling" stresses. On this basis, the amount of separation required seems to bear no relation to the strength of the scarf joint, and it appears necessary to apply the same spacing requirements regardless of scarf slope.

On the other hand, the likelihood of failure of scarf joints stressed well below the allowable value is small. It appears feasible, then, to reduce the spacing requirements in areas of low stress, as at the center of the depth of a flexure member or in areas of low moment. No data are available by which to substantiate any proposed method of varying spacing requirements. It is suggested, however, that minimum scarf-joint spacings be permitted to vary linearly from $0t$ in areas of zero stress to $24t$ in areas of maximum allowable stress.

The maintenance of a specific pattern of scarf-joint location, such as is contemplated above, necessitates either a preliminary layup of the member prior to spreading the glue on the laminations or considerable care in the lengths that are scarfed together to form a full-length lamination and in assembling such laminations. Manufacturing problems may be such as to preclude either system. In such a case, it is suggested that the requirement for a specific pattern of scarf-joint separation may be waived if the strength ratio (scarf-joint factor) applicable to a joint of a particular slope be reduced from those suggested earlier. It is suggested, in such a case, that the following scarf-joint factors be used.

Effective slope of scarf:	*Scarf-joint factor (percent)*
1 in 12 or flatter	85
1 in 10	80
1 in 8	75
1 in 5	60

This suggested change in procedure should not be taken to indicate that no attention need be paid to separation of scarf joints. In assembly, a conscious effort should be made to avoid concentrations of scarf joints and to keep them as well separated as possible.

The limitation of stress at a joint applies to interior laminations as well as to the lamination at the tension face. In a beam with 40 equal laminations, for example, the stress at the outer face of the second lamination is 95 percent of that at the outer face of the bottom lamination. Hence, if the bottom lamination were continuous and the second lamination contained a scarf joint sloping at 1 in 12 at the critical section, it would be necessary to restrict the working stress (stress in extreme fiber) to about 95 percent of the basic value in order not to exceed the 90 percent permissible at the outer face of the second lamination.

Data given in the appendix indicate that the strength reduction resulting from butt joints in laminations in the tension portion of the cross section of a flexure member is greater than would be computed by simply considering such laminations to be ineffective. Because of this, it is suggested that, wherever possible, butt joints not be used in the tension portion of the cross section. If, however, it is necessary to use them in such positions, it is suggested that the procedure outlined above be used in computing the net moment of inertia, except that the net moment of inertia so computed should be further reduced by multiplying it by a factor of 0.8. Butt joints should not be used in top or bottom laminations.

Effect of knots on flexural stresses.—For bending members with knots in the laminations, the percentage, F_k, of the basic flexural stress to be used in design is in accordance with the design curve shown in figure 55. The abscissa of this curve is $X=I_K/I_G$, where I_G is the moment of inertia of the full or gross cross section and I_K is the sum of the moments of inertia of the cross-sectional areas of all knots within 6 inches of a single cross section of a beam, both values being computed about the gravity axis of the full cross section.

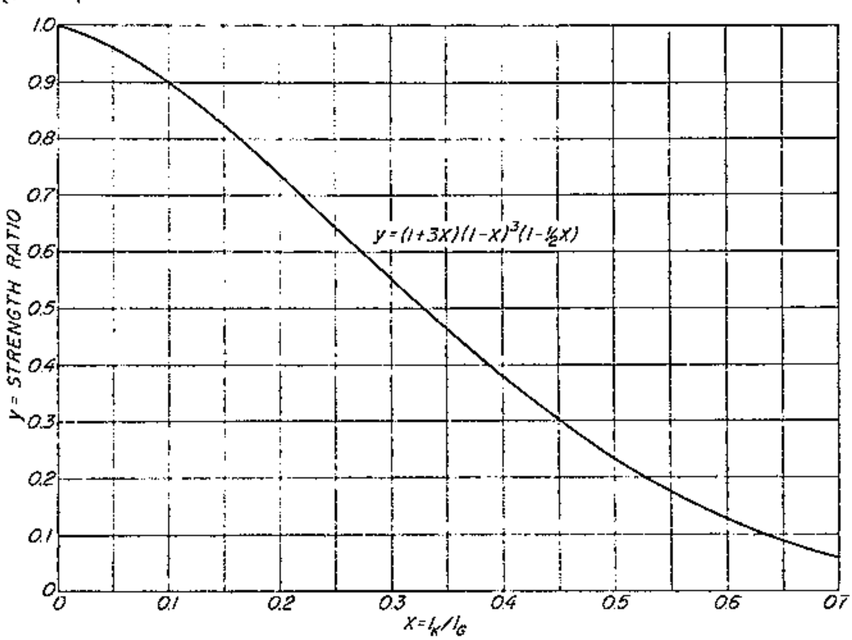

FIGURE 55.—Design curve relating allowable flexural stress to moment of inertia of areas occupied by knots in laminations of laminated beams.

With no restrictions on the location of knots within the member, some assumption must be made as to the concentration of knots about a critical cross section. One possible assumption is that the maximum permissible knot occurs in each lamination at the critical cross section. Experience indicates that the probability of such an occurrence is low and, therefore, that this would be a highly conservative assumption.

It is known that, within any grade, the maximum permissible knot occurs only infrequently and that some portions of many pieces contain no knots at all. It would seem, from this, that the sums of knot sizes within 1-foot lengths should follow some pattern of probability of occurrence. If so, it should be feasible to relate this probability pattern to the probability of occurrence of various knot concentrations in a laminated member. With this, a knot concentration at some sufficiently conservative level of probability could be used as a basis for establishing working stresses.

A study of several commercial grades has indicated the feasibility of such an approach. The study is discussed in the appendix.

Each commercial grade of lumber may be expected to have its own characteristic distribution of knot sizes. Working stresses based on a study of knot-size distribution for a specific grade cannot, therefore, be translated into working stresses for a different grade or a different species.

In establishing working stresses for random assembly of laminations, it is suggested that they be based on a study of the distribution of the sum of knot sizes in 1-foot lengths by the method described in the appendix. Lacking such an analysis, it is suggested that working stresses be based on the assumption described earlier—that each lamination contains a knot of maximum permitted size within 6 inches of the critical section.

Both the Southern Pine Association and the West Coast Lumbermen's Association have published stresses for laminated construction that are based on the statistical procedure just described.

The statistical method described in the appendix may be applied to beams containing laminations of a single grade or to beams containing laminations of two different grades. The method gives strength ratios applicable to the beam as a whole. It is possible, where there is a considerable difference in quality between the inner and outer groups of laminations, that the inner group of laminations may be overstressed by the application of such strength ratios to the basic stress of the outer group of laminations, particularly where the outer group is close-grained or dense and the inner group is neither close-grained nor dense. In such cases, the possibility of overstress in the inner group of laminations should be checked by the procedure described in the appendix.

In cases where it is not feasible to sample the grade and to go through the probability analysis, but an estimate is desired of the strength ratio that would be obtained by such an analysis, the following procedure may be used. First, calculate the value of I_K/I_G applicable if it were assumed that the largest permissible knot were present in every lamination at the critical cross section. Second, multiply this value by the ordinate to the curve of figure 56 for the proper number of laminations. Then, with this modified value of I_K/I_G, determine the applicable strength ratio from the curve of figure 55. This procedure is based on a consideration of the relative values of I_K/I_G by the two methods for the grades studied, and the factors suggested are only approximate. In general, however, they are probably sufficiently conservative to provide a satisfactory basis for estimating strength ratios that may be expected from a probability analysis. For use in design, one of the two procedures suggested earlier should be used.

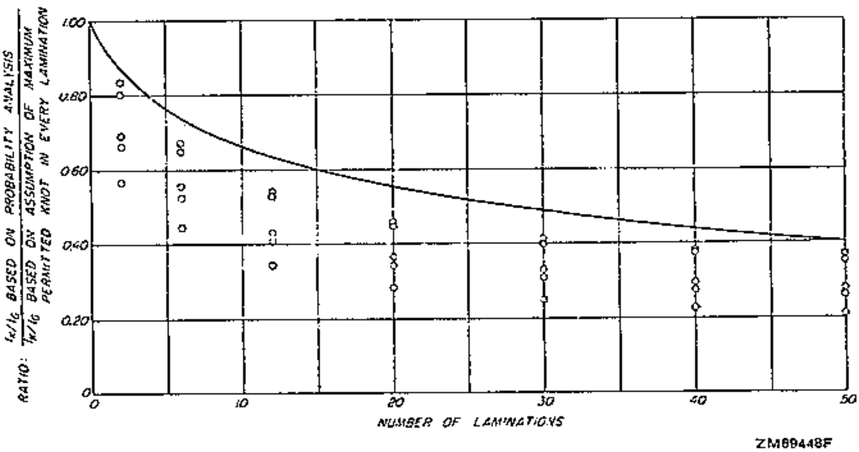

FIGURE 56.—Relation between values of I_K/I_G suggested for use in determining strength ratios for use in design of bending members and those that would have been determined by considering the largest permissible knot present in every lamination.

If it be assumed that the largest permitted knot is present in every lamination at the critical cross section, it is obvious that the value of I_K/I_G is equal to the ratio of knot size (K) to finished lamination width (b) for beams in which all laminations are of the same grade. That is, $I_K/I_G=K/b$. Computation of the value of I_K/I_G based on the same assumption for a beam consisting of a combination of two grades may perhaps best be explained by an example. Consider a beam of 15 laminations in which the outer one-fifth of the depth on each side consists of laminations in which $K/b=1/4$ and the inner three-fifths consists of laminations in which $K/b=1/2$. Thus, all laminations may be considered to have $K/b=1/4$, with the central nine laminations having an additional $K/b=1/4$. The value of I_K/I_G resulting from the first part is 1/4. The central nine laminations contribute, because of their position in the beam, only $(9/15)^3$ to the moment of inertia, so that the value of I_K/I_G resulting from the second part is $(1/4)(9/15)^3$. The value of I_K/I_G for the beam, is, then,

$$I_K/I_G=1/4+1/4(9/15)^3=1/4[1+(9/15)^3]=0.304$$

It is, of course, possible to limit knot concentrations in the assembly of beams and to develop, from the concentrations permitted, methods of computing applicable values of I_K/I_G. In general, this would require a layup "in the dry" to insure compliance with the restrictions on knots. Except for special cases, this would probably increase the labor cost to such a degree as to be impractical.

One such procedure, however, appears relatively simple of application and, as will be shown, will result, in some instances, in appreciably higher strength ratios than can be permitted for random assemoly of laminations. In assembly, the knots in all the laminations within 6 inches of a cross section may be restricted to two of the largest knots permissible in the grade or to the equivalent in smaller knots. In such a case, it should be assumed, for purposes of design, that 1 knot of maximum permissible size occurs in each outer lamination at any cross section where all laminations are of the same grade; or, where 2 grades are combined, that the 2 knots of maximum permissible size are in positions that give the greatest value of I_K/I_G.

Under this assumption, for a beam consisting of laminations of a single grade, the arrangement is such that the value of I_K/I_G is simply the product of the ratio K/b (K=maximum permitted knot size in the grade, b=lamination width) by the ratio of the moment of inertia of the outer laminations to that of the whole cross section. This latter ratio, for beams consisting of various numbers of laminations, is shown in figure 57. Thus a beam consisting of 15 laminations of a grade in which K/b=0.25, would have a value of $I_K/I_G=0.25\times0.35=0.087$.

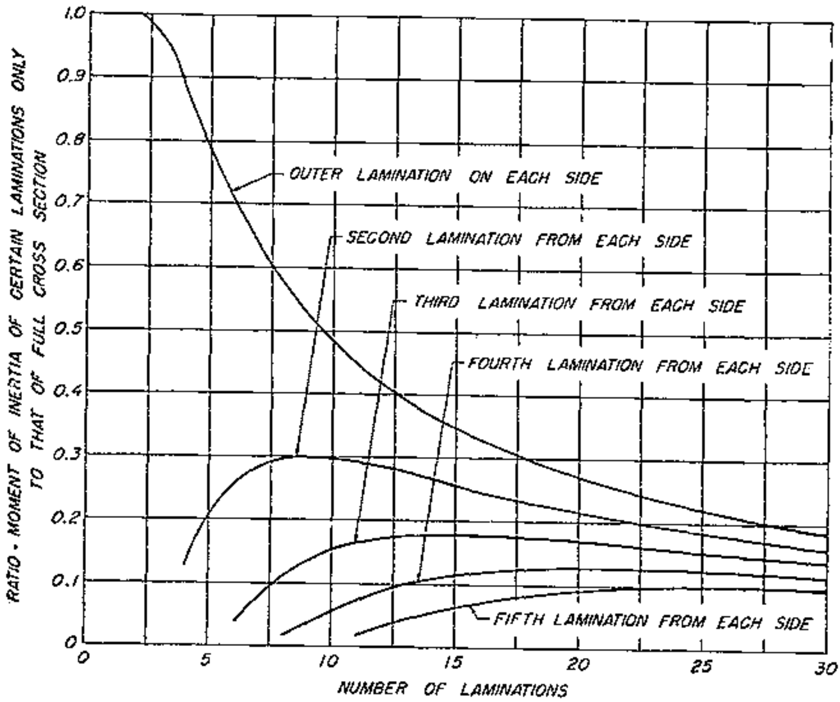

FIGURE 57.—Relation between number of laminations in a beam and the ratio of moment of inertia of certain laminations to that of the whole cross section.

For a combination of grades, where the outer group of laminations is clear, the assumption of knot location must be modified to place the maximum permissible knot in the outer laminations of the central group. In such a case, the value of I_K/I_G would be the product of K/b by the ratio of the moment of inertia of the laminations in which the knots are assumed to that of the whole cross section. This latter ratio is shown also in figure 57 for laminations located at various distances from the outside of the beam. As an example, consider a beam of 15 laminations with the 2 outer laminations on each side clear and the remainder of a grade for which maximum $K/b=0.25$. Then, assuming a knot of maximum permissible size in each outer lamination of the central group (third lamination from each side), $I_K/I_G=0.25\times 0.178=0.0445$.

For other combinations of grades, the knots in the outer laminations of the outer group may control; or, where the number of such laminations is relatively small and the difference in knot size is large, the knots in the inner group may control. Where two grades are combined, then, the maximum permissible knot corresponding to the grade of the outer group of laminations may be assumed to be in the top and bottom laminations, or the largest permissible knot corresponding to the grade of the inner laminations may be assumed to be in the outer laminations of this group, whichever gives the higher value of I_K/I_G.

Calculations such as are described above have been carried out for beams consisting of various grades and combinations of grades. The corresponding strength ratios are given in tables 7 and 8. A comparison of these tables with strength ratios based on the probability analysis described in the appendix for randomly assembled laminations shows that, in some instances, appreciably higher strength ratios may

TABLE 7.—*Strength ratios as determined by knots for beams consisting of laminations of a single grade and having not more than 2 maximum-size knots, or equivalent, within 6 inches of any cross section*

Number of laminations	Strength ratios for laminations of grade [1]			
	1	2	3	4
2	0.86	0.65	0.42	0.23
3	.87	.66	.44	.26
4	.89	.70	.50	.32
5	.90	.74	.56	.39
6	.92	.78	.62	.46
7	.93	.81	.67	.52
8	.94	.84	.71	.58
9	.94	.85	.74	.62
10	.95	.86	.77	.66
15	.97	.92	.86	.79
20	.98	.94	.90	.85
25	.98	.96	.92	.89
30	.98	.96	.94	.91
35	.99	.97	.95	.93
40	.99	.98	.96	.94
45	.99	.98	.96	.95
50	.99	.98	.97	.95

[1] Grade designations are sorting classes. See appendix p. 138 for further discussion.

be assumed where knots are restricted in the manner outlined above as compared with those that may be assumed with random assembly. It is possible that the higher strength ratios possible may result in sufficient advantage to offset the additional cost incurred in applying the restriction during assembly.

In general, it may be expected that laminated members will be made of laminations, all of which will be the same thickness. In special cases, however, laminations may be of different thicknesses, as where a thin, clear piece may be used as an outer lamination for appearance. For such cases, care must be taken, in evaluating the effect of knots, to take into account the actual thicknesses of the various laminations.

A somewhat different concept from that just described has been found by test not to be conservative. With this concept, it was

TABLE 8.—*Strength ratios, as determined by knots, for beams consisting of various combinations of 2 grades and having not more than 2 maximum-size knots, or equivalent, within 6 inches of any cross section*

1 LAMINATION EACH SIDE HIGHER GRADE

Number of laminations	Strength ratios for laminations of grades [1]									
	0–1	0–2	0–3	0–4	1–2	1–3	1–4	2–3	2–4	3–4
4	0.99	0.98	0.96	0.95	0.89	0.89	0.89	0.70	0.70	0.50
5	.98	.96	.93	.90	.90	.90	.90	.74	.74	.56
6	.98	.95	.90	.86	.92	.90	.86	.78	.78	.62
7	.98	.94	.89	.84	.93	.89	.84	.81	.81	.67
8	.97	.94	.88	.83	.94	.88	.83	.84	.83	.71
9	.97	.94	.88	.82	.94	.88	.82	.85	.82	.74
10	.97	.94	.88	.83	.94	.88	.83	.86	.83	.77
15	.98	.95	.91	.86	.95	.91	.86	.91	.86	.86
20	.98	.96	.93	.89	.96	.93	.89	.93	.89	.89
25	.98	.97	.94	.91	.97	.94	.91	.94	.91	.91
30	.99	.97	.95	.93	.97	.95	.93	.95	.93	.93
35	.99	.98	.96	.94	.98	.96	.94	.96	.94	.94
40	.99	.98	.96	.95	.98	.96	.95	.96	.95	.95
45	.99	.98	.97	.95	.98	.97	.95	.97	.95	.95
50	.99	.98	.97	.96	.98	.97	.96	.97	.96	.96

2 LAMINATIONS EACH SIDE HIGHER GRADE

Number of laminations	0–1	0–2	0–3	0–4	1–2	1–3	1–4	2–3	2–4	3–4
6	1.00	0.99	0.99	0.99	0.92	0.92	0.92	0.78	0.78	0.62
7	.99	.99	.98	.97	.93	.93	.93	.81	.81	.67
8	.99	.98	.97	.96	.94	.94	.94	.84	.84	.71
9	.99	.98	.96	.94	.94	.94	.94	.85	.85	.74
10	.99	.97	.96	.93	.95	.95	.93	.86	.86	.77
15	.99	.97	.94	.92	.97	.94	.92	.92	.92	.86
20	.99	.97	.95	.92	.97	.95	.92	.94	.92	.90
25	.99	.97	.96	.93	.97	.96	.93	.96	.93	.92
30	.99	.98	.96	.94	.98	.96	.94	.96	.94	.94
35	.99	.98	.96	.95	.98	.96	.95	.96	.95	.95
40	.99	.98	.97	.96	.98	.97	.96	.97	.96	.96
45	.99	.98	.97	.96	.98	.97	.96	.97	.96	.96
50	.99	.98	.98	.96	.98	.98	.96	.98	.96	.96

See footnote at end of table.

TABLE 8.—*Strength ratios, as determined by knots, for beams consisting of various combinations of 2 grades and having not more than 2 maximum-size knots, or equivalent, within 6 inches of any cross section*—Continued

3 LAMINATIONS EACH SIDE HIGHER GRADE

Number of laminations	Strength ratios for laminations of grades [1]									
	0–1	0–2	0–3	0–4	1–2	1–3	1–4	2–3	2–4	3–4
8	1.00	1.00	1.00	0.99	0.94	0.94	0.94	0.84	0.84	0.71
9	1.00	.99	.99	.99	.94	.94	.94	.85	.85	.74
10	1.00	.99	.99	.98	.95	.95	.95	.86	.86	.77
15	.99	.98	.97	.96	.97	.97	.96	.92	.92	.86
20	.99	.98	.96	.95	.98	.96	.95	.94	.94	.90
25	.99	.98	.96	.95	.98	.96	.95	.96	.95	.92
30	.99	.98	.97	.95	.98	.97	.95	.96	.95	.94
35	.99	.98	.97	.96	.98	.97	.96	.97	.96	.95
40	.99	.98	.97	.96	.98	.97	.96	.97	.96	.96
45	.99	.98	.97	.96	.98	.97	.96	.97	.96	.96
50	.99	.99	.98	.97	.99	.98	97	.98	.97	.97

4 LAMINATIONS EACH SIDE HIGHER GRADE

Number of laminations	0–1	0–2	0–3	0–4	1–2	1–3	1–4	2–3	2–4	3–4
10	1.00	1.00	1.00	1.00	0.95	0.95	0.95	0.86	0.86	0.77
11	1.00	1.00	1.00	.99	.96	.96	.96	.88	.88	.79
12	1.00	.99	.99	.99	.96	.96	.96	.90	.90	.82
13	1.00	.99	.99	.99	.96	.96	.96	.90	.90	.83
14	1.00	.99	.99	.98	.97	.97	.97	.91	.91	.84
15	.99	.99	.98	.98	.97	.97	.97	.92	.92	.86
20	.99	.98	.98	.97	.98	.98	.97	.94	.94	.90
25	.99	.98	.97	.96	.98	.97	.96	.96	.96	.92
30	.99	.98	.97	.96	.98	.97	.96	.96	.96	.94
35	.99	.98	.98	.96	.98	.98	.96	.97	.96	.95
40	.99	.98	.98	.97	.98	.98	.97	.98	.97	.96
45	.99	.99	.98	.97	.99	.98	.97	.98	.97	.96
50	.99	.99	.98	.97	.99	.98	.97	.98	.97	.97

[1] Grade designations are sorting classes. See appendix p. 138 for further discussion.

considered that, when the outer laminations of a beam are clear, no reduction in the strength of the beam is caused by a knotty interior lamination, provided the ratio of its strength to that of a clear lamination is at least as great as the ratio of the stress in the knotty lamination to the stress in the extreme fiber of the beam. A comparison of test results with fiber stresses computed by this method, however, indicates that the concept is not conservative and that the method involving the use of figure 55 gives more acceptable results.

Material graded under stress grade rules for joist and plank is commonly used in laminated beams. These grades have different limitations on defects in different parts of the piece. These differences are based on the assumption that the piece will be used in its full size as a simple beam, either edgewise or flatwise. When such a piece is used as a lamination of a horizontally laminated beam or arch, the more severe restrictions on knots near the edge of the wide face, based on possible use edgewise, are no longer necessary. For such use, therefore, the knot size permitted at the center of the wide face under joist and plank rules could be permitted anywhere in the piece.

The variation in stress along the length of a piece used as a part of the length of a lamination in a long beam may be much smaller than if the piece were used alone as a simple beam. Thus, the provision for limiting concentrations of knots in the center half of the length of a piece of joist and plank grade (par. 440, Lumber, American Standards for Softwood Lumber (*19*)) should be extended to apply to any part of the length rather than to the center half alone.

It should be noted that stress-grade material is intended for use in the size in which it is graded. Any stress-grade material that is resawed or ripped for use as laminations must, therefore, be regraded by the applicable rules.

Effect of cross grain on flexural stresses.—For beams with cross grain in laminations, the percentage of the basic flexural stress to be used in design is in accordance with table 9. In general, the strength ratio will be limited by the cross grain in the outermost laminations. Interior laminations should have the cross grain so limited that their strength is at least sufficiently high to resist the stresses imposed on them, assuming the stress in the beam to vary linearly from a maximum at the outermost fiber to zero at the neutral plane. For example, suppose the outer laminations contained cross grain having a slope of 1 in 16. The strength ratio of the beam, so far as cross grain is concerned, would be 80 percent, assuming cross grain in the interior laminations was properly limited.

Cross grain in interior laminations could be limited so as to be not steeper than 1 in 16; the same strength ratio could be used, however, with steeper cross grain in interior laminations. For example, laminations between the neutral plane and a point about one-eighth the distance from the outer fibers to the neutral plane could have slope of grain 1 in 12 without causing reduction in the strength ratio. Similarly, laminations between the neutral plane and a point about three-eighths the distance from the outer fibers to the neutral plane could have a slope of grain of 1 in 8. Similar relations, of course, can be worked out for other combinations.

It will probably be most convenient to establish a strength ratio based on the effect of knots and then to limit cross grain in such a way that the strength ratio for cross grain is as large as or larger than that resulting from knots. In this connection, it should be noted that, in the structural grades of joist and plank, cross-grain limitations are established to conform with the strength ratio resulting from knots, assuming the piece to be used as a one-piece sawn timber. Strength ratios based on a probability analysis of the occurrence of knots in randomly assembled laminations (see appendix) are considerably higher, because of knot dispersion, than for one-piece sawn timbers of the same grade. The same is true for members assembled with limitations imposed on knot concentrations in the manner described earlier (tables 7 and 8).

If advantage is to be taken of these higher strength ratios, then more severe limitations on cross grain, at least in the outer groups of laminations such as the outer 10 percent of the depth, must be imposed than are imposed by the grading rules. This necessitates an additional inspection and segregation for cross grain. Such additional inspection should not create a serious problem in manufacture, however, since samples of a number of structural grades have indicated that high percentages of the pieces have cross grain of 1 in 20 or flatter.

Cross-grain limitations are not generally imposed by grading rules for grades other than structural. Therefore, additional inspection for cross grain, where those grades are used, is a necessity.

TABLE 9.—*Strength ratios corresponding to various slopes of grain*

Slope of grain	Maximum strength ratio	
	For stress in extreme fiber in bending or for tension	For stress in compression parallel to grain
(1)	(2)	(3)
	Percent	*Percent*
1 in 6	------	56
1 in 8	53	66
1 in 10	61	74
1 in 12	69	82
1 in 14	74	87
1 in 15	76	100
1 in 16	80	------
1 in 18	85	------
1 in 20	100	------

Local deviations of grain are generally disregarded, only the general slope being measured. In many structures this will be satisfactory, but caution in this regard should be exercised in the manufacture of narrow members such as rafters. In such members, a local grain deviation may affect all, or nearly all, of the cross section of a lamination, whereas, in a larger member, only a relatively small proportion of the lamination cross section would be weakened.

It is suggested that pieces containing cross grain steeper than 1 in 8 not be used for the laminations of glued laminated structural members. While the direct effect of cross grain on strength could be evaluated so as to permit the use of material having steeper grain slopes, the occurrence of such steep slopes is likely to result in severe warping and twisting with resultant high stresses when such pieces are clamped in gluing.

Effect of knots on modulus of elasticity.—Results of tests (see appendix) show that the modulus of elasticity of members subject to flexure decreases with increasing I_K/I_G. The reduction in many cases will be on the order of 5 percent or less. In view of this and of the fact that deflection is not critical in many instances, it will frequently be satisfactory to use the basic value without reduction. Where more accurate evaluation of modulus of elasticity is required, the value may be computed by multiplication of the basic value by the appropriate factor from figure 58. The value of I_K/I_G for use with this figure is the same as that described earlier for determining working stresses in bending. By having the strength ratio for bending stress, figure 59 may be used to determine the strength ratio for modulus of elasticity directly.

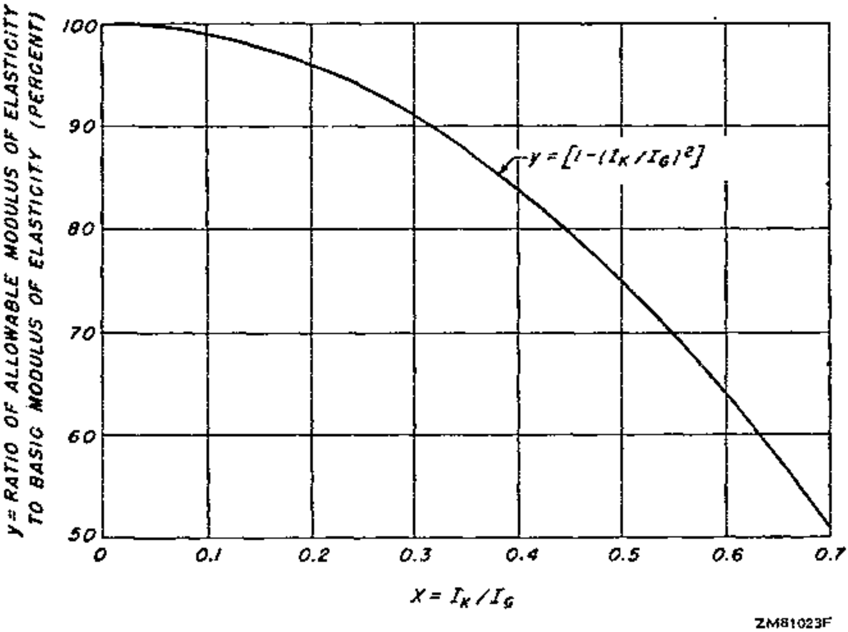

FIGURE 58.—Design curve for laminated beams and long and intermediate columns having knots in laminations and relating allowable modulus of elasticity to moment of inertia of areas occupied by knots.

Perhaps of more importance than relatively minor variations with grade is the necessity for adjusting values of modulus of elasticity or using other means for taking into account the deflection that occurs under long-continued load in addition to that which occurs immediately upon application of the load. This is discussed later in greater detail.

Provisions applicable only to curved members.—The above discussion of straight laminated members applies equally to curved members. Certain additional factors are applicable, however, to curved members.

The effects of end joints, knots, cross grain, and depth of members are applicable to curved as well as straight members. In addition, laminations of curved members must not contain knots or other imperfections that, when the laminations are bent to the required curve, cause localized irregularities in the curvature or prevent close contact between laminations. Thus laminations containing very large knots are likely to be usable only in straight members or in curved members of comparatively large radius.

Effect of curvature of laminations.—Because of stress induced when laminations are bent to the required form. the allowable flexural stress in curved members is less than in straight members (see appendix). The ratio of the allowable stress in curved members to that in straight members is expressed by the curvature factor

$$F_c=1.00-2{,}000\ (t/R)^2=1.00-\frac{2{,}000}{(R/t)^2} \qquad (1)$$

where t is the thickness of a lamination and R is the radius of the curve to which it is bent.

No curvature factor is to be applied to stress in straight parts of a member, regardless of the curvature in other portions.

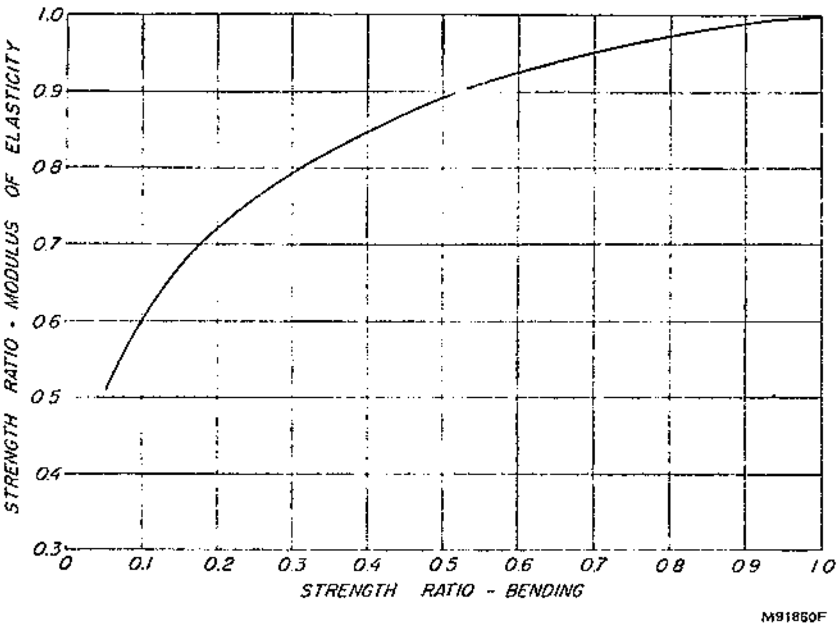

FIGURE 59.—Relation between strength ratio for stress in bending and that for modulus of elasticity in bending.

Radial tension or compression.—When a curved member is subjected to a bending moment, a stress is induced in a radial direction and thus at right angles to the grain. The maximum magnitude of this stress occurs at the neutral axis and is, approximately,

$$S_R=\frac{3}{2}\frac{M}{Rbh} \qquad (2)$$

where M is the bending moment, R is the radius of curvature, and b and h are, respectively, the width and height of the cross section. When M is in the direction tending to decrease the curvature (increase the radius), this stress is tension; and when M tends to increase the curvature (decrease the radius), the stress is compression.

Values of S_R should be limited to those shown in column 4 of tables 5 and 6 for stress in compression perpendicular to grain. Limitations of data make it difficult to establish reliable basic stresses for tension perpendicular to grain. It is suggested, however, that those curved members subjected to bending moments that produce stress in tension perpendicular to grain be so proportioned that this stress will be held to not more than about one-third (for softwoods) or three-eighths (for hardwoods) the working stress in shear.

VERTICALLY LAMINATED MEMBERS

Glued laminated members with vertical laminations have been less extensively studied by test than have those with horizontal laminations. Available test data indicate that the design curve shown in figure 55 is not applicable (see appendix). It is suggested that laminations be graded in accordance with the Forest Products Laboratory's recommendations as given in the Wood Handbook (7), and that allowable flexural stress be computed by multiplying the basic flexural stress by the grade factor F_g, which is equal to the strength ratio of the grade, or, where the various laminations differ in grade, is equal to the average of the strength ratios of the laminations. In computing the grade factor (average strength ratio) for a member containing laminations of differing grade, the strength ratios of the individual laminations should be weighted according to the proportion of the width of the member occupied by the corresponding laminations. Thus, if laminations occupying two-thirds the width had a strength ratio of 0.75 and the remainder had a strength ratio of 0.63, the grade factor would be

$$\begin{aligned} F_g &= (2 \times 0.75 + 1 \times 0.63)/3 \\ &= 0.71 \end{aligned} \qquad (3)$$

For use in dry locations, the strength ratio is not to be increased for the effect of drying as provided in the Wood Handbook, since this effect has been incorporated into the basic stresses of table 5.

The same allowance for end joints is made as for horizontally laminated members. To provide adequate shear resistance, vertically laminated beams require the use of one-piece or edge-glued laminations in those laminations required for shear resistance.

FACTOR FOR HEIGHT AND SHAPE OF BEAM

Unit strength values developed in tests of wood beams when calculated by usual engineering methods have been found to vary both with the height of the beam and the shape or form of the cross section. Decrease occurs as the height increases, and values for I and box beams are found to be lower than those for rectangular beams of the same height. An empirical formula that expresses the relation is

$$F_{hf} = 0.81 \left[1 + \left(\frac{H^2 + 143}{H^2 + 88} - 1 \right) S \right] \qquad (4)$$

where F_{hf} is the ratio of the modulus of rupture of a beam of I or box section to the modulus of rupture of a rectangular beam 12 inches in height, H is the height of the beam in inches, S is unity for a rectangular section and, for an I or box section

$$S=p^2\ (6-8p+3p^2)\ (1-q)+q \tag{5}$$

where p is the ratio of the height of the compression flange to the height of the beam, and q is the ratio of the total thickness of the web or webs to the overall width of the beam.

Since for a rectangular beam S equals 1, the formula reduces to

$$F_h=0.81\ \frac{H^2+143}{H^2+88} \tag{6}$$

Development of these formulas is shown in the appendix. The basic flexural stress is to be multiplied by the applicable factor to get the allowable design value.

APPLICATION OF FACTORS AFFECTING FLEXURAL STRESS

The factors by which the basic flexural stress is to be multiplied to get the design stress corresponding to the particular feature of the construction are:

1. F_j, factor for end joints.
2. F_k, factor for knots in horizontally laminated members, or F_g, factor for grade of lamination in vertically laminated beams.
3. F_{cg}, factor for cross grain.
4. F_h, factor for height of beam, or F_{hf}, factor for height and form of I or box beam.
5. F_c, factor for curvature.

The first four factors apply to either straight or curved members and are not to be combined. For straight beams, the values F_j, F_k (or F_g), F_{cg}, and F_{hf} (or F_h) are considered, and the lowest is taken as the ratio by which to multiply the basic flexural stress. For curved members, the resulting value is multiplied also by F_c, the curvature factor.

SHEAR STRESS

Allowable values of shear stress need not be reduced by reason of knots or end joints present in the laminations of a beam. In beams horizontally laminated from flat-grained stock, checks and splits, where present, will be essentially vertical and thus will have no effect on shear strength. In many cases, therefore, the basic stress in shear need not be reduced by reason of the presence of checks and splits. Shakes, while of infrequent occurrence, constitute more of a problem, since, if they are present in a horizontally laminated beam, they will have an effect on shear strength. It is suggested that laminations containing shake be discarded or, at least, used in areas of low shear. Where the character of the material and the method of construction necessitate it, allowable values of shear stress should be reduced from the basic stress for checks, shakes, and splits as for a solid member (7) relating the sizes of the checks, shakes, or splits to the finished width of the member.

BEARING STRESSES PERPENDICULAR TO GRAIN

Bearing stresses perpendicular to grain need not be reduced by reason of knots or end joints present in the laminations. The basic stresses given in tables 5 and 6 are applicable to bearings 6 inches or more in length and located anywhere in the length of a member, and to bearings of any length located at the end of a member. For bearings shorter than 6 inches located 3 inches or more from the end of a member, the stresses may be increased by multiplication by the following factors:

Length of bearing (inches):	*Factor*
½	1.75
1	1.38
1½	1.25
2	1.19
3	1.13
4	1.10
6 or more	1.00

For stress under a washer, the same factor may be taken as for a bearing whose length equals the diameter of the washer.

Compression Members

Laminations in a compression member may be arranged in a number of ways. While arrangements involving cover plates (fig. 60) are more efficient than those without such plates when mechanical fastenings are employed, there is, so far as is known, no such difference when the laminations are joined by glue. Laminations may also be of the same or of a variety of thicknesses. It is suggested that all laminations in a member be of the same grade except when, because of requirements for appearance, outer laminations are of higher grade than others. In such instances, laminations at opposite faces should be of the same grade and of the same thickness.

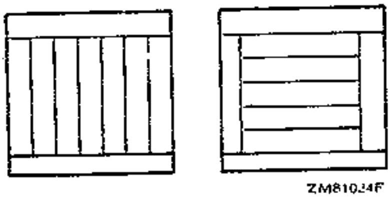

Figure 60.—Arrangement of laminations in compression members with cover plates.

Glued laminated compression members may be designed by use of the same formulas as are applicable to solid members. Where butt joints or stepped scarf joints are used, the effective area should be appropriately reduced. Both knots and cross grain affect the compressive strength and, where both are present, the strength ratio corresponding to the one causing the greater reduction should be used in computing the allowable compressive stress; the effects of the two factors should not be taken as cumulative. Since the allowable loads on long and intermediate columns are dependent on stiffness in bending, the effect of knots on stiffness, as given earlier for bending members, should be considered in computing the value of modulus of elasticity to be used.

END JOINTS IN COLUMNS

Butt joints are undesirable because they are difficult to fit accurately and because, even when accurately fitted, they are not fully effective. Butt joints or nonglued joints of other types may be used, provided all laminations at a single cross section having such joints are disregarded in computing the net or effective cross-sectional area. Butt joints in adjacent laminations should be separated as widely as possible, since, when they are closely spaced, the load-carrying capacity of the column tends toward that which would result if the two joints were at the same cross section. Limited data (see appendix) indicate that butt joints in adjacent laminations should be spaced 50 times the lamination thickness for optimum results. Figure 61 is a curve generalized from these data.

The cross section of a lamination adjacent to one containing a butt joint and itself containing a butt joint may be considered to be only partially effective, the degree of effectiveness increasing with increased spacing. This concept has been used in adapting the column test data of the appendix to the curve presented in figure 61. This curve shows the proportion of the cross-sectional area of a lamination that may be considered effective when that lamination contains a butt joint and is adjacent to a lamination containing a butt joint.

As an example of the use of this curve, consider a column made up of 12 laminations, in which laminations 2 and 11 contain butt joints at the same cross section and laminations 3 and 10 contain butt joints at a cross section $20t$ away with all other laminations continuous. At the cross section containing joints in laminations 2 and 11, there are 8 fully effective laminations, 2 partially effective laminations (3 and 10) and 2 noneffective laminations (2 and 11). From the curve of figure 61, laminations 3 and 10 are 80 percent effective. The proportion of the gross cross section of the column that can be considered effective in resisting compressive stress is, therefore, $[8+2(0.8)]/12=9.6/12=0.8$. If, in addition, there were butt joints in lamina-

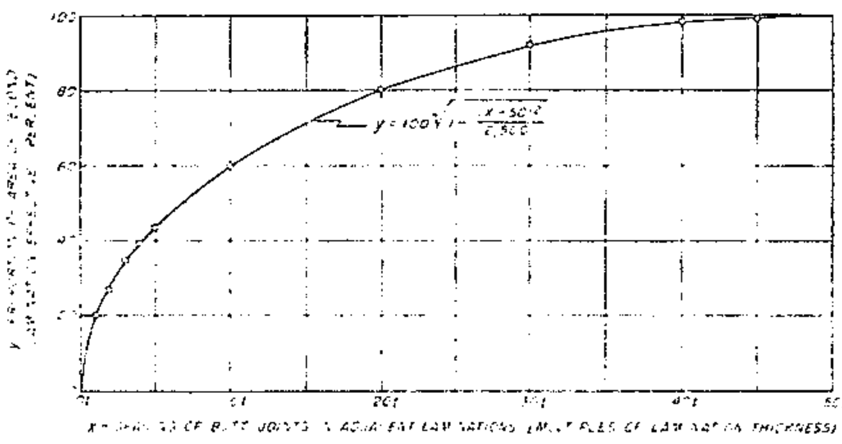

FIGURE 61.—Relation between spacing of butt joints in compression members and effective area of laminations adjacent to butt-jointed laminations.

tions 4 and 9 a distance of $20t$ from those in 3 and 10 and so arranged that the latter were intermediate between the others, the cross section containing joints in laminations 3 and 10 would become the critical cross section. Then, laminations 3 and 10 would be noneffective, and laminations 2, 4, 9, and 11 would be only partially effective. The proportion of effective cross section would then be $[6+4(0.8)]/12=9.2/12=0.77$.

End joints preferably should be of the plain or stepped scarf type, with a slope not steeper than 1:5. When the stepped type is used, the portion of the thickness occupied by the step (fig. 50, *B*) is considered as a butt joint and reduction in net section is made as for butt joints. No reduction in area need be made for glued scarf joints having a slope of 1:5 or flatter, except as provided for stepped scarf joints. Working stresses need not be reduced because of the presence of scarf joints having a slope of 1 in 5 or flatter. There are no requirements for spacing of scarf joints of 1 in 5 slope or flatter in compression members.

KNOTS IN COLUMNS

The stress on the net section of columns with knots is calculated in accordance with the design curve of figure 62. The abscissa of this curve is K/b, where K is the average (over all the laminations) of the sizes of the largest knot occurring in any 3-foot length in each of the laminations and b is the finished width of the lamination.

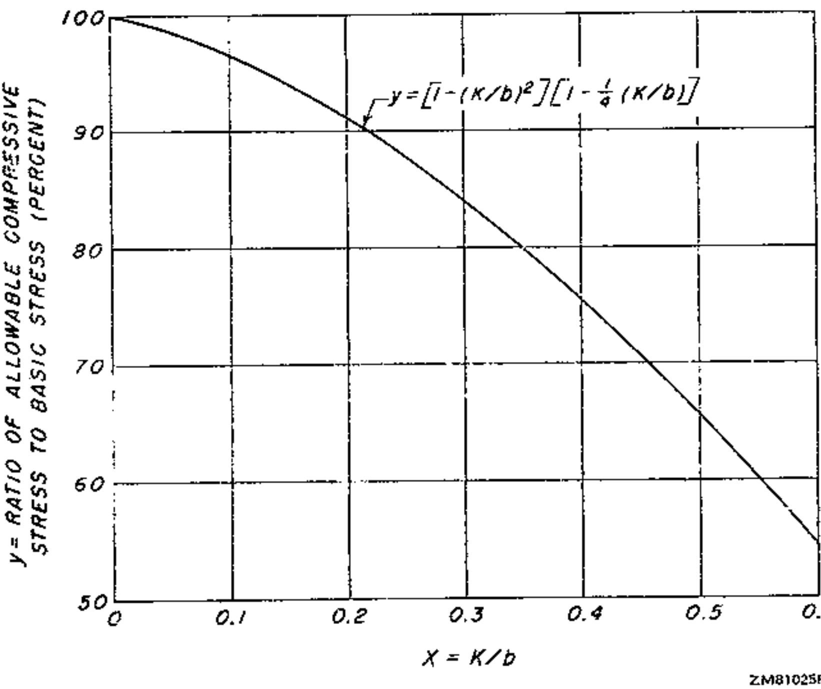

FIGURE 62.—Design curve for laminated short columns having knots in laminations and relating allowable compressive stress to knot size.

Here again, with no restriction on the location of knots within the member, some assumption must be made as to the concentration of knots within some critical 3-foot length. One possible assumption is that the maximum permissible knot will occur in every lamination within at least one critical length. As was pointed out earlier, this would be a highly conservative assumption, since such a large proportion of the lengths of pieces within a grade contain knots considerably smaller than the maximum or contain no knots at all.

In this case, too, it should be feasible to relate the frequency distribution of knot sizes within a grade to a value of K suitable for use in design. A study of a number of commercial grades indicates the feasibility of such an approach. That study is discussed in the appendix.

Each grade may be expected to have its own characteristic distribution of knot sizes. Working stresses based on a statistical study for a specific grade cannot, therefore, be translated into working stresses for a different grade or a different species.

In establishing working stresses for random assembly of laminations, it is suggested that they be based on a study of the distribution of the maximum knot sizes in 3-foot lengths by the method described in the appendix. Lacking such an analysis, it is suggested that the working stress be based on the assumption that the maximum knot permitted in the grade occurs in each lamination within at least one 3-foot length. That is, the value of K for use with figure 62 will be the maximum size permitted in the grade.

Both the Southern Pine Association and the West Coast Lumbermen's Association have published working stresses for laminated construction that are based on the statistical procedure just described.

In cases where it is not feasible to sample the grade and to go through the probability analysis, but an estimate is desired of the strength ratio that would be obtained by such an analysis, the following procedure may be used. First, calculate the value of K/b applicable if it were assumed that the largest permissible knot were present in every lamination. Second, multiply this value by the ordinate to the curve of figure 63 for the proper number of laminations. Then, with this modified value of K/b, determine the applicable strength ratio from the curve of figure 62. This procedure is based on a consideration of the relative values of K/b found by the two methods, and the factors shown are only approximate. In general, they are believed to be sufficiently conservative to provide a satisfactory basis for estimating strength ratios that may be expected from a probability analysis. For use in design, 1 of the 2 methods discussed earlier should be chosen.

Where columns are of more than one grade, working stresses applicable to the lower grade should generally be used. Where data on the occurrence of knots are available, there are methods of computation (see appendix) by which the smaller concentration of large knots in the higher-grade laminations may be taken into account in determining values of K/b.

CROSS GRAIN IN COLUMNS

For columns with cross grain in laminations, the percentage of the basic compressive stress to be used in design is in accordance with

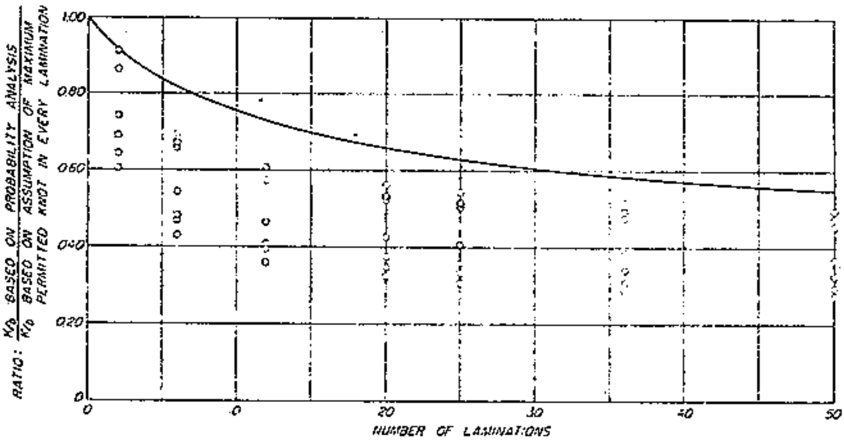

FIGURE 63.—Relation between values of K/b suggested for determining strength ratios for use in design of compression members and those that would have been determined by considering the largest permissible knot present in every lamination.

table 9. It is to be expected that all laminations in columns will be of the same grade. When laminations permitting differing grain slopes are used, however, the strength ratio corresponding to each grain slope should be weighted in accordance with the cross-sectional area occupied by the corresponding laminations to determine the average strength ratio for the full cross section.

Strength ratios based on a probability analysis of the occurrence of knots in randomly assembled laminations (see appendix) are appreciably higher, because of knot dispersion, than for one-piece sawn timbers of the same grade. If advantage is to be taken of these higher strength ratios, more severe limitations on cross grain must be imposed, for all laminations, than is contemplated by the grading rules. This necessitates an additional inspection and segregation for cross grain. Such additional inspection should not create a serious problem, however, since samples of a number of structural grades have shown that high percentages of the pieces have cross grain of 1 in 20 or flatter.

Tension Members

Tension members are subject to the same provisions with respect to arrangement of laminations, grading of laminations, types and spacing of end joints, and evaluation of K/b as are given for compression members.

END JOINTS IN TENSION MEMBERS

The stress at a plain scarf joint in a tension member must not exceed the percentages of the basic stress in tension parallel to grain given for members subject to flexure. Stepped scarf joints may be considered to have the same percentage of strength as plain scarf joints of the same slope; but the portion of the thicknesses of the laminations occupied by the steps is disregarded in computing the effective cross section of the member. Spacing requirements indicated earlier for the tension portion of flexure members should be used also for tension members. It is suggested that scarf joints be no steeper than 1 in 10.

It is suggested that butt joints not be used in tension members. If they are used, however, the procedure outlined for columns can be used in computing net area, except that an additional reduction of 20 percent should be made.

KNOTS IN TENSION MEMBERS

The basic flexural stress as given in table 5 or 6, pp. 100, 102, should be taken as basic tensile stress. Working stresses for design should be taken in accordance with the curve of figure 64. Values of K/b for use with this curve should be determined in the manner described earlier for columns.

CROSS GRAIN IN TENSION MEMBERS

The strength ratio for cross grain in tension members is given in table 9. As for columns, this effect, where laminations of different grades are used, should be weighted in accordance with the proportion of the cross section occupied by the various grades, and the effect of increased strength ratios resulting from knot dispersion should be reflected in more restrictive cross-grain limitations than are normally imposed by the grading rules.

Miscellaneous Topics Related to Working Stresses

CLOSE-GRAIN AND DENSE MATERIAL

The improved strength resulting when material of some species meets certain requirements with respect to rate of growth has been recognized in American Lumber Standards (*19*), which permit increased design stresses for Douglas-fir and redwood meeting specific requirements as to rate of growth (close grain), as well as for Douglas-fir and southern yellow pine meeting specific requirements as to rate of growth and percentage of summerwood (density). The increases apply to stress in extreme fiber in bending, compression parallel to grain, and compression perpendicular to grain, but not to shear or modulus of elasticity. These increased stresses are applicable to laminated construction, but certain cautions must be observed.

It is obvious that such increased stresses would be applicable to a beam constructed wholly of close-grained or dense material. It is obvious also that, in a beam containing a large number of laminations, with only the top and bottom laminations of close-grained or dense material, the increased bending stress would not apply to the beam as a whole. For example, if a beam contained 40 laminations, with the top and bottom laminations of dense material whose allowable stress was increased by one-sixth over that for nondense material, the stress in the outer surface of the second lamination would be

$$\frac{19}{20} \times \frac{7}{6} F = 1.11F$$

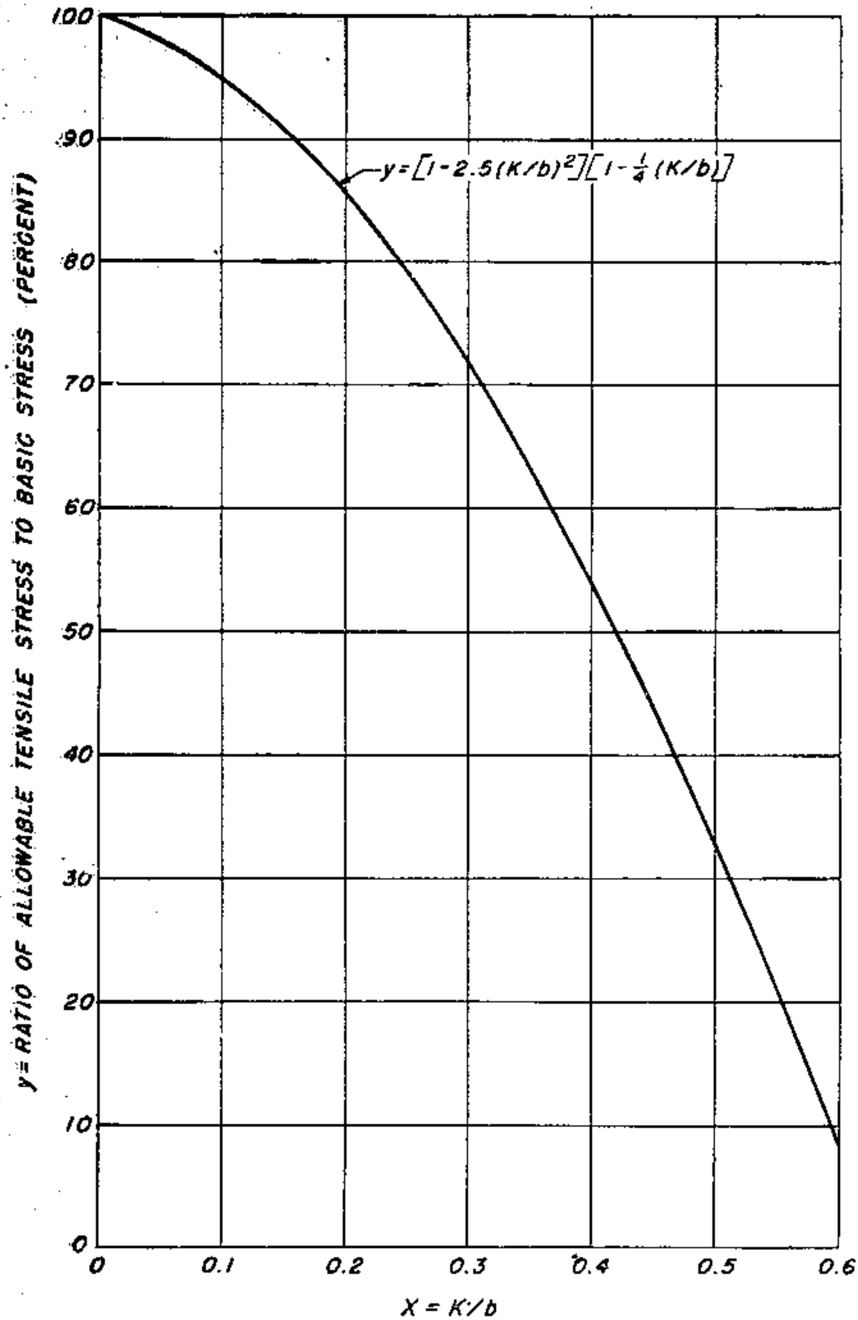

FIGURE 64.—Design curve for laminated tension members having knots in laminations and relating allowable tensile stress to knot size.

where F is the stress applicable to a nondense grade. Thus, in such a case, excessive stresses would be present in certain of the laminations near the top and bottom if the stress applicable to dense material were used.

The increased stresses pertaining to close-grained or dense material may be applied to the beam as a whole only when such material is used in a definite proportion of the beam. The number of dense laminations on each side of the beam must be at least one-fourteenth the total number of laminations in order that the increased stress may be applicable to the beam as a whole.

Similarly, close-grained Douglas-fir and redwood are granted increases of one-fifteenth, and again a minimum number of laminations of close-grained material are required on each side in order that the increased stresses may be applied to the beam as a whole. In this case, a group of laminations on each side containing not less than one thirty-second of the total number of laminations must be close-grained.

It should be noted that the proportions given above are applicable only when all laminations are of the same thickness. For other cases, the actual number of laminations should be converted to an equivalent number of laminations of a single thickness. Moreover, the proportions given are directly valid only when all laminations are of the same grade. When two different grades are used, the stress in the inner group of laminations should be checked by the method described earlier to be sure it is not excessive.

EFFECT OF END JOINTS IN VARIOUS PARTS OF MEMBERS

Since the stress is quite low in a lamination near the neutral axis, an end joint of relatively low efficiency is satisfactory at such locations. Thus, within the central two-thirds of the depth of a beam, plain scarf joints as steep as 1 in 5 are generally satisfactory, since the stress within this part of the beam is less than two-thirds the stress in the outermost lamination. Similarly, for beams whose loading is known to be such that certain parts of their length will never be subjected to high bending moments, such as those parts near the ends of a simple beam, the stresses will be such that scarf joints of steeper slope may be permitted, even in the outer parts of the depth, than would be permissible at points of high moment.

Regardless of such possibilities for the use of less efficient joints in certain areas, it may be found expedient to use only a single type of scarf joint in order to simplify manufacturing operations and to lessen the chance that joints of various types will be erroneously placed in a beam.

In general, a scarf-jointed outer lamination on the tension side of a beam will control the overall strength of the beam. Where the strength of the jointed lamination is very low, however, as compared with that of the continuous laminations, the load that would cause failure of the outer lamination at the joint would be insufficient to cause failure in the remaining laminations. There is, therefore, a "floor" below which the strength of the beam would not be expected to fall, regardless of the reduction in strength caused by a joint in the outer lamination.

Thus, a beam of 17 laminations having a jointed outer lamination on the tension side would be reduced in effectiveness to that of a beam of 16 laminations if the jointed lamination failed without causing failure of the rest of the laminations, and it would then have some 89 percent of the strength of the original beam. In such a beam, then, if the jointed outer lamination on the tension side had less than 89 percent of the strength of a continuous lamination, the overall strength of the beam would be taken as 89 percent of that of an unjointed 17-lamination beam rather than as determined by the strength of the jointed lamination.

It is possible, but not probable, that similar relations exist in beams with jointed laminations of low efficiency located near, rather than at, the tension face.

In compression and tension members, the stress requirements in different parts of the cross section and at different points along the length normally do not vary, so that the requirement is the same at all points.

As pointed out earlier, butt joints tend to concentrate shear stress in the interlamination glue joints near them. Both theoretical considerations and test data (see appendix) indicate a serious concentration of shear stress in the neighborhood of a concentrated load on a beam. It seems desirable, in order to reduce the possibility of failure by shear, to avoid combining these two concentrations. It is suggested, therefore, that if butt joints are used in laminated beams, they be kept well away from the location of any concentrated loads, particularly if the joints are in laminations located near the upper surface.

EFFECT OF KNOTS IN VARIOUS PARTS OF MEMBERS

The reduction in bending strength caused by a knot in a laminated beam is a function of the moment of inertia of the cross-sectional area occupied by the knot. A knot near the center of the depth of a beam has only a small fraction of the effect on bending strength that a knot of the same size would have if it were located at or near the outside of the beam.

Laminations of relatively low grade may therefore be used in the central parts of the depth of a beam without inordinately reducing its strength. Efficient and economical use of material may thus be attained by using pieces of high grade in the outer parts of the depth and pieces of low grade in the inner parts of the depth, where their inferior strength is not injurious to the strength of the beam as a whole. The relatively small effect of low-grade material occupying as much as the central three-fifths of the depth has been demonstrated in the statistical studies of knot effect mentioned earlier.

Similarly, laminations of lower grade may be permitted in parts of the length that will be subjected to small bending moments, such as those near the ends of a simply supported beam.

The curve of figure 55 was derived from tests on beams in which the outer laminations were generally of better quality than the inner laminations. Although such an arrangement is logical and economical, the use of figure 55 for beams having the reverse of the usual arrangement—that is, with low-quality outer laminations and higher-quality inner laminations—may result in an allowable stress for the beam that will produce an excessive stress in the outer laminations. It is improbable that a designer would use such an arrangement. If, however, a beam were misassembled and such an arrangement resulted, it might be desired to attempt to salvage the beam. In such a case, a new allowable stress can be computed by means of figure 55 but, in addition, the stress thus computed should be checked against the strength of the outer lamination.

MODIFICATION OF WORKING STRESSES FOR SPECIAL CONDITIONS OF LOADING

Working stresses computed by the methods here given and based on the basic stresses of table 5 or table 6, pp. 100, 102, are applicable to conditions of full duration (25 to 50 years) of maximum design load. Since wood has the desirable characteristic of being able to support higher loads for short than for long periods, higher working stresses are applicable to conditions where the full design loads are of shorter duration than 25 to 50 years.

Figure 65 presents data by means of which adjustments for duration-of-load effects may be made. For example, if the anticipated duration of full design load were 10 years, stresses could be increased about 10 percent over those allowable for conditions of full duration. It has been found that intermittent loading separated by a period of rest is cumulative as far as the durational effect is concerned. The duration to which figure 65 is applicable is, therefore, the sum of the durations of the expected loads. Loads less than those that would produce stresses at or below the permanent load level may be neglected in computing such durations.

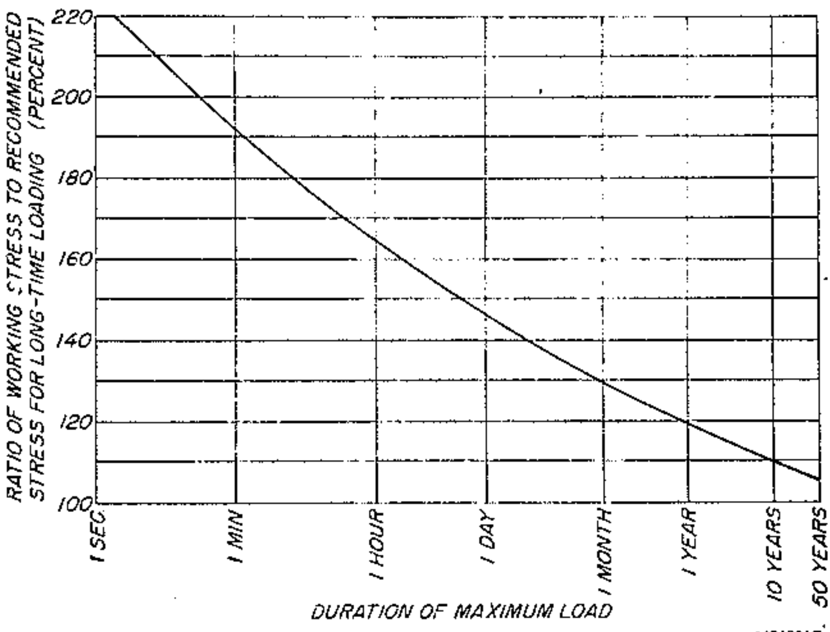

FIGURE 65.—Relation of working stress to duration of load.

Working stresses computed from the basic stresses of table 5 or table 6 may be used without regard to impact if the stress produced by impact does not exceed the allowable stress for permanent loading; but the sum of stresses induced by any combination of loading, such as impact, dead, long-time live, and short-time live loading, cannot exceed twice the allowable stress for permanent loading.

In no case can a structural member be used that is smaller than is required for permanent load alone.

Increases in stress for impact and other duration effects are not applicable to modulus of elasticity.

Wood under continuing load takes on a continuing increment of deformation known as plastic flow or yield, usually very slow but persistent over long periods of time. Deflection of this nature occurring in timbers acting as beams is sometimes known as "set" or "sag." This increase of deformation with time may become as much as the initial deformation without endangering the safety of the timber. This effect is of importance only where the long-continued load is at or near the maximum design level. It is necessary, where deformation or deflection under long periods of loading must be limited in amount, to provide extra stiffness. This can be done by doubling any dead or long-time loads when computing deformation, by setting an initial deformation limit at half the long-time deformation limit, or by using one-half of the recommended value of modulus of elasticity in computing the immediate deformation. In any case, it must be understood that the recommended values for modulus of elasticity will give the *immediate* deflection of a beam, and that this deflection will increase under long-continued load. The increase may be somewhat greater where the timber is subjected to varying temperature and moisture conditions than where the conditions are uniform.

DESIGN CONSIDERATIONS FOR LAMINATED WOOD

It is beyond the scope of this publication to discuss methods of structural analysis. Certain features of design, however, especially those peculiar to wood or laminated structures, are presented because they need to be considered.

Attempts to economize too thoroughly by varying requirements at different points in a structure can become complicated. It is true that stress requirements may permit the use of butt joints in some locations, the use of scarf joints of steeper slope in some locations than in others, and so on. By taking advantage of all such provisions, some savings in material and labor can be gained. Their use, however, necessitates extreme care in fabrication to insure that all material is properly placed.

Engineering Formulas

Engineering formulas applicable to solid-wood structures are generally applicable also to laminated structures, since the glued joints, if properly made, have shear strength approximately that of wood. The glued laminated member must accordingly behave as would a solid member. Lamination, however, introduces two possible cases in which the usual formulas are not applicable, and which are not encountered in structures of solid wood.

In the case of sharply curved flexure members, the ordinary equations for stress in a beam are not applicable and the special methods relating to curved beams should be used. Stresses computed by the usual equations will be low by about 5 percent when the radius of curvature of the center line of the member is about 6 times the depth of the member, and by about 11 percent when the ratio of radius to depth is about 3, with rapidly increasing percentage errors as the ratio of radius to depth becomes smaller (*25*). Limitations on the radii to which laminations may be bent without damage will generally operate to keep the ratio of center-line radius to total depth at a reasonable value. It is probable, therefore, that few members will be designed with ratios of radius to depth small enough to require special treatment, but all sharply curved members should be investigated to assure that the error involved in the use of the ordinary equations is small. The curve of figure 66 may be used to estimate, for flexural members of rectangular cross section, the error involved in the application of the ordinary equations for stress to curved flexure members having various ratios of center-line radius to depth.

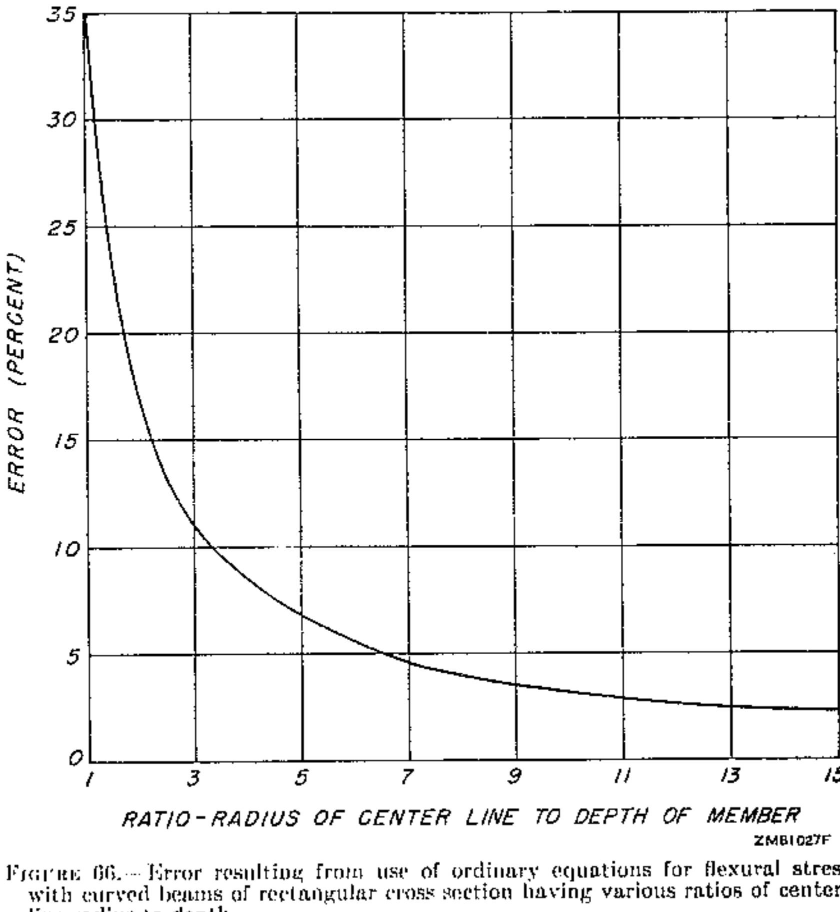

FIGURE 66.—Error resulting from use of ordinary equations for flexural stress with curved beams of rectangular cross section having various ratios of center-line radius to depth.

Cases may arise where it is desirable to use laminations of more than one species. If so, consideration should be given to the fact that, with laminated beams having laminations of markedly different moduli of elasticity, the usual assumption of linear variation of strain across the depth will lead to a nonlinear variation of stress. This will normally be of little consequence, particularly if the difference in modulus of elasticity is small or if the material of low modulus of elasticity is used in only a small part of the depth near the neutral axis. In the case of a beam having material of high modulus of elasticity in the outer two-fifths of the depth and low modulus of elasticity in the central three-fifths of the depth, errors of about 5 percent and 11 percent will be introduced for ratios of moduli of three-fourths and one-half, respectively. Such a case might arise where, for reasons of economy, a species of low strength and low modulus of elasticity is used in the central part of a beam.

Effect of High Moisture Content

The working stresses applicable to laminated members must be suitable for the general maximum moisture content that will be reached by the wood under use conditions. While most glued laminated members are used under dry conditions, some must withstand exposure to moisture. The direct effect of moisture content on strength has been considered in establishing the basic stresses of tables 5 and 6. There are, however, additional considerations involved where the use conditions result in high moisture content in the member.

The wood in glued laminated members intended for use conditions involving moisture and other conditions conducive to decay can be made durable by the application of preservative chemicals if the wood is not naturally durable. The wood may be treated in lumber form with preservatives before gluing, or the treatment may be given to the laminated member after the gluing has been completed. Such treatments do not protect the wood from absorbing moisture, and the moisture-content level of the treated wood under use conditions is generally the same as that of untreated wood, although certain fire-retardant treatments make the wood more hygroscopic than untreated wood. Consequently, preservatively treated wood and untreated wood require the same working stresses for similar use conditions. The use of untreated wood that is not naturally durable is not, however, recommended where the conditions of use are conducive to decay.

In general, design for conditions favorable to decay should be on a more conservative basis than where such a hazard is not present. In addition, attention should be given in design to the elimination of such features as might increase the decay hazard, such as the encasement of wood members in masonry. Timbers exposed to the hazards of decay should be inspected at frequent intervals and removed if decay appears in or near highly stressed areas.

Effect of High Temperature

It is known that wood has lower strength at high than at low temperatures, and investigations at the Forest Products Laboratory have shown that wood that has been exposed to high temperatures for long periods has had its strength reduced even though it may be used subsequently at normal temperatures. It is known also that strength reduction resulting from the effects of high temperature is greater for wood at high moisture content. Available data (*14*, *22*, *23*) are, however, too meager to permit the establishment of any rules for the effect of high temperature on strength.

Caution is suggested in the design of glued laminated structures for use under conditions of elevated temperatures, particularly if such temperatures are likely to persist over long periods. Where such conditions are expected, some reduction in working stress is desirable to reduce the possibility of damage to the structure from the effects of high temperature.

Since the temperature of the wood and not of the surrounding air determines the amount of strength loss, if any, recognition should be given to the fact that high air temperatures do not necessarily mean high temperatures in the wood. Wood is a good insulator, and, therefore, high temperatures must persist for long periods before the wood temperature rises much, particularly if the member is large in cross section. In considering the possible necessity for strength reduction for high temperature, therefore, consideration needs to be given not only to the temperature to which the member will be exposed, but also to the anticipated duration of the exposure.

The probability of long-continued high temperatures should be considered, also, in the choice of a glue, since certain glues are adversely affected by such exposure (part I).

Effect of Shrinkage or Swelling on Shape of Curved Members

A wood member tends to shrink or swell across the grain with loss or absorption of moisture, but practically no change occurs in the dimension along the grain. For a section of a curved wood member such as is shown in figure 67, the angle α must change to accommodate the change in thickness, since the lengths L and l do not change.

It has been shown (*28*) that if the thickness t is changed to a thickness $t(1+k)$, the angle α changes to a value $\alpha(1+q)$, where $q=-k$ (approximately), so that the change in angle is $-k\alpha$. Hence, if t is changed by a small percentage k, the angle α will be changed by approximately the same percentage, but in the opposite direction; that is, radial swelling causes a decrease, and radial shrinkage causes an increase, in the angle α between the ends of a curved member.

It may be noted that the percentage change in angle is independent of the length of the section, the dimensions of the cross section of the piece, and the radius of curvature. The foregoing relation may therefore be used regardless of the form of the member.

In deriving this relation, an approximation was used that consisted of considering that $-k\ /\ (1+k)$ was equal to $-k$, since k is small compared with unity. Slightly greater accuracy will be obtained by computing the change of angle to be $-k\ \alpha\ /\ (1+k)$.

It should be noted that, in the application of this method, several approximations cannot be avoided. These include:

(1) An average value of shrinkage must be assumed as applicable to the member. The actual shrinkage may differ considerably from the average value, and the value k will be in error by the amount of the difference.

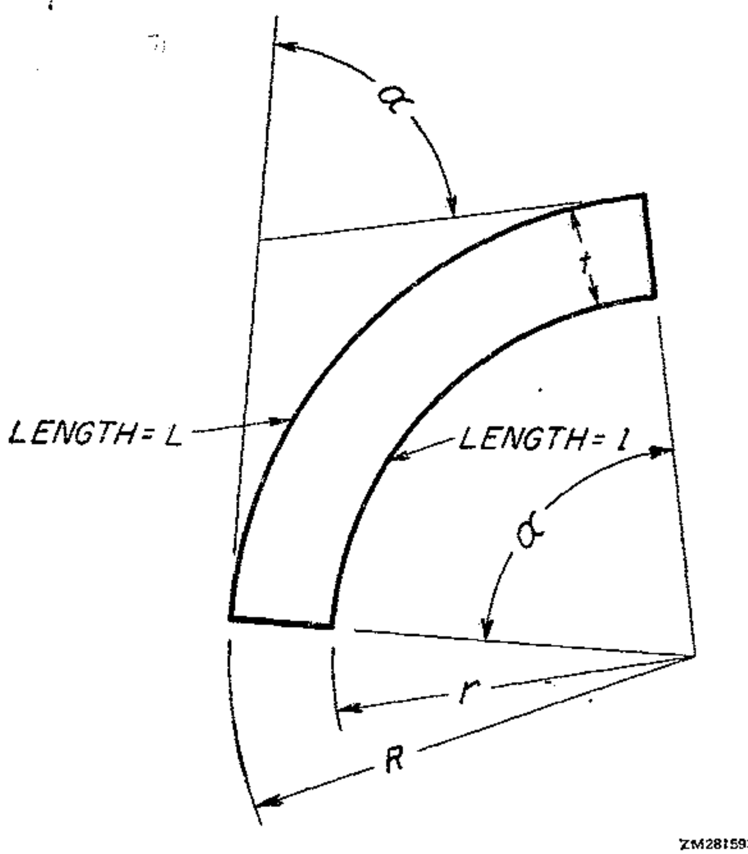

FIGURE 67.—Diagram showing notation used in deriving the formula for change of curvature produced in a curved wood member by radial swelling or shrinking.

(2) The relation used is based on the assumption that the percentage shrinkage is the same at all points. In large cross sections, the shrinkage near the outside of the cross section may be different from that in the inner part simply because of the greater time required for the moisture content to change in the inner part. Similarly, for members varying considerably in depth, a thin section will reach equilibrium throughout sooner than will the thicker section, and thus the effective value of k will be different at the two points. With sufficiently long exposure, however, and reasonably constant conditions, the value of k for all points in the member will be the same.

The effects of shrinkage or of swelling should be considered in any computation of deflection or of final position of a curved laminated member. In the case of three-hinged arches of such shape that they are horizontal, or nearly so, at the crest of a roof, such effects may be of considerable importance. In such arches there may be shrinkage enough to form a depression, or trough, at the crest of the roof that will create serious drainage problems. For an arch of this type, consideration should be given to the moisture content of the member at the time of fabrication, the moisture content to be expected in service, and the change in angle between the two ends of the member that will result from changes in moisture content and the consequent shrinkage across the grain.

Consideration should be given to the provision of effective hinge details in joints of arches where such joints have been assumed in design. With such details provided, the line of action of the forces on the member will be as assumed, regardless of changes in shape of the member.

Where deformation in a curved laminated member is restrained, as in a boat frame connected to a deck beam, the tendency to deform will cause stress in the member. The method just outlined will furnish the data necessary to calculate the magnitude of these stresses.

Considerations in the Design of Continuous Beams

Caution should be exercised in the use of butt joints in continuous beams because of the reversal of moment, and thus of the location of the compression section of the beam, at points near the supports, since the treatment of butt joints in design is different for the tension and compression sections of beams. Furthermore, in structures subject to variations in load, the point of moment reversal may vary somewhat, so that the areas in which butt joints may be used will also vary. In addition, the use of scarf joints of steeper slope and of laminations containing knots of larger size is rendered more difficult, for moments are no longer small near the supports, as in simple beams.

It is recommended that butt joints not be permitted at any point in a continuous beam, and that no attempt be made to vary the requirements for slope of scarf joint or knot size at various points along the length.

Fastening Design

Allowable loads or allowable stresses and methods of design for bolts, connectors, and other fastenings that are applicable to fastenings used in one-piece sawn members, are applicable also to laminated members. However, in the design of fastenings in laminated members, problems may arise. For example, in connecting an arch rib to a foundation, it is common practice to bolt the rib to a metal channel or shoe attached to the foundation. With a rather deep section, the bolts may be widely separated. If a large decrease in moisture content occurs, the tendency of the member to shrink between the widely separated bolts will be considerable; and, if the bolts are held in position by the metal channels, a considerable stress in tension perpendicular to grain will be set up, and splitting may occur.

This tendency will be reduced if the moisture content at the time of erection is approximately the same as that to be reached in service. Some relief may also be gained if the bolt holes in the steel channels are slotted to permit movement of the bolts. It is probable that friction on the bolts will be large enough to prevent free movement, but such an arrangement may relieve the tensile stresses across the grain somewhat. Cross bolts will assist in preventing separation if splitting does occur.

Elastic Instability

HEIGHT-WIDTH RATIO OF BEAMS

According to the usual flexure formulas, strength and stiffness vary as the second and third powers, respectively, of the height of a beam, but only as the first power of the width. Consequently, the amount of material required for strength and stiffness is minimized by making the height as great as other considerations permit, within certain limitations imposed by the effect of the height factor.

The extent to which strength and stiffness can be augmented by increasing the height and decreasing the width is limited, because large ratios of height to width lead to lateral instability and to failure by twisting and lateral buckling at loads less than those computed by the usual flexure formulas. The critical bending moment or load depends on the modulus of elasticity and the modulus of rigidity (in torsion), the length and cross-sectional dimensions of the member, location or distribution of load, and on the way in which the ends and edges of the member are supported and restrained.

Formulas for critical moment or load have been developed theoretically and checked experimentally for several combinations of these factors (*7*). The formulas were derived for straight beams. Adequate information along similar lines is lacking for curved members. The following ratio has been suggested by the Forest Products Laboratory (*28*).

The ratio of the depth to width in a curved member with rectangular cross section should not exceed 4 when 1 edge is braced at frequent intervals, as by girts or roof purlins, and should not exceed 3 when such bracing is lacking. The length of members that are braced along one edge is probably not important. It is suggested that the combined bending and compressive stress in unbraced members be limited to one-third of the stress that, according to the Euler formula, would cause lateral buckling in straight members of the same cross section and of a length equal to the chord length of the curved member.

Formulas for critical moment or load for beams having cross sections other than rectangular are somewhat more complicated. Formulas for a number of cases for beams of I section are given in National Advisory Committee for Aeronautics Report 382 (*26*). The formulas for beams of rectangular section may be used for beams of box section if the appropriate torsion constant is used.

For use in the formulas mentioned above, a value of mean modulus of rigidity may be taken that is equal to one-sixteenth the modulus of elasticity.

WRINKLING AND TWISTING OF COMPRESSION MEMBERS HAVING THIN OUTSTANDING FLANGES

Compression members having thin outstanding flanges may fail by wrinkling of the thin outstanding parts or through twisting of the entire member about its longitudinal axis rather than by the usual modes of failure appropriate to their length. Both wrinkling and twisting phenomena are governed by individual laws and differ from the usual column behavior. Failure of any kind, whether it be crushing, as for a short column, flexure, as for a long column, wrinkling, or twisting, will come from that particular stress or combination of stresses to which the member has least resistance.

Criteria for determining the critical stress for wrinkling or twisting failure have been developed (*7*). These criteria may be used to determine whether the critical stresses for these secondary modes of failure are greater or less than the stress associated with the primary mode of failure.

SUGGESTED SPECIFICATION REQUIREMENTS

Specification requirements suggested herein for glued laminated structures and structural members must necessarily be general. Such requirements can, however, offer guidance in considering the more important points that affect a specification for a particular structure and may, in some instances, be applicable in themselves. They are, where possible, based on the best available test data; where test data are not available, they are based on the best judgment of the authors and others. Some of the provisions have been taken from United States Department of Agriculture Technical Bulletin 691 (*28*), which has been widely used as a source of specification requirements since its publication in 1939. The following requirements are presented for the purpose of serving as general aids to specification preparation.

Design

LOADS

Both the magnitude and the duration of the loads to be encountered in service shall be considered in design. The loading to be considered in the design shall include dead load, snow load, wind load, impact, earthquake, and others as applicable, and shall include such combinations of these loads as are applicable. The types of loading to be considered and the magnitudes of the various loads shall be determined by the best usual practice or as dictated by applicable codes or ordinances. Loads to be encountered in erection shall also be considered in the design.

ALLOWABLE WORKING STRESSES

Allowable working stresses shall be determined in accordance with the provisions of this publication. Allowable design loads or stresses for fastenings shall be determined as for fastenings in solid wood members.

Material

GLUE

A glue shall be used that is adequate to develop and retain the full strength of the wood under the conditions expected for the anticipated service life of the structure. (Glue types suitable for use under various service conditions are described in part I of this publication, in which some references to specifications for these glues are given.)

LUMBER CLASSIFICATION

Each piece of lumber, before assembly into a glued laminated member, shall be classified and suitably marked or segregated to identify its grade. Where a piece is resawed, ripped, or cut into shorter lengths, each piece resulting from such cutting shall be regraded and suitably marked or segregated so that its grade identity is retained.

Moisture content.—The moisture content of the lumber immediately prior to assembly into the laminated member shall be such that the completed member shall have a moisture content as near as possible to that expected in service. The range of moisture content of various laminations assembled into a single member shall not exceed 5 percent (for example, 6 to 11 percent or 10 to 15 percent) at the time of gluing.

Limitations for stress grades.—Laminations may be of material graded under the rules for stress-grade material as given in the Wood Handbook (7) and in the grading rules of the various organizations publishing grading rules and providing inspection, except:

1. For use in horizontally laminated members subject to bending, the size of knot permitted at the center of the wide face of pieces of joist and plank grade may be permitted at any location on the wide face.

2. The rule limiting knot concentration in the center half of the length shall be applicable to all portions of the length.

3. Laminations sawed from material graded under the rules for stress-grade material or edge-glued from such material shall be regraded in the new size.

Limitations for other commercial grades.—Grades of lumber that do not have limitations on all factors affecting strength shall not be used in glued laminated structural members unless they have been regraded in accordance with the principles set forth for stress grades or have been classified in accordance with the provisions of the following section.

Limitations for special lamination classes.—It may sometimes be necessary or desirable to use grades of lumber in which the defects are not adequately limited to permit their use in structural members. In common grades of lumber, for example, cross grain is not limited. The classes suggested below are essentially sorting classes, which may be used in a plant to classify commercial grades of lumber for use in laminations.

Decay is not permitted in any piece in which the largest permitted knot is required to be smaller than one-half the width of the piece. In pieces where decay is permitted, it shall, at its maximum point, occupy a proportion of the cross section of the piece no greater than one-half that occupied by the largest permitted knot. Pieces containing decay shall not be used in the outer laminations of members subjected to bending loads.

Sap stain is permitted.

Sound, encased, loose, or pith knots shall be admitted. Unsound (decayed) knots may be admitted provided the decay does not extend into the surrounding wood to an extent greater than is permitted by the requirement given above. Knotholes shall be measured and limited as specified for knots.

Knots may be measured as specified in the Wood Handbook (7) or in lieu thereof, the following method of measurement may be used. The size of a knot in a typical flat-grained piece is to be taken as the distance between lines touching the knot and parallel to the edges of the piece on the face on which the size of the knot is the greater, except that the greatest dimension of the remaining portion of a knot that is partially cut away at the edge of the piece shall be taken as the size. In the case of a spike knot or of a knot extending across the wide face of an edge-grained piece, the ratio of the maximum cross section of the knot to the cross section of the piece shall not exceed the fraction specified for the ratio of the size of a knot to the width of the piece.

The sum of the sizes of all knots within any 8 feet of the length of a piece shall not exceed 4½ times the maximum permitted size. When knots are in tandem or partially so, as in figure 68, the measurement *a* may be used instead of the sum of the individual sizes.

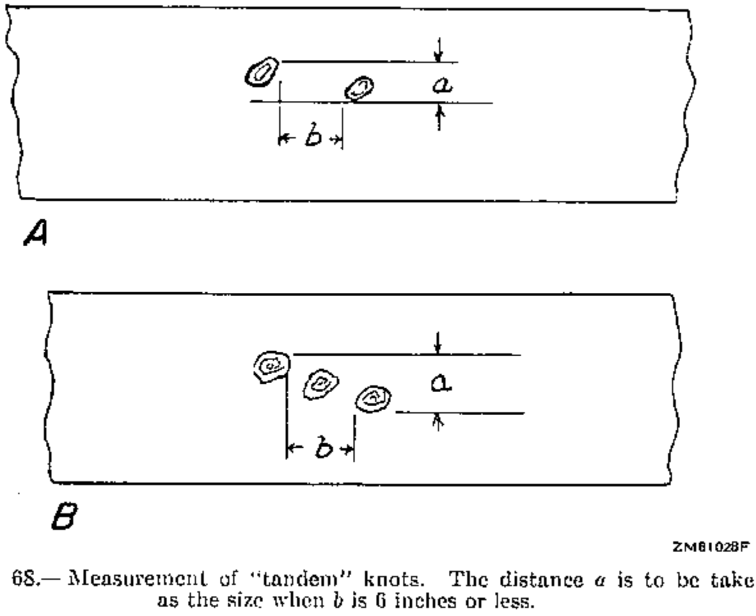

FIGURE 68.—Measurement of "tandem" knots. The distance *a* is to be taken as the size when *b* is 6 inches or less.

The slope of grain is to be measured over a distance sufficiently great to determine the general slope, but disregarding slight local deviations. Particular attention is to be given to spiral grain, which is detectable on tangential (flat-grain) surfaces only.

Laminations shall be free from checks, shakes, or splits that make an angle of less than 45° with the wide face of the piece, and free from pitch pockets whose width measured on the wide face exceeds 1½ inches or one-eighth the width of the piece, whichever is the lesser.

Wane is permissible if its greatest width does not exceed the finished thickness of the piece or one-eighth the finished width, whichever is the lesser.

CLASS 0 shall be free from knots greater than ¾ inch in size or one-sixteenth the width of the piece, whichever is the lesser. The slope of grain shall not be steeper than 1 in 20 for members stressed primarily in bending or tension nor steeper than 1 in 15 for members stressed primarily in compression.

CLASS 1 shall be free from knots greater in size than 1½ inches or one-eighth the width of the piece, whichever is the lesser. The slope of grain shall not be steeper than 1 in 18 for members stressed primarily in bending or tension nor steeper than 1 in 14 for members stressed primarily in compression.

CLASS 2 shall be free from knots greater in size than 3 inches or one-fourth the width of the piece, whichever is the lesser. The slope of grain shall not be steeper than 1 in 14 for members stressed primarily in bending or tension nor steeper than 1 in 10 for members stressed primarily in compression.

CLASS 3 shall be free from knots greater in size than 3 inches or three-eighths the width of the piece, whichever is the lesser. The slope of grain shall not be steeper than 1 in 10 for members stressed primarily in bending or tension nor steeper than 1 in 8 for members stressed primarily in compression.

CLASS 4 shall be free from knots greater in size than 3 inches or one-half the width of the piece, whichever is the lesser. The slope of grain shall not be steeper than 1 in 8.

Fabrication

TECHNIQUES

Techniques used in fabrication shall be in accordance with part I of this publication.

QUALITY OF GLUE JOINTS

Glued joints between laminations of members of all types and glued edge joints in laminations for vertically laminated members shall be of such quality that they will meet the requirements appropriate to the conditions expected in service, as given under Methods of Evaluation of Product in part I of this publication. Glued edge joints in laminations for horizontally laminated members and for compression and tension members should preferably also meet the foregoing requirements.

JOINTS IN THE WIDTH OF LAMINATIONS

Laminations composed of 2 or more pieces edge glued to each other prior to final surfacing may be considered as 1-piece laminations. In vertically laminated beams, all laminations required for shear resistance shall be 1-piece. For members to be exposed to the weather or equally severe service, it is preferable that all laminations be one piece. In horizontally laminated members for interior use, laminations may be 1 piece or may be of 2 or more pieces, not edge glued. Edge joints in adjacent laminations, particularly for severe conditions of exposure, should be separated by not less than the lamination thickness.

JOINTS IN THE LENGTH OF LAMINATIONS

Types.—Butt joints may be used. They should preferably not be used in the laminations of tension members, in the laminations comprising the tension section of flexure members, nor in any laminations of the curved section of a member. Due account shall be taken in design of the effect of butt joints in reducing the effective area of axially stressed members and the net moment of inertia of flexure members.

Plain or stepped scarf joints may be used. Scarf joints steeper than 1 in 5 for interior use or 1 in 10 for exterior or equally severe service shall not be used.

End joints of other types may be used provided (*a*) adequate information is available on which to base limitations of slope, spacing, and placement, and on which to calculate allowable design stresses for members having laminations containing such joints, or (*b*) they are placed and treated, in the design of the member, as if they were butt joints.

No end joints of any type shall be permitted in the laminations of the outer one-fifth of the depth of a flexure member where the radius of curvature to which the lamination is bent is less than 125 times the thickness of the lamination.

Spacing.—Butt joints in adjacent laminations of axially stressed members shall be spaced not closer longitudinally than 50 times the lamination thickness unless account is taken in design of the effect of closer spacing. In flexure members, the minimum longitudinal spacing shall be 10 times the lamination thickness.

Where scarf joints occur in compression members or in the compression portion of flexure members, there are no limitations on the spacing of joints in adjacent laminations, but some dispersion is desirable. In tension members or the tension section of flexure members, scarf joints in adjacent laminations shall be longitudinally spaced, center to center, at least 24 times the lamination thickness where the design stress is at the full allowable value. For lesser values of stress, the minimum required spacing may decrease linearly to zero in areas of zero stress.

ARRANGEMENT OR DISTRIBUTION OF TAPER

The tapering of members that vary in depth shall be accomplished by one of the following methods:

1. The member shall be built up to approximately the desired depth and formed to the desired shape. If, by this procedure, the slope of grain with respect to the outer surfaces of the member becomes steeper than the grain slope permitted in the outer laminations, one of the following procedures shall be used.

2. A group of outer laminations totaling at least one-fifth of the depth of the member at the point of maximum depth, or one-half the depth of the member at the point of minimum depth, shall run parallel to each face of the member, with the remaining laminations so arranged that it will not be necessary to taper their ends to a slope, with respect to the grain direction, steeper than that permitted for scarf joints in the outer group of laminations. Such tapering shall

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be done by the use of techniques that will insure that glue joints between the inner and outer groups of laminations will have a quality equal to that between laminations.

3. All laminations shall run parallel to the center line of the member, except the last one at each face, which shall follow the curvature of the face. Fitting of the ends of the central group of laminations shall be done by the use of techniques that will insure that glue joints between the outer laminations and the central group will be of a quality equal to that between laminations.

4. The total taper shall be divided with approximate uniformity among all laminations; that is, each lamination shall be tapered in the same proportions as the member itself.

Inspection

Plant or other inspection to insure quality of the finished product should cover at least the following points: (1) quality of materials, (2) proper fabrication techniques, (3) quality of glue joints, and (4) proper placement of edge and end joints and material of various grades.

GLOSSARY

Air-dried or *air-seasoned.* See Seasoning.

Arch. A structural element whose general form is that of a curve and which is so supported that horizontal as well as vertical motion is resisted. When the ends of the arch are fixed in position with respect to the abutments and the member is continuous between abutments, it is known as a fixed arch; when it is supported at the abutments by connections incapable of transmitting moment and the member is continuous between hinges, it is known as a 2-hinged arch; when it is supported as is a 2-hinged arch, but is made of 2 parts joined at an intermediate point, usually the center of the length, by a connection incapable of transmitting moment, it is known as a 3-hinged arch.

Basic stress. See Stress.

Beam. A structural element, supported at one or more places along its length, the principal function of the element being to support loads acting more or less transversely to the long dimension.

Butt joint. See End joint.

Check. A separation along the grain extending, generally, across the rings of annual growth.

Chord. One of the principal members of a truss, usually horizontal, braced by the web members.

Close-grain rule. Rules for classification of lumber on the basis of rate of growth (rings per inch). The rules at present apply only to Douglas-fir and redwood and differ slightly. Structural material of these species meeting the requirements of these rules is assigned somewhat higher working stresses than is material not meeting these requirements.

Column. A vertical compression member on which the principal loads are parallel to the axis (a line joining the centers of gravity of all cross sections) of the piece. Short columns are those which fail primarily by shearing or crushing; intermediate columns are those which fail by a combination of shearing or crushing and flexure; long columns are those which fail in flexure; simple columns are those whose cross section at all points is a closed area; spaced columns are those composed of two or more simple columns spaced some distance apart and connected at two or more points, usually with metal connectors at the juncture of the simple column and the spacing element.

Cross grain. Lack of parallelism between the longitudinal elements of the wood and the axis of a piece. Applies to either diagonal or spiral grain or to a combination of the two.

Diagonal grain. A form of cross grain resulting from sawing at an angle with the bark of the tree.

Spiral grain. A form of cross grain resulting from the growth of the longitudinal elements of the wood spirally about instead of vertically along the bole of the tree.

Defect. Any irregularity in or on wood that may lower its strength.

Delamination. Separation of two laminations due to failure of the adhesive.

Density rule. Rules for classification of lumber based on percentage of summerwood and rate of growth (rings per inch). The rules at present apply only to southern yellow pine and Douglas-fir and differ slightly. Structural material meeting the requirements of these rules is assigned somewhat higher working stresses than is material not meeting these requirements.

Diagonal grain. See Cross grain.

Edge joint. The juncture of two pieces joined edge to edge, commonly by gluing. This may be done by gluing two squared edges as in a plain edge joint or by use of machined joints of various kinds, such as tongue and groove.

Edge grain. Lumber that has been so sawed that the annual growth rings form an angle of 45 degrees or more with the wide surface of the piece.

End joint. The juncture of two pieces joined end to end, commonly by gluing.

Butt joint. An end joint formed by abutting the squared ends of two pieces. Because of the inadequacy and variability of glued butt joints, they are not generally glued.

Scarf joint. An end joint formed by joining with glue the ends of two pieces that have been tapered to form sloping plane surfaces, usually to a feather edge, and with the same slope of the plane with respect to the length in both pieces. In some cases, a step or hook may be machined into the scarf to facilitate alinement of the two ends, in which case the plane is discontinuous and the joint is known as a stepped or hooked scarf joint.

Flat grain. Lumber that has been so sawed that the annual growth rings form an angle of less than 45 degrees with the wide surface of the piece.

Form factor. A factor to be applied to the usual formula for resisting moment in a beam to take account of the difference between the stresses developed in beams having certain cross-sectional shapes and those developed in a beam having a solid 2- by 2-inch cross section when computed by means of the usual engineering formulas.

Grade. The designation of the quality of a manufactured piece of wood.

Hardwoods. The botanical group of trees that are broadleaved. The term has no reference to the actual hardness of the wood. Angiosperms is the botanical name for hardwoods.

Height factor. A factor to be applied to the usual formula for resisting moment in a beam to take account of the difference between the stresses developed in beams of various heights and those developed in a beam having a solid 2- by 2-inch cross section when computed by means of the usual engineering formulas.

Joist and plank. Pieces (nominal dimensions 2 to 4 inches in thickness by 4 inches and wider) of rectangular cross section graded with respect to their strength in bending when loaded either on the narrow face as joist or on the wide face as plank.

K n-dried. See Seasoning.

Knot. That portion of a branch or limb that has been surrounded by subsequent growth of the wood of the trunk or other part of the tree; also a cross section of such a branch or limb on the surface of a piece of wood.

Decayed knot. A knot which, due to advanced decay, is softer than the surrounding wood.

Encased knot. A knot whose rings of annual growth are not intergrown with those of the surrounding wood.

Intergrown knot. A knot whose rings of annual growth are completely intergrown with those of the surrounding wood.

Pith knot. Sound knot having pith hole not over ¼ inch in diameter.

Round knot. A knot whose sawn section is oval or circular.

Sound knot. A knot which is solid across its face, at least as hard as the surrounding wood, and shows no indication of decay.

Spike knot. A knot cut approximately parallel to its long axis so that the exposed section is definitely elongated.

Laminated wood. An assembly made by bonding layers of veneer or lumber so that the grain of all laminations is essentially parallel.

Horizontally laminated wood. Laminated wood in which the laminations are so arranged that the wider dimension of the lamination is approximately perpendicular to the direction of the loads.

Vertically laminated wood. Laminated wood in which the laminations are so arranged that the wider dimension of the lamination is approximately parallel to the direction of the loads.

Lamination. One layer in, or to be used in, laminated wood. It may consist of a single piece or of a number of pieces in width or length, with the edge and end joints glued or unglued.

Moisture content. The amount of water contained in the wood, usually expressed as a percentage of the weight of the oven-dry wood.

Plain-sawed. Another term for flat grain.

Plywood. A cross-banded assembly made of layers of veneer or veneer in combination with a lumber core or plies joined with an adhesive. Two types of plywood are recognized, namely: (1) veneer plywood, and (2) lumber-core plywood.

NOTE.—Generally the grain of one or more plies is approximately at right angles to that of the other plies and almost always an odd number of plies are used.

Quarter-sawed. Another term for edge grain.

Radial. Coincident with a radius from the axis of the tree or log to the circumference.

Rate of growth. The rate at which a tree has grown wood, measured radially in the trunk or in lumber cut from the trunk. The unit of measure in use is the number of annual growth rings per inch.

Ring, annual. The annual growth layer as viewed on a cross section of a stem, branch, or root.

Scarf joint. See End joint.

Seasoning. The removal of moisture from green wood in order to improve its serviceability.

Air-dried or air-seasoned. Dried by exposure to the air, usually in a yard, without artificial heat.

Kiln-dried. Dried in a kiln with the use of artificial heat.

Shake. A separation along the grain extending, generally, between the rings of annual growth.

Softwoods. The botanical group of trees that have needle or scalelike leaves, and are evergreen for the most part, baldcypress, western larch, and tamarack being exceptions. The term has no reference to the actual hardness of the wood. Softwoods are often referred to as conifers, and botanically they are called gymnosperms.

Spiral grain. See Cross grain.

Split. A lengthwise separation of the wood extending from one surface generally across the rings of annual growth through the piece to the opposite surface or to an adjoining surface; a through check.

Springwood. The portion of the annual growth ring that is formed during the early part of the season's growth. It is usually less dense and weaker mechanically than summerwood.

Strength. The term in its broader sense embraces collectively all the properties of wood that enable it to resist different forces or loads. In its more restricted sense, strength may apply to any one of the mechanical properties, in which event the name of the property under consideration should be stated, such as strength in compression parallel to the grain, strength in bending, or hardness.

Strength ratio. A ratio representing the strength of a piece of wood remaining after making allowance for the maximum effect of the permitted knots, cross grain, shakes, and other defects.

Stress. Force per unit of area.

Basic stress. The working stress for defect-free material. It has in it all the factors appropriate to the nature of structural timber and the conditions under which it is used except those that are accounted for in the strength ratio.

Working stress. The stress for use in design of a wood member that is appropriate to the species and grade. It is obtained by multiplying the basic stress for the species and strength property by the strength ratio of the grade.

Summerwood. The portion of the annual growth ring that is formed after the springwood formation has ceased. It is usually more dense and stronger mechanically than springwood.

Tangential. Strictly, coincident with a tangent at the circumference of a tree or log, or parallel to such a tangent. In practice, however, it often means roughly coincident with a growth ring.

Timber, one-piece sawn. A timber consisting of a single piece of wood and formed to its final dimensions by no other manufacturing operations than sawing or sawing and subsequent planing of one or more surfaces.

Truss. A framework consisting of straight members, with axes all lying in the same plane, so connected as to form a triangle or series of triangles. In some cases, as in a bowstring truss, the chord members may be slightly curved, but the curvature is generally so slight that it complies essentially with the definition.

Veneer. A thin layer or sheet of wood.

Rotary-cut veneer. Veneer cut in a continuous strip by rotating a log or bolt against a knife.

Sawed veneer. Veneer produced by sawing.

Sliced veneer. Veneer that is sliced off by moving a log, bolt, or flitch against a knife.

Vertical grain. Another term for edge grain.

Wane. Bark, or lack of wood or bark from any cause, on an edge or corner of a piece.

Working stress. See Stress.

LITERATURE CITED

(1) American Society for Testing Materials.
1949. TENTATIVE METHODS FOR ESTABLISHING STRUCTURAL GRADES OF LUMBER. ASTM Designation: D245-49T, ASTM Standards, Part 4, pp. 589-616.

(2) Dunlap, M. E., and Bell, E. R.
1951. ELECTRICAL MOISTURE METERS FOR WOOD. U. S. Forest Prod. Lab. Rpt. R1660, 11 pp., illus. [Processed.]

(3) Eickner, H. W.
1942. THE GLUING CHARACTERISTICS OF 15 SPECIES OF WOOD WITH COLD-SETTING UREA-RESIN GLUES. U. S. Forest Prod. Lab. Rpt. 1342, 4 pp., illus. [Processed.]

(4) ———
1942. RATE OF SETTING OF COLD-SETTING, UREA-RESIN GLUE JOINTS. U. S. Forest Prod. Lab. Rpt. R1422, 8 pp., illus. [Processed.]

(5) Forest Products Laboratory.
1924. FORM FACTORS OF BEAMS SUBJECTED TO TRANSVERSE LOADING ONLY. THE INFLUENCE OF THE FORM OF A WOODEN BEAM ON ITS STIFFNESS AND STRENGTH—II. Natl. Advisory Committee for Aeronautics Rpt. 181, 19 pp., illus.

(6) ———
1940. THE DETECTION AND RELIEF OF CASEHARDENING. Tech. Note 213, 4 pp. [Processed.]

(7) ———
1940. WOOD HANDBOOK. U. S. Dept. Agr. Unnumbered Pub., 326 pp., illus.

(8) ———
1941. GLUES FOR USE WITH WOOD. Tech. Note 207, 4 pp. [Processed.]

(9) ———
1941. SYNTHETIC-RESIN GLUES. U. S. Forest Prod. Lab. Rpt. 1336, 21 pp. [Processed.]

(10) Hunt, G. M., and Garratt, G. A.
1938. WOOD PRESERVATION. 457 pp., illus. New York and London.

(11) Luxford, R. F.
1944. STRENGTH OF GLUED LAMINATED SITKA SPRUCE MADE OF ROTARY-CUT VENEERS. U. S. Forest Prod. Lab. Rpt. 1512, 13 pp. [Processed.]

(12) LUXFORD R. F. AND KRONE, R. H.
1946. END JOINTS OF VARIOUS TYPES IN DOUGLAS-FIR AND WHITE OAK COMPARED FOR STRENGTH. U. S. Forest Prod. Lab. Rpt. R1622, 13 pp., illus. [Processed.]

(13) MACLEAN, J. D.
1943. RATE OF TEMPERATURE CHANGE IN LAMINATED TIMBERS HEATED IN AIR UNDER CONTROLLED RELATIVE HUMIDITY CONDITIONS. U. S. Forest Prod. Lab. Rpt. R1434, 17 pp., illus. [Processed.]

(14) ———
1945. EFFECT OF HEAT ON THE PROPERTIES AND SERVICEABILITY OF WOOD: EXPERIMENTS ON *THIN* WOOD SPECIMENS. U. S. Forest Prod. Lab. Rpt. R1471, 12 pp., illus. [Processed.]

(15) MARKWARDT, L. J.
1938. FORM FACTORS AND METHODS OF CALCULATING THE STRENGTH OF WOODEN BEAMS. U. S. Forest Prod. Lab. Rpt. R1184, 9 pp., illus. [Processed.]

(16) MATHEWSON, J. S.
1930. THE AIR SEASONING OF WOOD. U. S. Dept. Agr. Tech. Bul. 174, 56 pp., illus.

(17) ———
1935. EFFECT OF STORAGE ON THE MOISTURE CONTENT OF LUMBER. U. S. Forest Prod. Lab. Rpt. R1071, 4 pp., illus. [Processed.]

(18) ———
1937. MOISTURE FLUCTUATIONS IN LUMBER WITHIN CLOSED STORAGE SHEDS CONTROLLED WITH ELECTRICAL EQUIPMENT. U. S. Forest Prod. Lab. Rpt. R1140, 3 pp., illus. [Processed.]

(19) NATIONAL BUREAU OF STANDARDS.
1939. LUMBER: AMERICAN LUMBER STANDARDS FOR SOFTWOOD LUMBER. U. S. Dept. Com. Simplified Practice Recommendation R16-39, 99 pp., illus.

(20) RUDD, W. C.
1948. FEDERAL COMMUNICATIONS GOVERNING ELECTRONIC HEATING. Forest Prod. Res. Soc. Proc. 2: 292–295.

(21) SMITH, C. B.
1944. EFFECT OF ELLIPTIC OR CIRCULAR HOLES ON THE STRESS DISTRIBUTION IN PLATES OF WOOD OR PLYWOOD *CONSIDERED* AS ORTHOTROPIC MATERIALS. U. S. Forest Prod. Lab. Rpt. 1510, 24 pp., illus. [Processed.]

(22) SULZBERGER, P. H.
1946. THE EFFECT OF TEMPERATURE ON THE STRENGTH OF WOOD, PLYWOOD, AND GLUED JOINTS. Prog. Rpt. 3, 2d Rpt. on Experiment T. P. 10–3–Y–1. THE EFFECT OF TEMPERATURE AND MOISTURE ON THE STRENGTH OF WOOD IN COMPRESSION PARALLEL TO GRAIN. Div. Forest Prod., Council for Sci. and Indus. Res., Melbourne, Australia. 23 pp., illus. [Processed.]

(23) ———
1947. THE EFFECT OF TEMPERATURE ON THE STRENGTH OF WOOD, PLYWOOD, AND GLUED JOINTS. Prog. Rpt. 7, 3d Rpt. on Experiment T. P. 10–3–Y–1. THE EFFECT OF TEMPERATURE ON THE STRENGTH OF WOOD AT VARIOUS MOISTURE CONTENTS IN STATIC BENDING. Div. Forest Prod., Council for Sci. and Indus. Res., Melbourne, Australia.

(24) THELEN, ROLF
1929. KILN DRYING HANDBOOK. U. S. Dept. Agr. Bul. 1136, 96 pp., illus.

(25) TIMOSHENKO, S.
1930. STRENGTH OF MATERIALS. Pt. II. ADVANCED THEORY AND PROBLEMS. 510 pp., illus. New York.

(26) TRAYER, G. W., AND MARCH, H. W.
1931. ELASTIC INSTABILITY OF MEMBERS HAVING SECTIONS COMMON IN AIRCRAFT CONSTRUCTION. Natl. Advisory Com. Aeronaut. Rpt. 382, 42 pp., illus.

(27) TRUAX, T. R.
1929. THE GLUING OF WOOD. U. S. Dept. Agr. Bul. 1500, 77 pp., illus.

(28) WILSON, T. R. C.
1939. THE GLUED LAMINATED WOODEN ARCH. U. S. Dept. Agr. Tech. Bul. 691, 123 pp., illus.

APPENDIX

Effect of End Joints

JOINTS IN BEAMS

Laminated beams with end joints in the laminations have been tested at the Forest Products Laboratory. The types of end joints tested and their locations are shown in figures 69 and 70.

The variation in longitudinal strains within beams having joints in laminations was measured in typical beams of all types for loads below the proportional limit. In every instance, the variation of strains on a cross section was essentially linear, except in the immediate vicinity of the joint, and the point of zero strain was at or very near the midheight of the beam. These facts indicate that, under working loads, the deflection of the beams and the general stress distribution are determined by the properties of the full cross section, with the joint acting as a stress raiser to cause local variations in stress.

The strains in the neighborhood of a joint were found to reach measured values as much as 2¼ times as great as the strain at the same vertical position in a cross section that was at some distance from the joint and subjected to the same moment. It was not possible to measure the strains on the most highly stressed fibers, and it is therefore safe to say that strains in excess of measured values exist.

These findings are consistent with mathematical investigations (*21*) dealing with stresses in beams of orthotropic material. The intensity of stress at the extremities of the major axis of an elliptical hole with a ratio of major to minor axis of 50, and oriented with the major axis perpendicular to the direction of principal stress, is shown to be some 240 percent as great as the stress at some distance from the hole. Such a condition is somewhat analogous to that of a butt joint in a lamination.

Data for each beam with joints are plotted in figures 71 and 72. In each diagram the abscissa is the ratio of I_n, the net moment of inertia (computed as if all jointed laminations were totally ineffective) of the jointed beam, to I_g, the moment of inertia of the full cross section (or moment of inertia of the control beam), with both moments of inertia being taken about the axis at midheight of the cross section. The ordinate in each is the ratio of the load on the jointed beam to the load on the matched control beam. The heavy dotted lines represent the load ratios to be expected from the ratios of moments of inertia.

Butt joints.—The diagrams indicate that the proportional-limit ratios for beams with butt joints in the bottom laminations are much lower than the ratios of moment of inertia would indicate, although the ratios for modulus of rupture approximate the expected values. Beams with butt joints in the lamination next to the bottom one fell somewhat short of expected load ratios. Even with the greatest spacing used, joints in the second and third laminations from the bottom appeared to lower the strength below that estimated by assuming both jointed laminations to be totally ineffective.

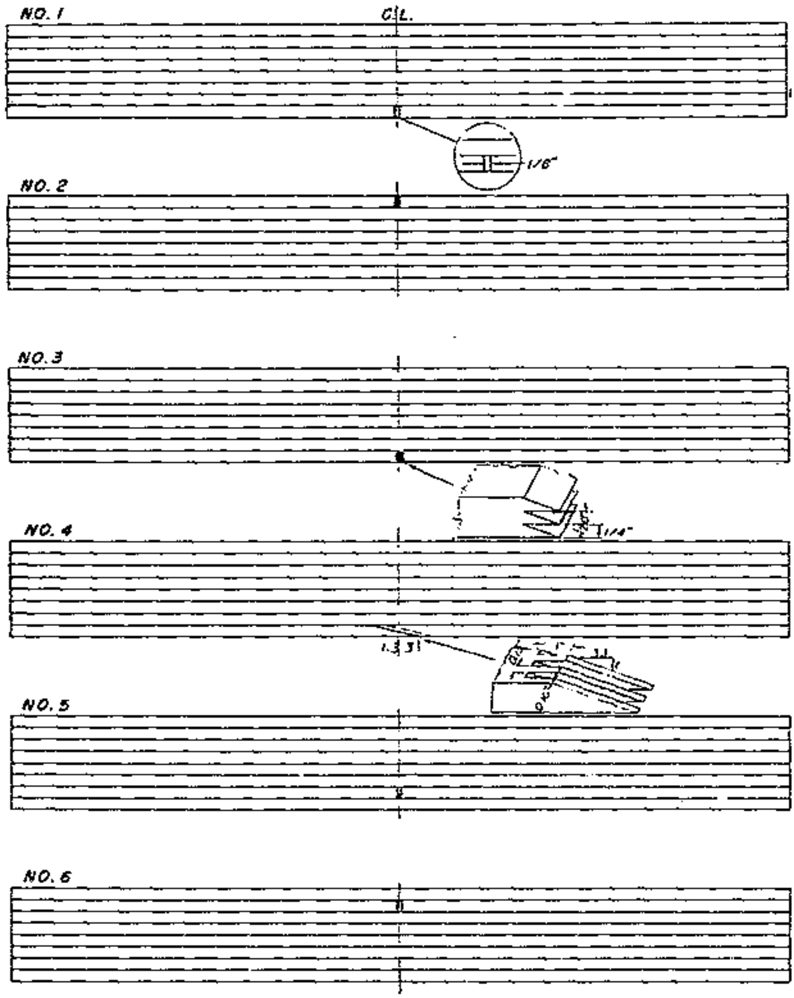


FIGURE 69.—Jointing patterns for laminated beams. Patterns 1, 2, 5, and 6 are butt joints in single laminations. Pattern 3 is an Onsrud joint. Pattern 4 is a serrated scarf joint.

Expected load ratios are approximated by beams with butt joints in the top lamination or in the lamination next to the top. Data for beams with butt joints in the second and third laminations from the top indicate that, even with the greatest spacing used, the strength was no greater than would be estimated from the assumption that both laminations were ineffective.

These data indicate that butt joints have somewhat more serious effects when in the tension than in the compression half of a beam. Table 10 affords a comparison of the effects of butt joints in the two locations. Average ratios of the properties of beams containing butt joints to those of beams containing no joints are shown for comparable

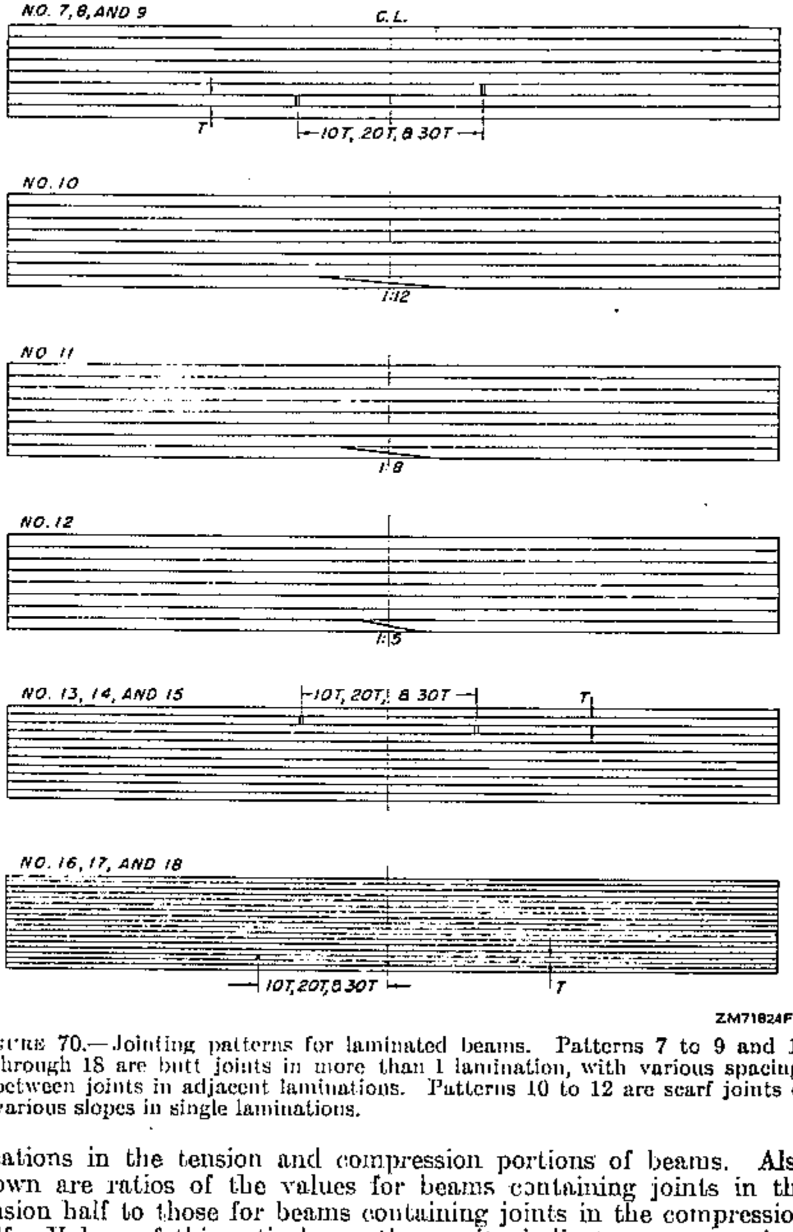


FIGURE 70.—Jointing patterns for laminated beams. Patterns 7 to 9 and 13 through 18 are butt joints in more than 1 lamination, with various spacings between joints in adjacent laminations. Patterns 10 to 12 are scarf joints of various slopes in single laminations.

locations in the tension and compression portions of beams. Also shown are ratios of the values for beams containing joints in the tension half to those for beams containing joints in the compression half. Values of this ratio lower than unity indicate a more serious effect for joints on the tension than for those on the compression side.

The data of table 10 are somewhat erratic. It is apparent, nevertheless, that the ratios tend to be lower than unity, particularly for butt joints in the outer lamination on the tension side. This fact, together with the erratic nature of the data, indicate the desirability of avoiding butt joints in the tension half of a flexure member. If

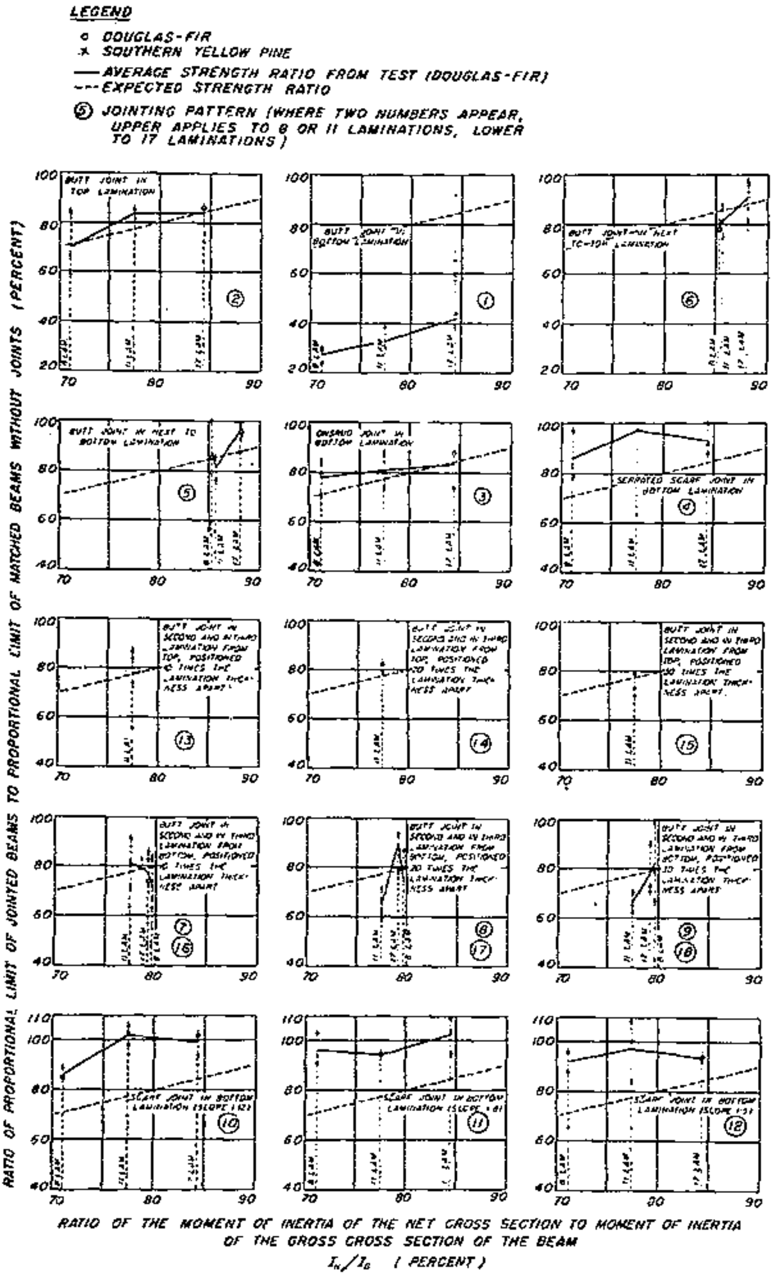


FIGURE 71.—Ratio of proportional-limit load for beam with joints to proportional-limit load on control beam. Net moment of inertia computed as if all jointed laminations were totally ineffective.

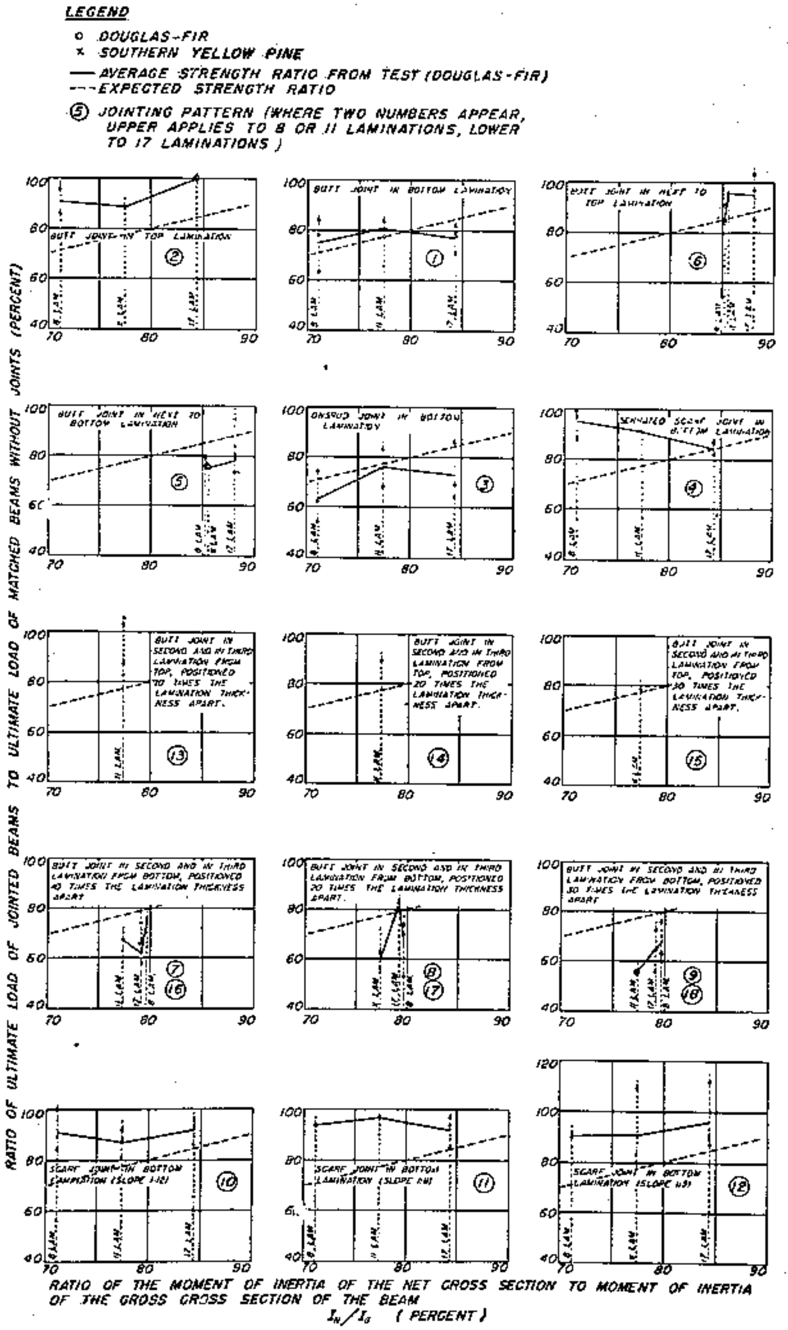


FIGURE 72.—Ratio of ultimate load for beam with joints to ultimate load on control beam. Net moment of inertia computed as if all jointed laminations were totally ineffective.

butt joints are used, an additional factor should be considered in computing the strength-reducing effect of butt joints beyond that used for butt joints in the compression half. Considering the data of table 10, it appears that a reduction of at least 20 percent should be applied to the moment of inertia computed by considering the jointed laminations ineffective. Where a butt joint is located in the outer lamination on the tension side, the reduction should be at least 40 percent.

TABLE 10.—*Comparison of properties of beams having butt joints in tension laminations with those of beams having butt joints in compression laminations*

8-LAMINATION BEAMS

Location of joints	Fiber stress at proportional limit: Ratio of jointed to nonjointed beams. Joints in— Compression laminations	Fiber stress at proportional limit: Ratio of jointed to nonjointed beams. Joints in— Tension laminations	Fiber stress at proportional limit: Ratio (3)/(2)	Modulus of rupture: Ratio of jointed to unjointed beams. Joints in— Compression laminations	Modulus of rupture: Ratio of jointed to unjointed beams. Joints in— Tension laminations	Modulus of rupture: Ratio (6)/(5)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Outside lamination	0.70	0.28	0.40	0.91	0.75	0.82
Second lamination from outside	.79	.89	1.12	.87	.78	.90
Average			.76			.86

11-LAMINATION BEAMS

Location of joints	(2)	(3)	(4)	(5)	(6)	(7)
Outside lamination	0.84	0.33	0.40	0.89	0.81	0.91
Second lamination from outside	.81	.81	1.00	.96	.76	.79
Second and third laminations from outside:						
Spaced 10*t*	.82	.81	.99	.98	.67	.68
Spaced 20*t*	.81	.64	.79	.89	.60	.67
Spaced 30*t*	.74	.66	.89	.79	.56	.71
Average			.81			.75

17-LAMINATION BEAMS

Location of joints	(2)	(3)	(4)	(5)	(6)	(7)
Outside lamination	0.84	0.42	0.50	0.99	0.77	0.78
Second lamination from outside	.91	.97	1.06	.95	.78	.82
Average			.78			.80
Average of all			.80			.79

To supplement the joint spacing data discussed above, an additional set of 12-lamination beams was tested. The second and fourth laminations from the top contained butt joints in the same cross section, and the third and fifth laminations contained butt joints in a cross section 4, 7, or 10 times the lamination thickness distant from that containing joints in the second and fourth laminations.

The results of these tests are shown graphically in figure 73; shown also are the data from the earlier series. The horizontal dashed lines in the figure are drawn at levels representing the ratio of strength of jointed to unjointed beams, by assuming that the strength of the jointed beam is proportional to the net moment of inertia computed by assuming certain combinations of laminations ineffective. The upper dashed lines in the left half of the figure at 81.5 percent have had the second and fourth laminations from the top omitted from the computation of net moment of inertia. The lower lines at 69.3 percent have had the second, third, fourth, and fifth laminations omitted. The corresponding lines in the right half of the figure have had the second and the third laminations from the top omitted in the computations represented by the lines at 85.5 and 77.3 percent, respectively. The upper lines represent the strength when only the butt joints at a single cross section contribute to strength reduction, while the lower lines represent the strength when all butt joints contribute to strength reduction, as if all were at a single cross section.

In the left half of figure 73 the trend is toward the upper line with increasing spacing, with the average ratio corresponding essentially with the upper line at a spacing of 10 times the lamination thickness; thus, a joint spacing of $10t$ appears adequate. In the right half of the figure, the trend is generally downward. The reason for this decline is not known, but it may result from the concentration of shear stress in the vicinity of the load points as discussed later. At a joint spacing of $30t$, the joints were only about 1.65 inches from the load points. It is possible, therefore, that the stress concentration near the load points has contributed to the strength reduction at the greater spacings and that, had the joints been farther from the load points, higher values would have been obtained. It appears desirable, from this, to keep butt joints in beams well away from concentrated loads.

Modulus of elasticity appears to be unaffected by butt-joint spacing, although there appears to be some lowering when the joints are near the load points.

Onsrud joints.—Beams with Onsrud joints in the bottom laminations were no better in modulus of rupture than those having butt joints similarly located; at proportional limit, the two types gave essentially the same results. Other tests (*12*) have shown low efficiency in tension for joints of this type, so that they cannot be expected to be essentially different from butt joints with respect to their behavior in a beam.

Scarf joints.—The data indicate that beams with scarf joints (serrated scarf and plain scarf with slopes of 1 in 12, 1 in 8, or 1 in 5) are nearly equal in strength to beams with continuous laminations, and considerably better than the prediction based on the assumption that the jointed lamination is totally ineffective. The data afford little basis for differentiation among the 4 kinds of joints, but the efficiency of plain scarf joints in tension in another series of tests (*12*) averaged about 95 percent at a slope of 1 in 20, about 85 percent at a slope of 1 in 10, and decreased rapidly with further increase in steepness of slope to an average value of less than 70 percent at a slope of 1 in 5. A serrated scarf joint of the type used in the beams averaged about 64 percent.

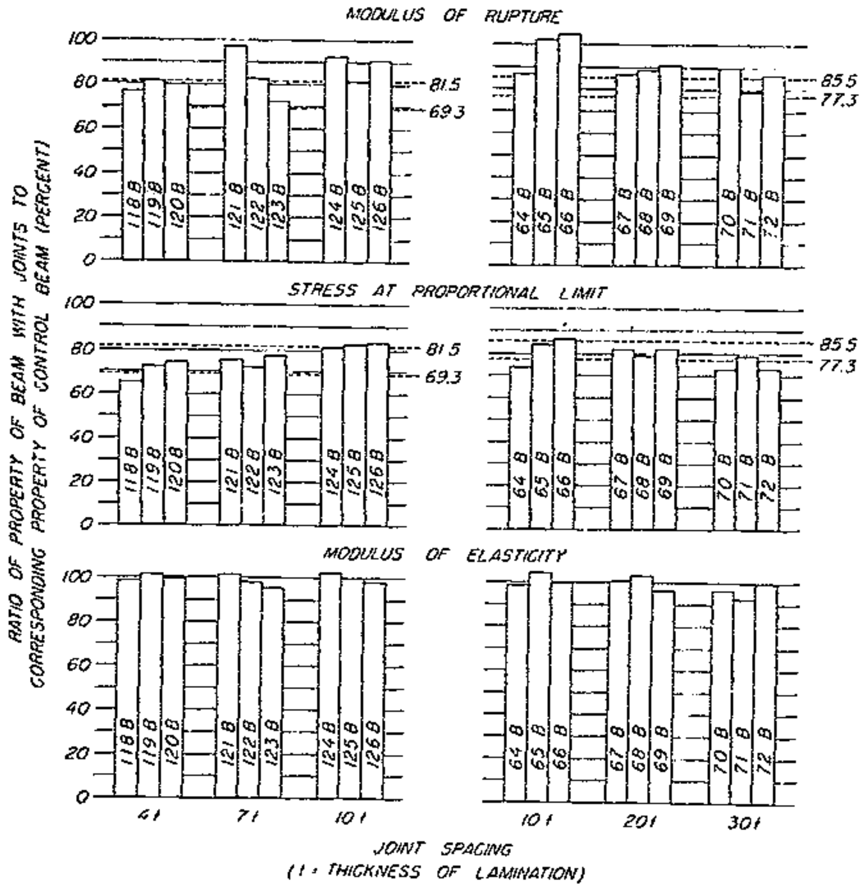


FIGURE 73.—Ratios of properties of beams with spaced butt joints to corresponding properties of unjointed beams.

In these tension tests and in the tests of beams, end joints were formed by cutting a lamination or board in two at approximately the desired slope and, after machining the parts, by gluing them together in approximately their original positions. This was done in order to get the best possible matching between jointed specimens and those without joints. It resulted in summerwood being glued to summerwood and springwood to springwood more consistently than can be expected generally. In commercial fabrication, summerwood will be joined to comparatively weak springwood over part of the area of the joint. Even with the best technique in fitting and gluing, therefore, lowered efficiency is to be expected.

In some beams with joints in the outer lamination on the tension side, the strength of the jointed lamination is very small as compared to that of a continuous lamination. The load that would cause failure of the outer lamination would, in such beams, be insufficient to cause failure of the reduced beam formed by considering the failed outer lamination to be ineffective. There would, therefore, be a "floor" below which the strength of the jointed beam would not be expected to fall regardless of the reduction in strength of the outer lamination caused by the joint. These floors, represented by the strength of the reduced beam, would be at 77, 83, and 89 percent of the strength of an unjointed full-depth beam for 8, 11, and 17 laminations, respectively.

The expected strengths, computed on this basis, are shown in table 11 as calculated for efficiencies of 92, 84, and 70 percent for plain scarfs having slopes of 1 in 12, 1 in 8, and 1 in 5, respectively, and 64 percent for a serrated scarf (*12*). These expected strengths are given in table 11 as percentages of the strengths of unjointed beams, together with the average ratios from tests.

The lack of agreement between expected and test values may be explained on the basis of errors in choosing the efficiencies for calculating the expected values. The range in efficiencies at any given slope of scarf is great, and the actual efficiencies of the jointed laminations of the beams may have been considerably greater than those chosen for the calculations. In only three instances were the test averages below the expected values.

TABLE 11.—*Expected strength of beams with serrated and plain scarf joints in outer tension lamination, and test values for the same beams* [1]

Number of laminations	Serrated scarf strength		Plain scarf strength					
			Slope 1:12		Slope 1:8		Slope 1:5	
	Expected	Average from tests	Expected	Average from tests	Expected	Average from tests	Expected	Average from tests
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
8	77	95	92	91	84	94	77	90
11	83	91	92	87	84	97	83	91
17	89	84	92	92	89	92	89	96

[1] Expressed as percentages of the strength of comparable unjointed beams.

It appears reasonable to require that the stress in a jointed lamination be no greater than some specified percentage of that for an unjointed lamination, and to calculate the strength of beams containing jointed laminations as outlined above. Considering the range in efficiency demonstrated in tension tests of jointed specimens and the probable lowered efficiency of jointed laminations in general as compared to those tested, lower values than the average efficiencies found from test should be used in calculating the percentage reduction in strength of a jointed lamination.

In the original series, no tests were made of beams containing scarf joints in adjacent laminations at various spacings. A supplementary series of tests were made to investigate this variable. Twelve-lamination beams containing scarf joints in the lower five laminations at spacings of *0t*, *5t*, and *7t* were tested. The data are shown in figure 74.

The results indicate little choice between the spacings investigated. The average strength at all spacings is on the order of that to be expected of a beam containing scarf joints at a slope of 1 in 5.

The failure to develop higher strengths with increased joint spacings may be explained on the following basis. When the joint in the outer lamination fails, this lamination tends to peel away from the remainder of the beam and, at the location of the adjacent joint, the beam is effectively shallower, so that the stress on that joint is immediately excessive and it fails. Had the adjacent joint been sufficiently far away from the failed joint so that the "peeling" extended only a fraction of the distance between the two joints, the full beam depth would have remained effective, and stress on the second joint would not have been excessive.

The data are not extensive enough to show what the spacing should be. In view of the fact that a spacing of *24t* has been used for some years, this spacing is suggested until test data are available to permit modification.

Modulus of elasticity appears to be unaffected by scarf-joint spacing.

JOINTS IN COLUMNS

Figure 75 shows the type and location of joints in laminated columns tested in compression. In figure 76, the average ratio of the maximum stress on the gross cross section carried by a jointed column to that carried by a matched control column is plotted against the gross cross-sectional area minus that of two laminations.

Butt joints.—The diagrams in figure 76 for columns with butt joints in the 2 outer laminations at the same level show that the ratio of loads is at least as great as the ratio of net to gross area. For those in which butt joints in the 2 outer laminations were spaced 30 times the thickness of a lamination from joints in the adjacent laminations, the load on the jointed column was less than would be expected from the ratio of net to gross area. That is, the overlap of 30 times the lamination thickness was insufficient to transfer and distribute the load from jointed laminations.

Additional data on butt-joint spacing in columns were obtained from a supplemental series of tests of short columns in which joints in adjacent laminations were spaced *10t*, *20t*, and *40t* in addition to the *30t* spacing of the earlier series. The results of these tests (fig. 77) indicate that a spacing of *50t* is required for optimum results. At lesser spacings, joints in adjacent laminations tend to act as if they were at the same cross section. Considered in another way, the cross section of a lamination adjacent to one containing a butt joint is only partially effective. This consideration was used in adapting the data of figure 77 to the curve of figure 61.

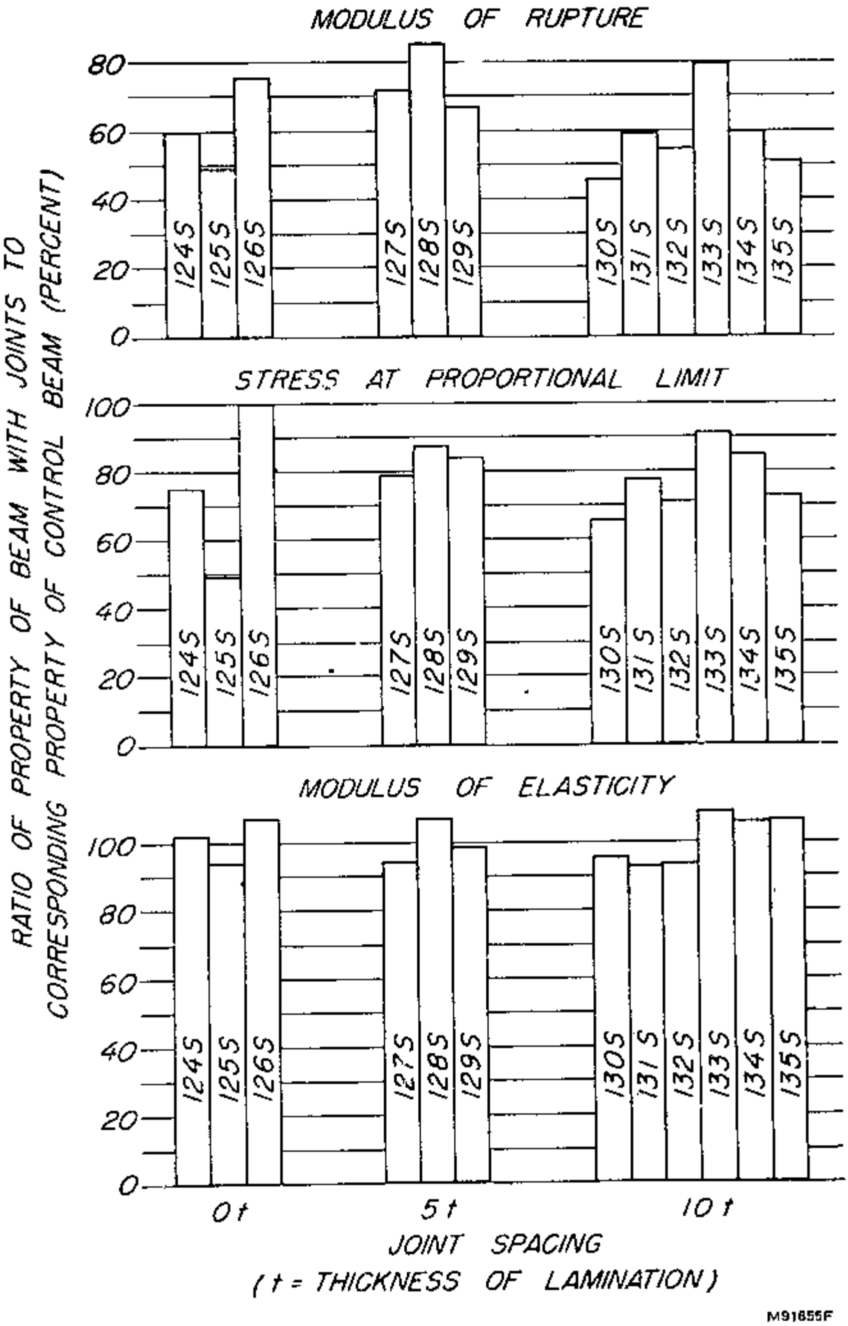


FIGURE 74.—Ratios of properties of beams with 1-in-5 scarf joints to corresponding properties of unjointed beams. Designations 124S, etc., are specimen numbers. Each bar represents test on one beam.

247040°—54——11

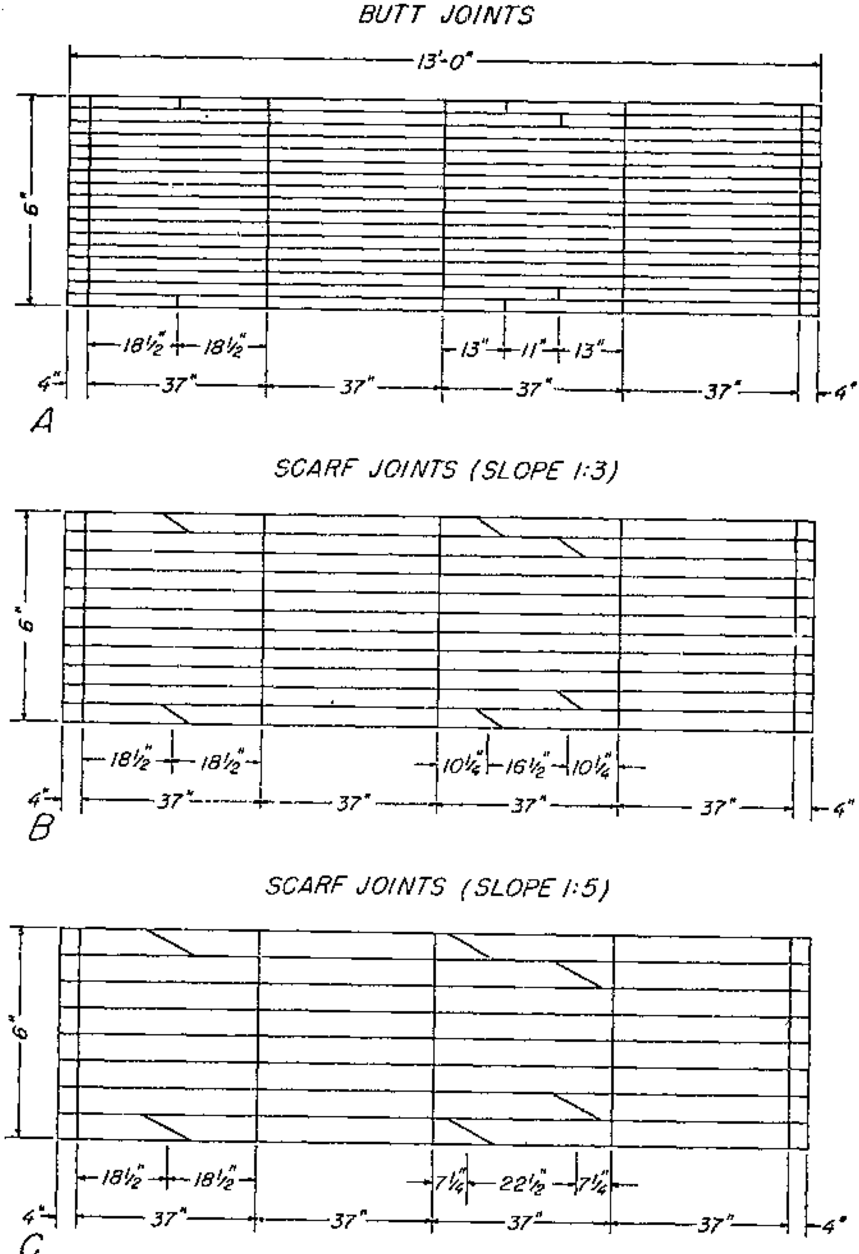


FIGURE 75.—Jointing patterns for laminated columns tested in compression, showing spacing of joints: *A*, Butt joints in 17-lamination columns: *B*, scarf joints with slope of 1:3 in 11-lamination columns: *C*, scarf joints with slope of 1:5 in 8-lamination columns. All 3 types of joints tested in 8-, 11-, and 17-lamination columns cut from 13-foot lengths as shown and compared with unjointed controls adjacent to jointed columns. Cutting plan allowed ½ inch at each end of each specimen for squaring before test.

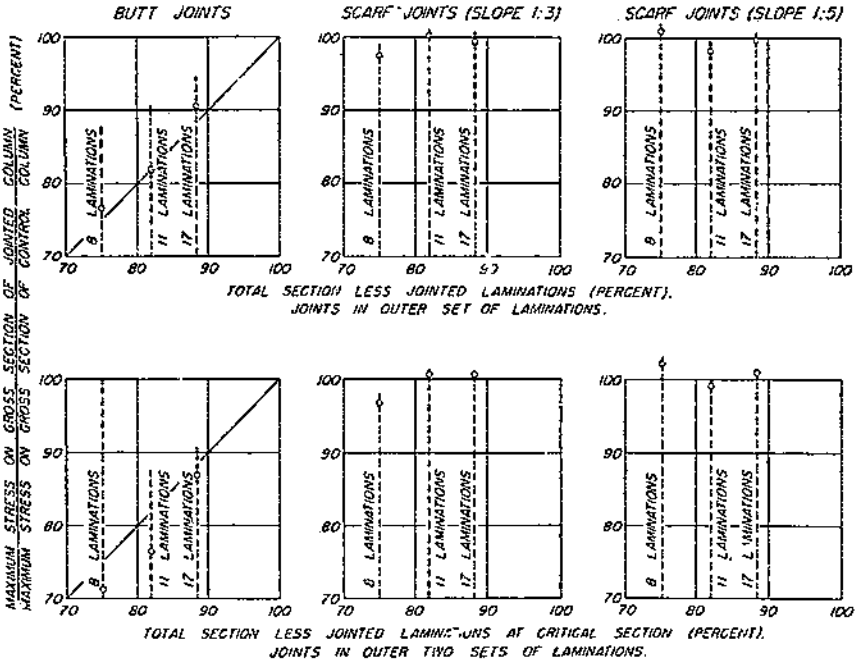


Figure 76.—Columns with joints in laminations compared to columns with all laminations continuous. Joints in outer two sets of laminations spaced 30 times the lamination thickness.

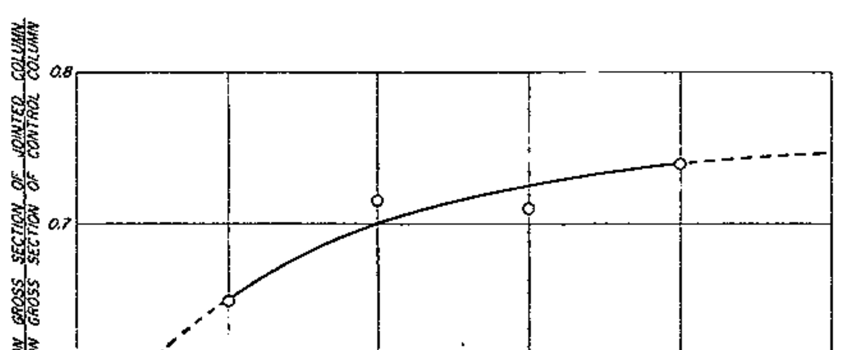


Figure 77.—Relation between ratios of strength of butt-jointed to that of control columns and the joint spacing expressed in multiples of the lamination thickness.

Scarf joints.—The diagrams for the 4 scarf-jointed constructions indicate that, with the possible exception of the 8-lamination columns having joints with a slope of 1 in 3, there is no deficiency in strength as compared to the control columns, which have continuous laminations. It is doubtful that the small deficiency in these instances is significant. From this, it appears unnecessary to modify the strength of a laminated column for scarf joints as steep as 1 in 5, and possibly for joints with slopes of 1 in 3 as well.

Supplementary data on the effect of scarf-joint spacing was obtained from tests of short columns containing scarf joints (slope 1 in 5) spaced 0*t*, 10*t*, and 24*t* in adjacent laminations. The results (fig. 78) indicate no loss in strength even where the joints are immediately adjacent (0*t*). These results, indicating high efficiency for scarf joints stressed in compression, indicate also that no restrictions need be made, from the standpoint of strength, on scarf-joint spacing in

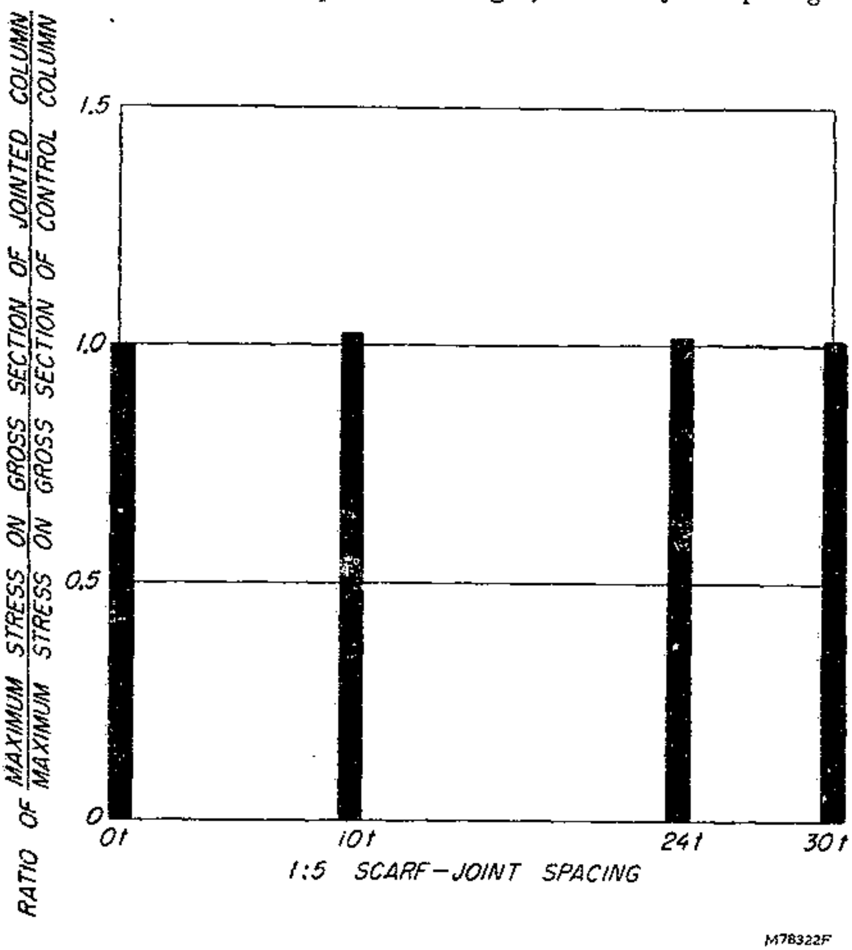


FIGURE 78.—Ratios of strength of 1-in-5 scarf-jointed to control columns for various joint spacings expressed in multiples of the lamination thickness.

compression members. Since the tests were made on members containing relatively steep scarf joints, it must be assumed that similar results would be obtained for joints of flatter slope.

STRENGTH OF END JOINTS OF VARIOUS TYPES

The tests of beams and compression members upon which the limitations on joints were based, included only a limited number of types of joints in a limited number of locations. Joint types studied included butt, Onsrud, serrated scarf, and plain scarf with slopes of 1 in 12, 1 in 8, and 1 in 5. In tests of beams, only butt joints were included at or near the compression face, while all types were included at or near the tension face. Only butt joints and plain scarf joints of slopes of 1 in 3 and 1 in 5 were included in the tests of compression members.

Many types of joints have been used to join laminations end to end. Some of these types have been tested in compression and tension, and data from these tests *(12)* are included here to serve as a guide in the choice of joints as well as in determining the percentage of full strength that may be assigned to a lamination containing such a joint.

Figures 79 through 85 indicate the ratios of strength of jointed to unjointed specimens. Table 12 indicates the range of ratios for those specimen types for which ranges are not shown in the figures.

In the tests to which these data pertain, end joints were formed by cutting a board in two at approximately the specified slope and, after machining the parts, gluing them together in approximately their original positions. This was done in order to get the best possible matching between jointed specimens and specimens without joints. It resulted in summerwood being glued to summerwood and springwood to springwood more consistently than can be expected generally. In actual fabrication, summerwood will be glued to springwood over part of the area of a joint and the strength of that part will be dependent on the strength of the weaker springwood, so that, even with the best technique in fitting and gluing, lowered efficiency is to be expected.

In spite of the care with which the joints were made, a considerable range in efficiency was found for all joint types. Because of this range and the probability that factory-made joints in general will be somewhat less efficient than those of the tests, the design ratio of strength of a jointed to an unjointed lamination probably should be based on values somewhat below the average values shown.

Effect of Knots

FLEXURAL DESIGN FOR HORIZONTALLY LAMINATED MEMBERS

In figure 86 are plotted the results of tests on 90 Douglas-fir beams with knots in the horizontally placed laminations. Each point represents the value derived from a test of an individual beam plotted vertically against I_K/I_G. Circles connected by dotted lines each represent average values for a group of 10 beams. Curve *(A)* is drawn as an average relation between modulus of rupture and I_K/I_G.

It was found that, for stress at proportional limit and for modulus of rupture, the vertical dispersion of the individual points increases on a percentage basis as I_K/I_G increases. The dispersion shown at the

TABLE 12.—*Ratios of tension- and compression-parallel-to-grain values of specimens with end joints to those without joints—Douglas-fir and white oak*

TENSION-PARALLEL-TO-GRAIN

Species and type of end joint	Slope of scarf	Specimens		Ratio of strength of jointed to control specimens based on—						
		Jointed	Control	Average of all test values	Matched pairs of specimens			Matched boards [1]		
					Average of all ratios	Maximum	Minimum	Average of all ratios	Maximum	Minimum
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
		Number	*Number*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Douglas-fir:										
Plain scarf	1:3	37	37	53	56	94	25			
Do	1:6	37	37	78	82	108	44			
Do	1:10	37	37	86	87	124	58			
Do	1:12	17	17	103	108	167	73			
Do	1:15	37	37	94	95	142	65			
Do	1:20	38	38	94	95	145	57			
White oak:										
Plain scarf	1:3	20	20	41	42	57	28			
Do	1:6	18	18	71	74	101	47			
Do	1:10	18	18	86	87	120	62			
Do	1:15	19	19	92	92	128	65			
Do	1:20	18	18	95	96	117	76			
Douglas-fir:										
Serrated scarf	1:3	15	25	55				57	63	39
Square-toothed scarf	1:3	15	25	72				72	82	61
Serrated scarf	1:3	18	18	60				64	82	42
Fingered		14	25	45				46	52	35

Onsrud	--------	15	25	25	--------	--------	--------	25	29	21
Do	--------	18	18	33	--------	--------	--------	34	45	16
Fingered	--------	12	17	18	--------	--------	--------	18	22	14
White oak:										
Serrated scarf	1:3	14	24	48	--------	--------	--------	53	62	44
Square-toothed scarf	1:3	13	23	54	--------	--------	--------	55	66	51
Fingered	--------	15	25	43	--------	--------	--------	43	50	40
Onsrud	--------	15	25	25	--------	--------	--------	26	34	20
COMPRESSION-PARALLEL-TO-GRAIN										
Douglas-fir:										
Serrated scarf	1:3	15	15	100	100	104	96	--------	--------	--------
Square-toothed scarf	1:3	15	15	97	97	103	80	--------	--------	--------
Fingered	--------	15	15	79	79	90	67	--------	--------	--------
Onsrud	--------	15	15	100	100	115	94	--------	--------	--------
Fingered	--------	12	12	74	74	85	62	--------	--------	--------
White oak:										
Serrated scarf	1:3	15	15	102	102	107	98	--------	--------	--------
Square-toothed scarf	1:3	15	15	95	95	109	70	--------	--------	--------
Fingered	--------	15	15	98	99	142	86	--------	--------	--------
Onsrud	--------	15	15	99	100	112	88	--------	--------	--------

[1] Each board furnished 3 specimens with joints and 5 controls—ratios therefore based on average of specimens from a board rather than on matched pairs.

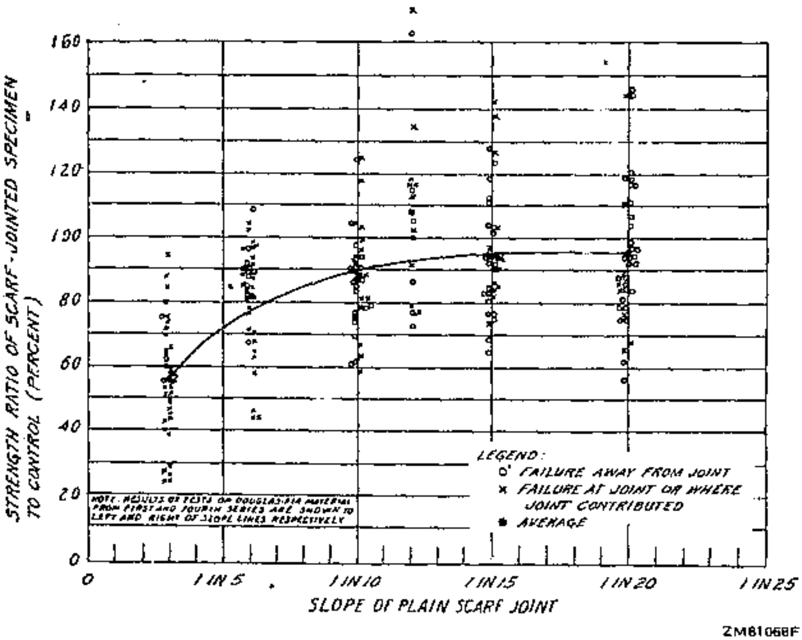


FIGURE 79.—Maximum strength in tension parallel to grain as related to slope of plain scarf joint in Douglas-fir.

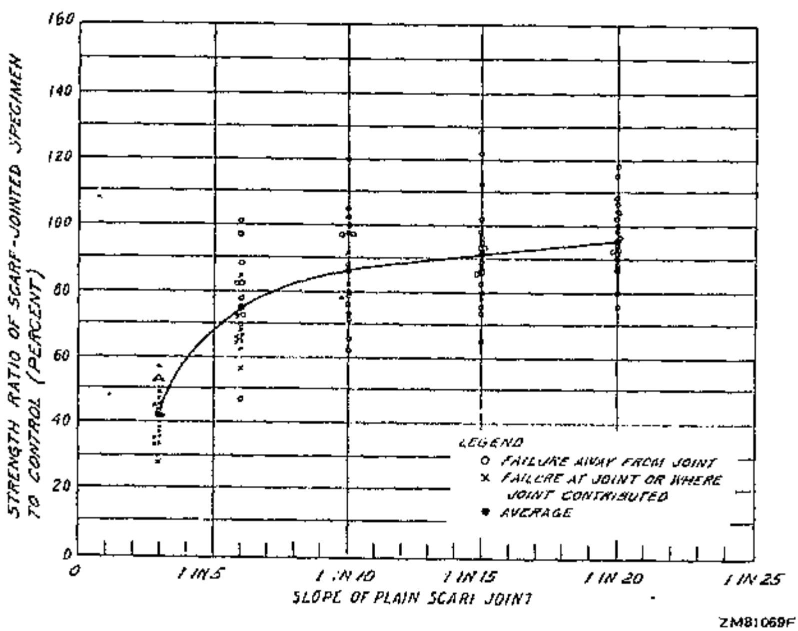


FIGURE 80.—Maximum strength in tension parallel to the grain as related to slope of plain scarf joint in white oak.

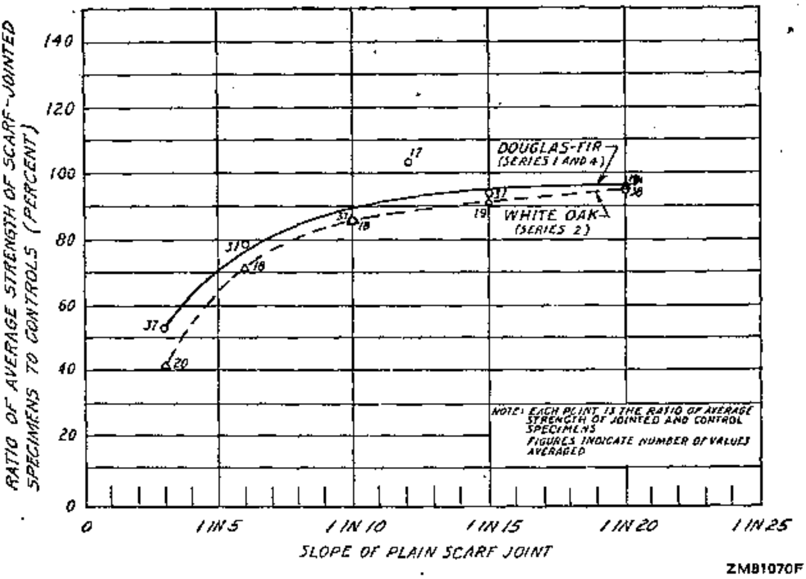


FIGURE 81.—Maximum strength in tension parallel to grain as related to slope of plain scarf joint in Douglas-fir and white oak.

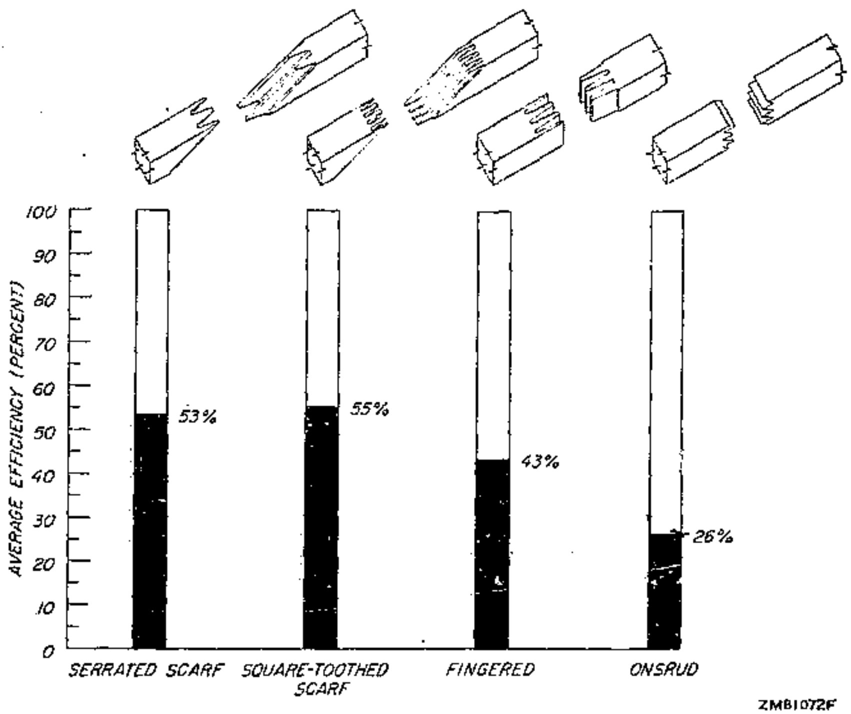


FIGURE 82.—Strength in tension parallel to the grain of white oak specimens with various end joints compared to corresponding controls.

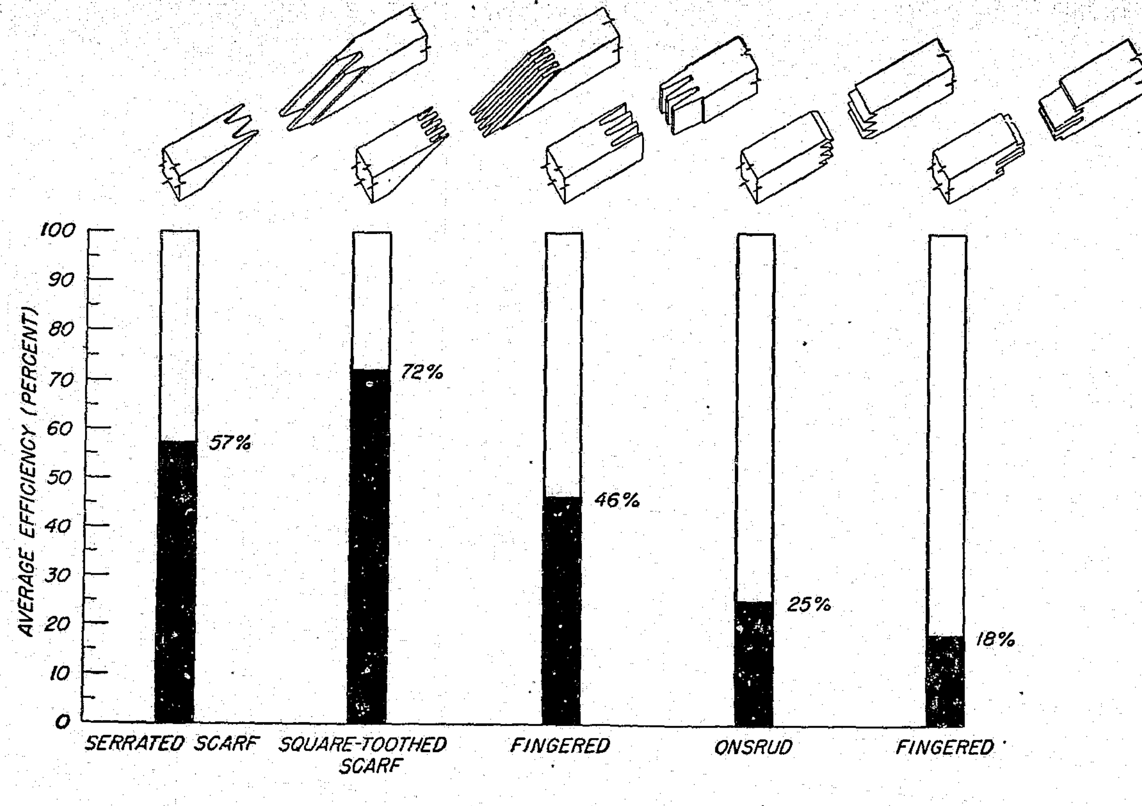


FIGURE 83.—Strength in tension parallel to the grain of Douglas-fir specimens with various end joints compared to corresponding controls.

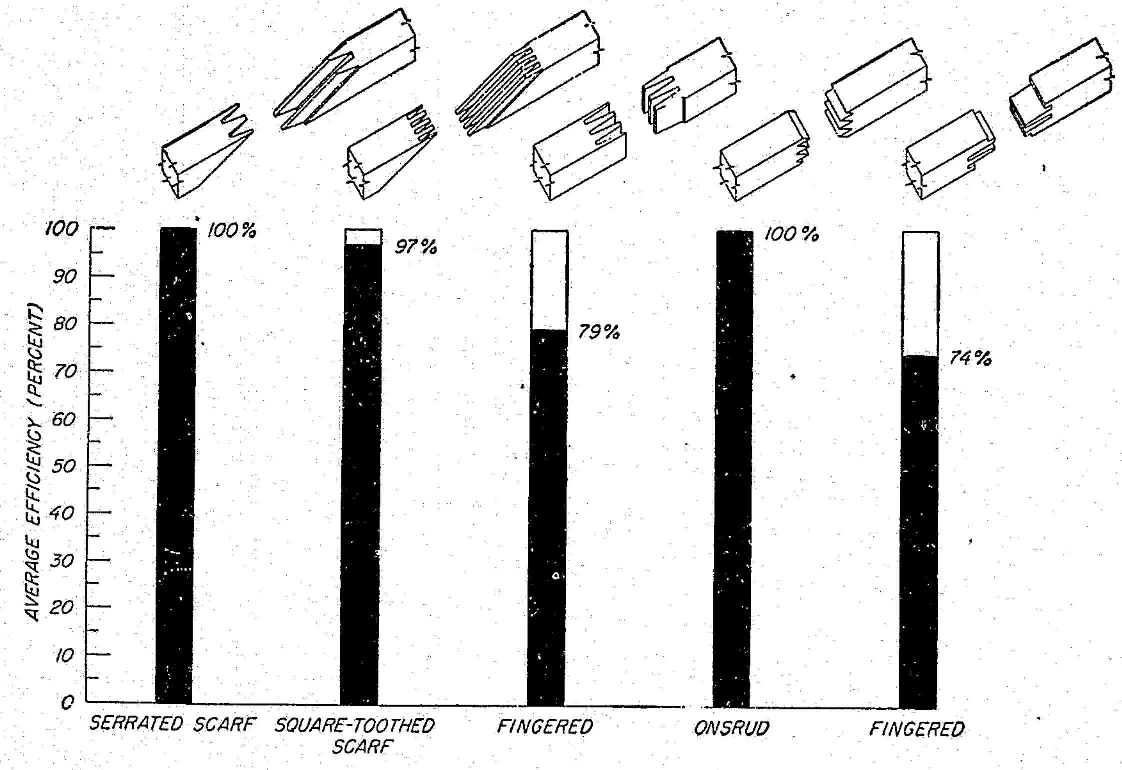


FIGURE 84.—Strength in compression parallel to the grain of Douglas-fir specimens with various end joints compared to corresponding controls.

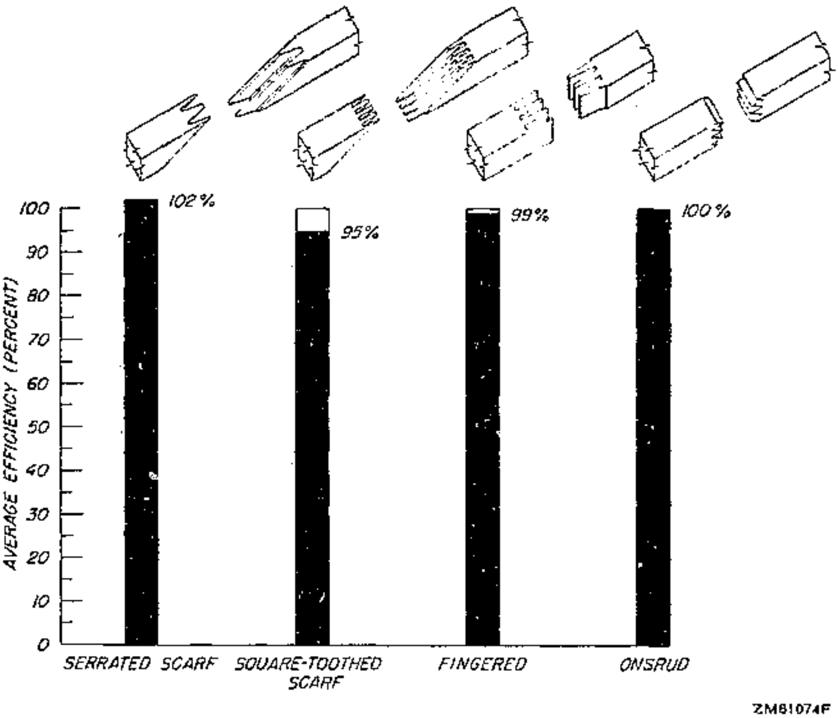


FIGURE 85.—Strength in compression parallel to the grain of white oak specimens with various end joints compared to corresponding controls.

left edge is considered to be due principally to variability in the strength of the clear wood, and the increase in variability as I_K/I_G increases results from increase in the variability of knot effect as the size of knots increases. Allowance for variability of clear material has been made in deriving the basic flexural stress; in connection with design stresses for beams with knots in the laminations, however, consideration needs to be given to the variability in knot effect. Consequently, to form curve (*C*), the average curve has been depressed by a percentage that increases uniformly from zero at the left edge to 25 percent at $I_K/I_G=0.50$. Curve (*C*) is then the basis for a suggested design curve (fig. 55).

The depression of curve (*C*) below curve (*A*) represents about 1¼ times the estimated standard deviation of the knot effect as found from a study of the variance due to variations in clear material and that resulting from knot effect. The equation of curve (*A*) is

$$Y_1=9{,}907\ (1+3x)\ (1-x)^3 \tag{7}$$

where Y_1 is the modulus of rupture and $x=I_K/I_G$. The equation of curve (*C*) is

$$Y_2=9{,}907\,(1+3x)(1-x)^3\left(1-\frac{x}{2}\right) \tag{8}$$

where Y_2 is the value of modulus of rupture as read from this curve. Conversion of the ordinates of this curve to a unit basis gives

$$F_K=(1+3x)(1-x)^3\left(1-\frac{x}{2}\right) \tag{9}$$

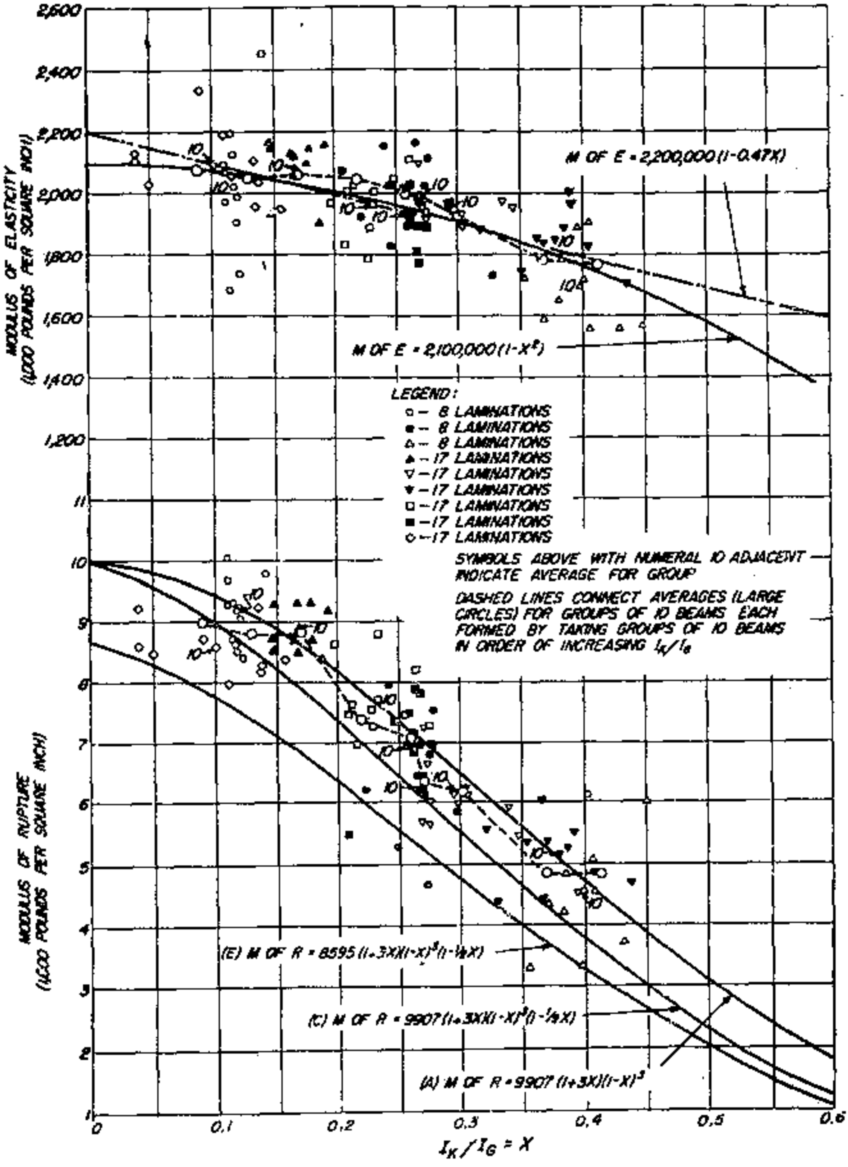


FIGURE 86.—Variation of strength properties of horizontally laminated Douglas-fir beams with knots with the ratio I_K/I_G.

as the equation of the design curve shown in figure 55 where F_K is the ratio of the allowable stress to the basic stress in flexure. The correlation of flexural strength with I_K/I_O implies that the strength is reduced by a knot at any point in the cross section, and the form of the average curve (curve (A)) implies further that the percentage reduction exceeds the value of the ratio of I_K to I_G.

Similar relations were found for stress at proportional limit. Actually, both modulus of rupture and stress at proportional limit were considered in fitting the average curves. While the curve for modulus of rupture is slightly high and a corresponding curve for stress at proportional limit is slightly low for the data, it is considered that, when both sets of data are considered, the average curve shown is an acceptable representation of the average.

A somewhat different concept has been used as the basis of design by some fabricators of laminated construction. According to this concept, when the outer laminations of a beam are clear, no reduction in the strength of the beam is caused by a knotty interior lamination, provided that the ratio of its strength to that of a clear board is as great as the ratio of the distance of its outer face from the neutral surface to the half-depth of the beam, which latter ratio is equal to the stress at the outer surface of the lamination divided by the stress in the outermost fiber of the beam. According to this concept, if it is assumed that laminations with knots equal in diameter to one-fourth the width of the beam have three-fourths the strength of clear laminations, such knotty laminations could occupy the middle three-fourths of the depth of a beam having clear laminations in each outer one-eighth without detriment to the strength as compared to a beam composed entirely of clear laminations. Figure 87 has been prepared to compare computations from this concept with the results of tests. Values of modulus of rupture are plotted against D, the computed percentage or proportionate strength deficiency, which was found as follows:

Let b represent the width of the beam, K the diameter of a knot in the nth lamination from the neutral plane, N the total number of laminations, and R the computed ratio of the strength of the beam to that of a beam composed of clear laminations. Then:

$$R=\frac{b-K}{b}\div\frac{n}{\frac{N}{2}} \tag{10}$$

From the recorded data on knot sizes, width of beam, and number of laminations, a value of R was computed for each lamination (including the outer one) on the tension side of a beam and the minimum was taken as the value of R for that beam. Then

$$D=1-R_{min}. \tag{11}$$

where D is the value plotted as abscissa in figure 87. The straight line shown is drawn from the point representing the average for control beams (modulus of rupture equals 9,907, D equals zero) to the point representing zero strength at $D=1.00$. The trend of the plotted

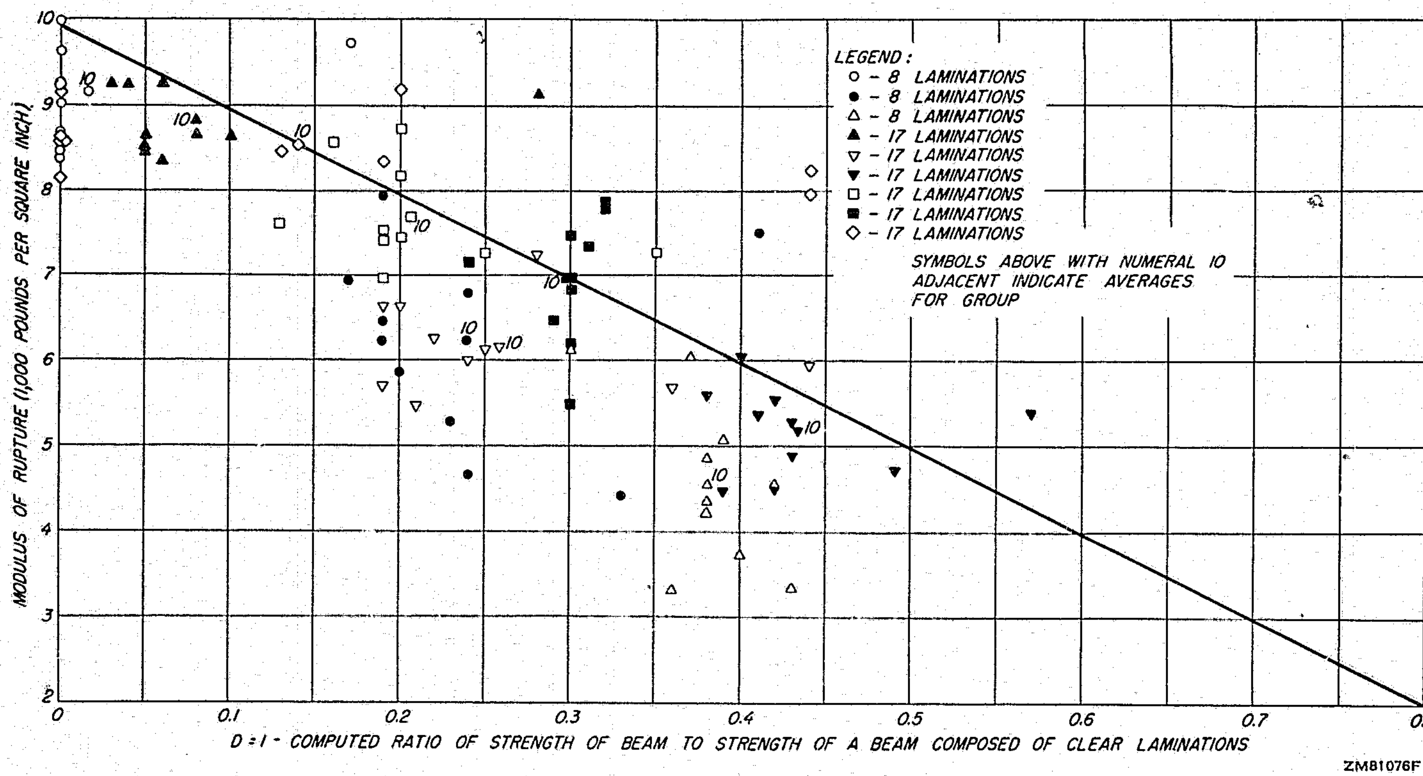


FIGURE 87.—Variation of modulus of rupture of horizontally laminated Douglas-fir beams with D, a factor theoretically relating bending strength with size and position of knots.

points should be along this line if the concept is valid. It is obvious that the majority of the points are below the line. Moreover, for all but 1 of 14 beams for which D equals zero (I_K/I_G is not zero for these), the modulus of rupture is below the average for control beams and 3 of the 14 are below the minimum for controls. The vertical spread of points that are within a limited range of the abscissa, furthermore, is considerably greater than in figure 86, and, consequently, conformity with any curve that could be drawn in figure 86 would be less good. The concept, therefore, is much less valid for design purposes than the one that assumes the strength of a beam with knots in the laminations to be correlated with the value of I_K/I_G.

It is evident, from figure 86, that modulus of elasticity decreases with increasing I_K/I_G. The type of curve relating strength properties to I_K/I_G descends too rapidly with increasing I_K/I_G to be applicable to modulus of elasticity. A linear regression line (shown as a dashed line) indicates too high a value at low values of I_K/I_G. The curve shown is considered to be an acceptable representation of the data.

ESTIMATION OF I_K/I_G

Since the factor I_K/I_G is the determinant of the effect of knots on the strength of laminated beams, means must be developed to estimate the value of this factor for beams of various grades or combinations of grades. One approach is to assume that the maximum knot permitted by the grading rules is present in every lamination within the 1-foot length centered at the critical cross section and to use the corresponding value of I_K/I_G in design. Obviously, some degree of dispersion of knots would occur, and the dispersion would make the probability of such a concentration of knots quite low. It is desirable, therefore, to find some means of evaluating the probability of occurrence of various levels of I_K/I_G and to use, in design, a value of I_K/I_G at some reasonable level of probability. A study made by the National Lumber Manufacturers' Association and the Forest Products Laboratory has led to a procedure for estimating values of I_K/I_G.

Data on knot size and location were gathered in the field on several commercial lumber grades by mapping knot size and location for each piece. Each grade was represented by from 50 to about 200 pieces, with the samples for each grade being taken from a number of sources in order to get a more adequate representation of the grade. Sample pieces were chosen in such a way as to be sure of random sampling.

The tests described earlier had shown that the properties of laminated beams were affected by the knots within a 1-foot length centered at a critical cross section. It was necessary, therefore, to study the sums of knot sizes within various 1-foot lengths.

It was assumed that any point in any piece could be at the midpoint of a 1-foot length centered at a single cross section of an assembly. Hence it was not sufficient to use the 1-foot lengths established by measurements from the ends of the pieces. Instead, sums of knot sizes were measured in the feet beginning at each 2-inch point, thus approximately meeting the criterion mentioned above and considerably increasing the number of feet available for study.

The first procedure for establishment of probabilities of occurrence of various values of I_K/I_G that was studied consisted of computing values of I_K/I_G for a considerable number of assemblies with randomly chosen laminations and then studying the distribution of computed values. Computations were made for 100 assemblies, each of 2, 4, 6, . . . 16 laminations. The feet to be assembled for the various "beams" were randomly chosen by means of a table of random numbers from the various feet of length selected as described above.

Cumulative frequency distributions of I_K/I_G resulting from such computations are shown in figure 88 for 1 of the grades studied. The ruling of the graph is such that a standard frequency distribution would plot as a straight line intersecting the 50-percent horizontal at the average value of the abscissa. The graph for 16 laminations conforms reasonably well to these criteria, while for lesser numbers of laminations the conformity is less good.

From these curves, the values of I_K/I_G at various levels of probability can be chosen. The irregularity of the graphs makes difficult any positive choice of a value at a specific level of probability. The ranges in values computed in several ways from single samples of 2 commercial grades are shown in figure 89 for an exclusion limit of 1 percent. By a 1-percent exclusion limit is meant the value of I_K/I_G that will be exceeded not more frequently than about once in 100 times.

The ranges shown in figure 89 indicate a downward trend of I_K/I_G at the 1-percent level with increasing numbers of laminations. The same general trend is apparent for both grades.

The procedure just described is too laborious for easy application. Accordingly, a second procedure was evolved. It was conceived that if the distribution of knot sizes in each grade of lumber were studied, it would be possible to use the characteristics of these distributions in accordance with established statistical procedures to compute limiting values of I_K/I_G for assemblies made up of a single grade or of a specified combination of grades. This concept formed the basis for the method finally adopted.

If the distribution of knot sizes were normal, it would be completely described by the two parameters, $\bar{x}$, the average, and σ, the standard deviation. Further, any combination of items drawn from a number of normal distributions and individually weighted would be normally distributed, and the average and standard deviation of the combination could be readily computed.

Assuming a normal distribution, the computation of a 1-percent exclusion limit for I_K/I_G would proceed as shown in the following example for a 6-lamination assembly. Values of $\bar{x}=1.546$ and $\sigma=2.271$, which will be used in the example, correspond with the sample for which ranges of I_K/I_G are shown in figure 89, *A*. Values of $\bar{x}$ and σ are in ⅛-inch units. The weighting factors (table 13) reflect the effect of the position of the lamination in the assembly with respect to the neutral axis.

Then $\bar{I}_K$, the average value of I_K, would, according to the accepted statistical procedure, be taken as $54\bar{x}$ and the standard deviation $\bar{\sigma}$ of I_K as $\sqrt{822\sigma^2}$. In a normal distribution, 99 percent of the values are less, and 1 percent is greater than the average plus 2.326 times the standard deviation.

Hence, the 1-percent exclusion limit for I_K would be computed as

$$\bar{I}_K+2.326\bar{\sigma}=54\bar{x}+2.326\sqrt{822\sigma^2} \qquad (12)$$

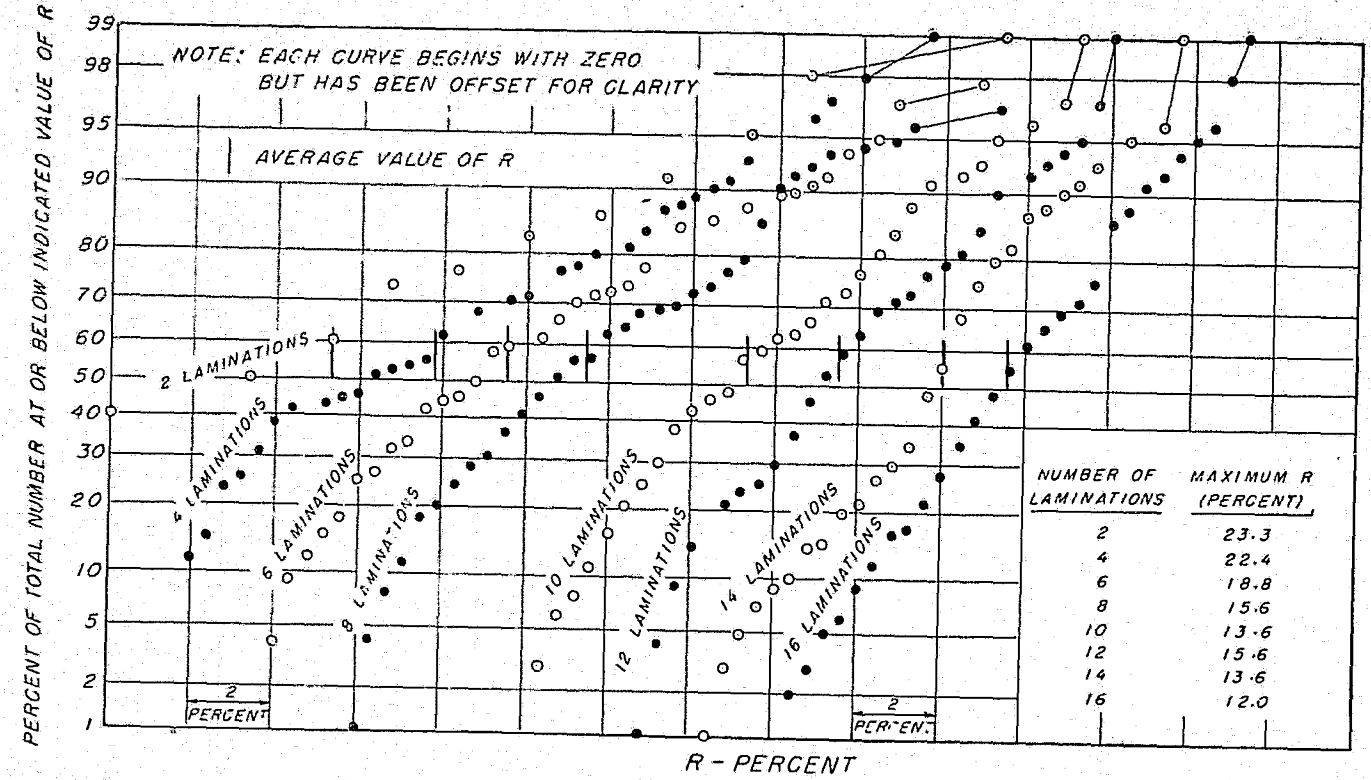


FIGURE 88.—Cumulative distribution of 100 computed values of I_K/I_G (R) for beams composed of 2 to 16 laminations. Computations based on random selection of laminations from a sample of a commercial lumber grade.

For the particular sample chosen,

$$\bar{I}_K + 2.326\bar{\sigma} = 54 \times 1.546 + 2.326 \times 2.271\sqrt{8\overline{22}} = 234.9$$

Dividing this by the value of $I_G (I_G = 30 \sum F = 30 \times 54 = 1{,}620)$ gives

$$I_K/I_G = 0.145 \text{ or } 14.5 \text{ percent.}$$

as a 1-percent exclusion limit.

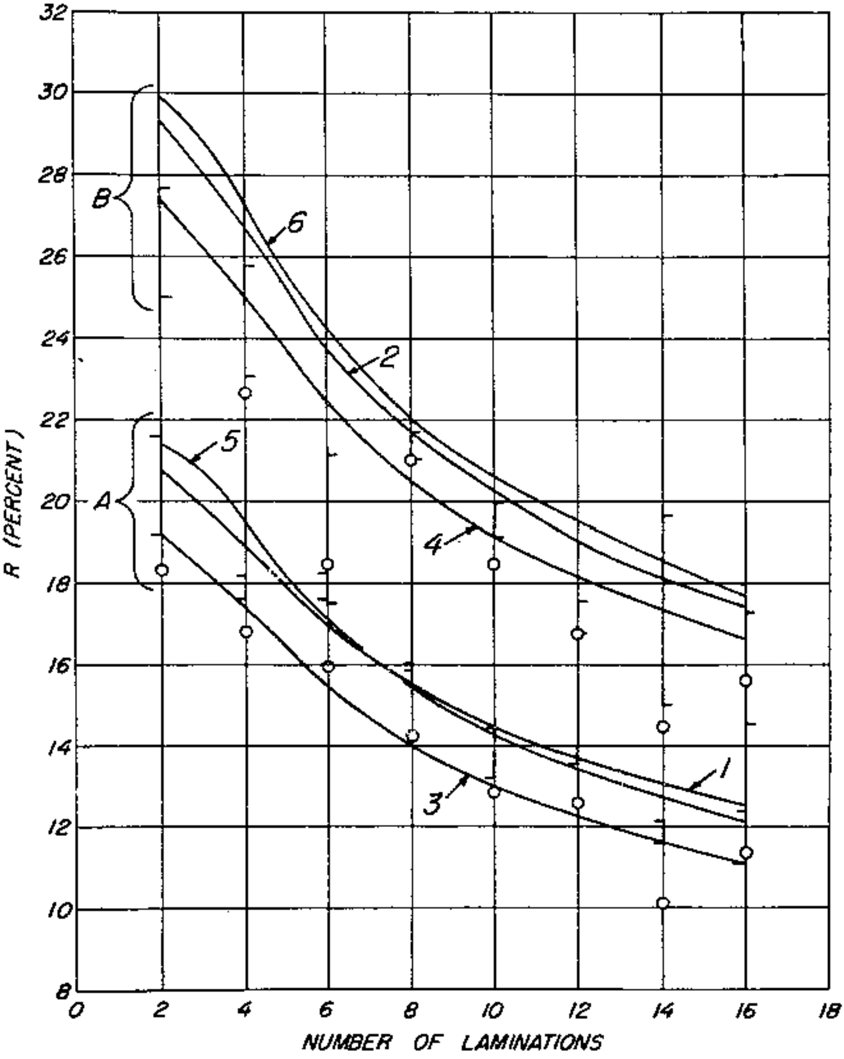


FIGURE 89.—Comparison of various methods of determining limiting values of I_K/I_G. Ranges shown by brackets represent range of estimates of 1-percent exclusion limits based on 100 individual computations of $R(I_K/I_G)$. Curves and circles represent exclusion limits based on computations by statistical methods.

TABLE 13.—*Method of application of weighting factors in computing certain statistical characteristics of a laminated beam containing knots*

Weighting factor F	Average value of $F\bar{x}$ (x=knot size)	Standard deviation ($F\sigma$)	Variance, or square of standard deviation $(F\sigma)^2$
19	$19\bar{x}$	19σ	$361\sigma^2$
7	$7\bar{x}$	7σ	$49\sigma^2$
1	$\bar{x}$	σ	σ^2
1	$\bar{x}$	σ	σ^2
7	$7\bar{x}$	7σ	$49\sigma^2$
19	$19\bar{x}$	19σ	$361\sigma^2$
Summations: 54	$54\bar{x}$		$822\sigma^2$

Comparison with figure 89 indicates that this is lower than was predicted by the other method. That is, the factor 2.326 is incorrect for the distribution of I_K/I_G for the sample considered. The product $2.326\bar{\sigma}$ represents the difference between the value of I_K at the 1-percent level and the average value. It may be noted from the computation above that $2.326\bar{\sigma}=2.326\sigma\sqrt{\sum F^2}$. Therefore, the product 2.326σ represents the difference between the knot size at the 1-percent level and the average value. Since the factor 2.326 is incorrect for this nonnormal distribution, we may replace the product 2.326σ by the difference between the knot sizes at the 1-percent level and at the average actually taken from a plotted distribution. Thus I_K/I_G at the 1-percent level would be

$$\frac{\bar{x}\sum F+(m-\bar{x})\sqrt{\sum F^2}}{I_G} \tag{13}$$

where m is the knot size at the 1-percent level.

Such computations have been made for the two samples for which ranges in I_K/I_G are shown in figure 89 and are shown in the same figure as curves 1 and 2. Reasonable agreement between the two methods is evident, indicating the applicability of the method.

Similar computations were carried out using, instead of the data for the particular samples involved, values of m and $\bar{x}$ for a combination of all samples of the two grades. These computations are represented by curves 3 and 4 of figure 89. It will be noted that these curves are, in many cases, lower than the maximums of the ranges shown for computations by the first method. The samples of a particular grade varied considerably in their characteristics, and thus it is apparent that 1-percent exclusion limits of I_K/I_G computed on the basis of all samples of a grade would be exceeded more than 1 percent of the time by assemblies made from one of the poorer samples.

Curves 5 and 6 of figure 89 represent ½-percent exclusion limits of I_K/I_G and are, in general, above the plotted data. Thus, it is recommended that, as a basis for design, values of I_K/I_G based on the characteristics of all samples of a grade be computed at the ½-percent level. Even on this basis, values of I_K/I_G so computed may be exceeded more than 1 percent of the time for specific lots of lumber.

The method just described appears, therefore, to be suitable for use in estimating values of I_K/I_G for use in design. Following is a step-by-step description of the procedure to be used in applying the method to any particular grade.

1. Obtain data on knot size and location. It is suggested that not less than 50 pieces of a grade be used as a sample and that they be randomly chosen from a number of sources so as to be representative of the grade. No special selection of the pieces to be sampled should be made. The only requirement is that they meet the rules for the grade. A convenient form for recording knot size and location and other pertinent data is shown in figure 90. The method of recording the data is indicated on the form and is illustrated by the sample data shown thereon.

2. Tally the sums of knot sizes in the 1-foot lengths in the sample. In order to take into account the fact that any 1-foot length in any board may be at the critical cross section of a member and, effectively, to increase the size of the sample, it is desirable to sum knot sizes in 1-foot lengths at closer intervals than the 1-foot marks on the grid of the data sheet (fig. 90). It is suggested, therefore, that the knots be summed in all the 1-foot lengths formed by taking the beginning of the feet at 2-inch intervals on the grid. To take into account the knots at the end of the board, consider it to be bent to form a circle and tally the knots in the feet thus formed. Table 14 shows a sample tally for the 12 pieces shown in figure 90. The figures to the left in each column show the individual occurrences of the particular sum for that piece. The number to the right of the equality sign shows the total number of occurrences of a particular sum in a particular piece. It is convenient to show the number of 1-foot lengths in each piece in order to check the tallying; the number of 1-foot lengths in each piece must equal the total of the tallies. Since the feet, for purposes of summing, are taken as beginning at 2-inch intervals, the number of 1-foot lengths equals 6 times the length of the piece in feet.

3. Summarize the data on occurrence of the various sums of knot sizes as tallied in step 2. A sample summary is shown in table 15. The particular sample shown in figure 90 and tallied in table 14 is shown in the summary as sample 4. Such a summary for all samples of the grade gives an overall view of the frequency of occurrence of various knot-size sums.

4. Compute the average sum of knot sizes for the grade. The total of column 13 (table 15) divided by the total of column 10 gives the average sum of knot sizes. For the sample shown in table 15,

$$\begin{aligned}\text{Av. sum of knot size} &= \text{Total} \times \text{sum/total}\\ &= 20{,}081/17{,}114\\ &= 1.17\ (\tfrac{1}{4}\text{ inch units})\end{aligned}$$

5. Plot, on arithmetical probability paper, the cumulative frequencies in percent against the corresponding knot-size sums. A sample plot of the data summarized in table 15 is shown in figure 91.

6. Approximate the plotted points by a straight line. Arithmetical probability paper is so ruled that a normal frequency distribution plots

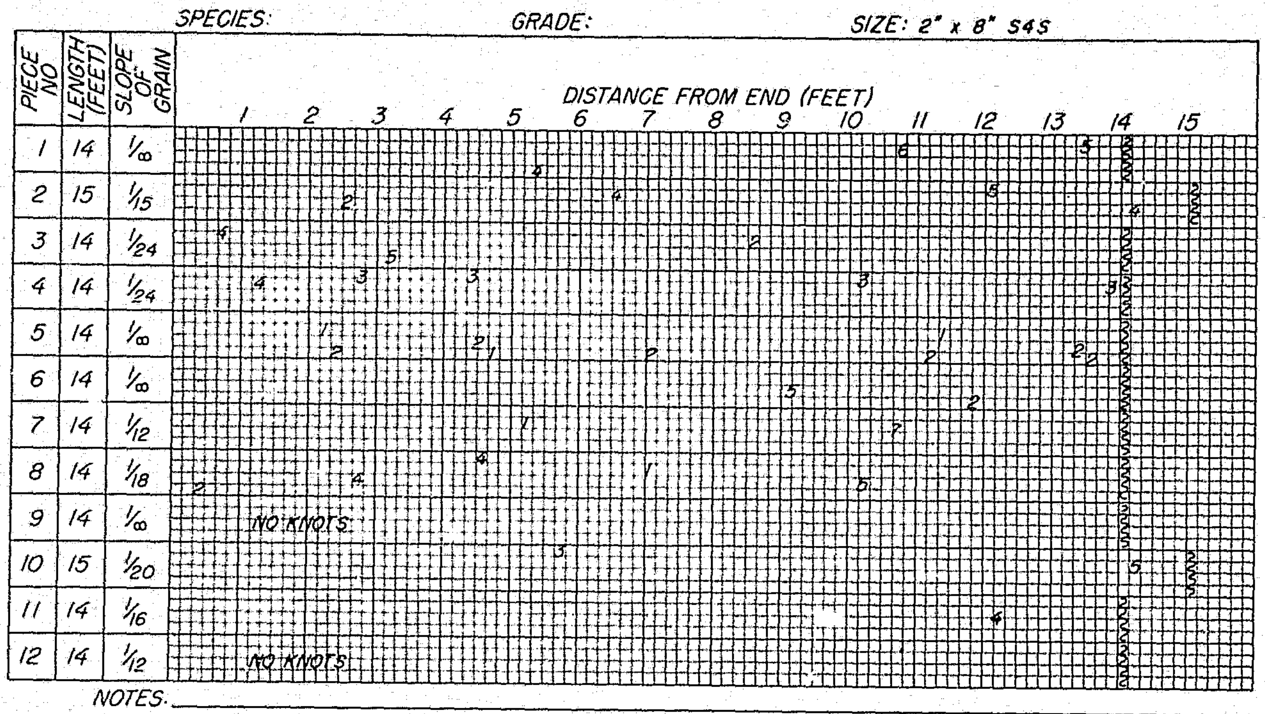


FIGURE 90.—Form for recording knot size and location with sample record of data. Size of knot is recorded in ¼-inch units, thus: 4 for 1-inch knot or 7 for 1¾-inch knot. Record this figure on grid at position of knot. Record over-all length of piece and its general slope of grain, as 1 in 10, 1 in 15, in columns provided. Chart can be lengthened for any length of lumber.

TABLE 14.—*Sample tally of sums of knot sizes in 1-foot lengths*

Piece No.	Number of 1-foot lengths [1]	Sum of knot sizes in 1-foot lengths in ¼-inch units							
		0	1	2	3	4	5	6	7
1	84	66				6= 6	6= 6	6=6	
2	90	66		6= 6		6+6=12	6= 6		
3	84	66		6= 6		6= 6	6= 6		
4	84	54			6+6+6+6=24	6= 6			
5	84	50	1+1+1= 3	1+1+6+1+1+1=11	5+5+5=15	5= 5			
6	84	72		6= 6			6= 6		
7	84	72	6= 6						6=6
8	84	54	6= 6	6= 6		6+6=12	6= 6		
9	84	84							
10	90	78			6= 6		6= 6		
11	84	78				6= 6			
12	84	84							
Total	1,020	824	15	35	45	53	36	6	6

[1] Length of piece in feet multiplied by 6.

TABLE 15.—*Sample summary of distribution of sums of knot sizes in 1-foot lengths*

Sum of knot sizes ¼-inch units	Frequency of occurrence of sums in sample number—								All samples			
	1	2	3	4	5	6	7	8	Total	Cumulative total	Cumulative frequency percent	Total x sum
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
0	3, 177	981	1, 491	824	874	908	684	3, 213	12, 152	12, 152	71. 01	0
1	84	0	15	15	7	15	8	60	204	12, 356	72. 20	204
2	315	53	62	35	42	101	54	253	915	13, 271	77. 54	1, 930
3	353	53	41	45	61	36	43	308	940	14, 211	83. 04	2, 820
4	581	138	154	53	45	33	105	169	1, 278	15, 489	90. 50	5, 112
5	233	53	45	36	63	31	93	106	660	16, 149	94. 36	3, 300
6	205	59	56	6	38	14	36	76	490	16, 639	97. 22	2, 940
7	95	22	24	6	0	11	51	36	245	16, 884	98. 66	1, 715
8	44	37	17	0	5	0	5	6	114	16, 998	99. 32	912
9	23	3	7	0	0	3	7	13	56	17, 054	99. 65	504
10	12	1	0	0	3	0	4	14	34	17, 088	99. 85	340
11	2	0	8	0	2	0	0	0	12	17, 100	99. 92	132
12	3	0	0	0	0	0	1	6	10	17, 110	99. 98	120
13	3	0	0	0	0	0	1	0	4	17, 114	100. 00	52
Total	5, 130	1, 400	1, 920	1, 020	1, 140	1, 152	1, 092	4, 260	17, 114	----------	----------	20, 081

as a straight line. This step, then, defines the normal frequency distribution that approximates the actual distribution.

7. Pick off, from the straight line drawn in step 6, the sum of knot sizes at the ½-percent exclusion limit. Following up the 99.5-percent vertical from the lower scale to the straight line and reading off the corresponding sum gives the sum that has a probability of being exceeded not more than once in 200 times. For the sample shown in figure 91, this sum is 8.6 units of ¼ inch. Other exclusion limits could be chosen, but study has indicated that the ½-percent exclusion limit is suitable.

8. Using the values of average sum of knot sizes (step 4) and the sum of knot sizes at the ½-percent exclusion limit (step 7), compute values of I_K/I_G for the member.

For a member having all laminations of a single grade,

$$R(v;2n)=\frac{\overline{x}_v}{b}+\frac{h_v}{b}\sqrt{\frac{\sum_o^{2n}F^2}{\sum_o^{2n}F}} \qquad (14)$$

where $R(v;2n)$ = value of I_K/I_G for a beam of $2n$ laminations of grade v at an exclusion limit depending upon the choice of the value h.

$\overline{x}_v$ = average sum of knot sizes in grade v (step 4)

h_v = difference between sum of knot sizes at the exclusion limit chosen (step 7) and $\overline{x}_v$.

b = finished width of laminations.

F = weighting factor depending upon the number of laminations in the member. Values of F, $\sum F$, etc., are given in table 16.

For the grade of table 15 and figure 91, and for a member containing 16 laminations, the computation would be as follows:

$\overline{x}_v=1.17/4=0.2925$ inch (step 4)

$h_v=(8.60-1.17)/4=7.43/4=1.8575$ inches (step 7)

$b=7.5$ inches

$$\sqrt{\sum_o^{2n}F^2}/\sum_o^{2n}F=0.334 \text{ (table 16)}$$

$$R(v;16)=\frac{0.2925}{7.5}+\frac{1.8575}{7.5}\times 0.334=0.122$$

For a member having a group of clear, straight-grained laminations on each side, with the balance of the laminations of another grade,

$$R(o,v;2N,2n)=\frac{\overline{x}_v\sum_o^{2n}F+h_v\sqrt{\sum_o^{2n}F^2}}{b\sum_o^{2N}F} \qquad (15)$$

where $R(o,v;2N,2n)$ = value of I_K/I_G for a beam of $2N$ laminations, of which the central $2n$ are of grade v and the others are clear and straight-grained (grade o) and the other terms are as described earlier.

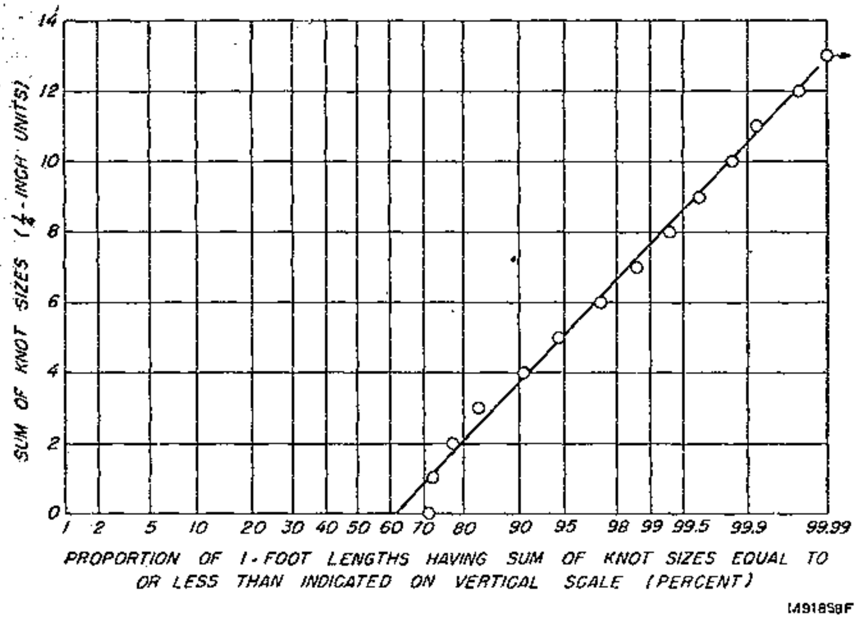


FIGURE 91.—Sample plot, on arithmetical probability paper, of cumulative frequencies of occurrence of sums of knot sizes in 1-foot lengths.

TABLE 16.—*Factors for use in computing values of I_K/I_G from characteristics of knot distributions*

Number of lamination $=2N$	Weighting factor for Nth lamination from neutral axis $F=3N^2-3N+1$ $=N^3-(N-1)^3$	For $2N$ laminations		
		$\Sigma F=2N^3$	$\Sigma F^2=⅖N(9N^4-5N^2+1)$	$\frac{\sqrt{\Sigma F^2}}{\Sigma F}$
1	¼	¼	1/16	1.000
2	1	2	2	.707
3	3¼	6¾	21 3/16	.682
4	7	16	100	.625
5	12¼	31¼	321 5/16	.573
6	19	54	822	.531
8	37	128	3, 560	.466
10	61	250	11, 002	.420
12	91	432	27, 564	.384
14	127	686	59, 822	.357
16	169	1, 024	116, 944	.334
18	217	1, 458	211, 122	.315
20	271	2, 000	358, 004	.299
22	331	2, 662	577, 126	.285
24	397	3, 456	892, 344	.273
26	469	4, 394	1, 332, 266	.263
28	547	5, 488	1, 930, 684	.253
30	631	6, 750	2, 727, 006	.245
40	1, 141	16, 000	11, 504, 008	.212
50	1, 801	31, 250	35, 125, 010	.190

The computations would be as follows for a beam of 16 laminations, of which the outer two on each side are defect-free and the others are of the grade illustrated in table 15 and figure 91.

$$R(o,v;16,12)=\frac{0.2925\times 432+1.8575\sqrt{27{,}564}}{7.5\times 1{,}024}=0.057$$

For a member having a group of outer laminations on each side of one grade, and the inner laminations of another grade,

$$R(w,v;2N,2n)=\frac{\bar{x}_w\sum_{2n}^{2N}F+\bar{x}_v\sum_{o}^{2n}F+\sqrt{h_w^2\sum_{2n}^{2N}F^2+h_v^2\sum_{o}^{2n}F^2}}{b\sum_{o}^{2N}F} \quad (16)$$

where $R(w,v;2N,2n)$ = value of I_K/I_G for a beam of $2N$ laminations, of which the central $2n$ are of grade v and the others of grade w

$\bar{x}_v$ = average sum of knot sizes for grade v

$\bar{x}_w$ = average sum of knot sizes for grade w

h_v = difference between sum of knot sizes at the exclusion limit chosen and $\bar{x}_v$

h_w = difference between sum of knot sizes for the exclusion limit chosen and $\bar{x}_w$

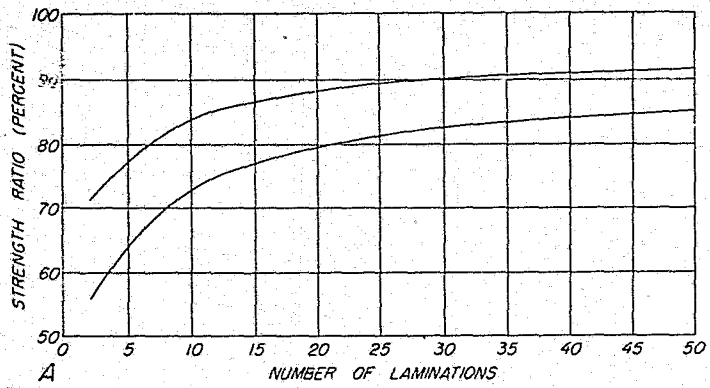
The computations would be as follows for a beam of 16 laminations, of which the outer 2 on each side are of the grade illustrated in table 15 and figure 91, and the inner laminations are of a lower grade. For the inner laminations, $\bar{x}_v=0.5225$ inch, and $h_v=2.4275$ inches.

$$R(w,v;16,12)=\frac{0.2925(1024-432)+0.5225\times 432+\sqrt{1.8575^2(110{,}944-27{,}564)+2.4275^2\times 27{,}564}}{7.5\times 1024}=0.141$$

9. With the values of I_K/I_G computed in step 8, enter the curve of figure 55 to determine the corresponding strength ratios. For the 3 examples of step 8, the strength ratios are 0.87, 0.96, and 0.84, respectively. For convenience in design, strength ratios for various grades and grade combinations may be computed at suitable intervals and plotted. Strength ratios for a member containing any given number of laminations may then be picked off the curve without the necessity for computing each case. Samples of such curves are shown in figure 92, *A*, *B*, and *C*.

10. With the strength ratios computed in step 9, working stresses may be computed by multiplying the appropriate basic stress by the strength ratio. For members composed of more than one grade, the basic stress to be used is that applicable to the outer group of laminations except as indicated below.

The strength ratios found in step 9 are applicable to the member as a whole and may result in overstress in the inner group of laminations of a member composed of 2 grades if (*a*) there is a considerable difference in quality between the laminations of the 2 groups, (*b*) the outer groups constitute a very small proportion of the total depth of the beam, or (*c*) the laminations of the outer groups are close-grained or dense while those of the inner group are not.



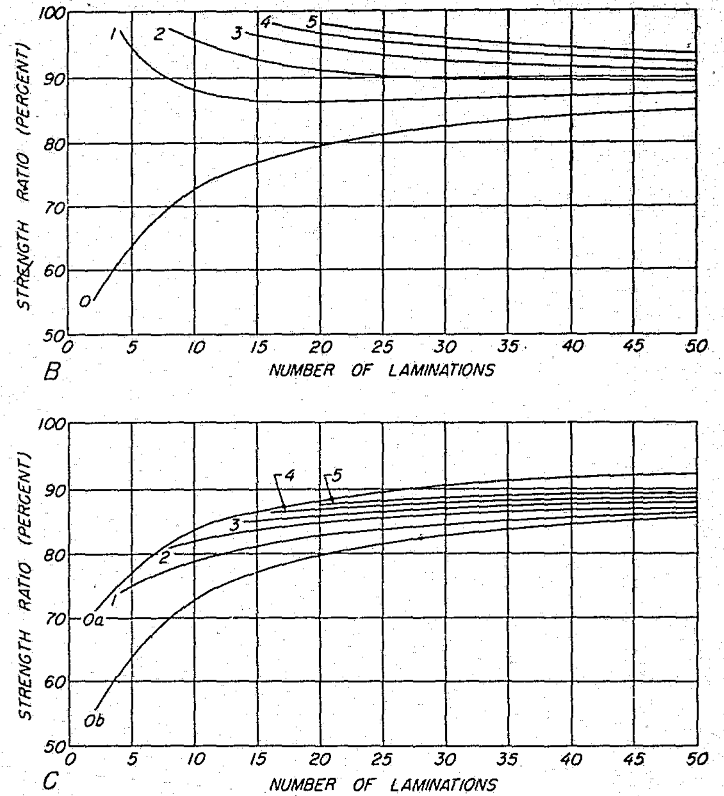


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FIGURE 92.—Sample plots of strength ratios for laminated bending members containing various numbers of laminations as based on a survey of knot size and location. *A*, Two typical grades; *B*, a typical grade in inner laminations combined with defect-free outer laminations (curve numbers indicate number of clear laminations on each side); *C*, two typical grades in various combinations (curve numbers indicate number of laminations on each side that are of higher grade, except curve *Oa* representing beams in which all laminations are of higher grade, and curve *Ob* in which all are of lower grade).

To check for overstress the following procedure is suggested:

(a) Determine the strength ratio for a beam having the number of laminations and grade of lumber contained in the inner group of laminations.

(b) Multiply this strength ratio by the basic stress appropriate to the grade of lumber contained in the inner group of lamination. This gives the working stress appropriate to the "inner beam."

(c) Determine the stress in the extreme fiber of the "inner beam" that would result from application to the complete member of the working stress (for the whole member) as determined in the early part of step 10. By assuming linear distribution of stress through the depth of the beam, this may be done by multiplying the working stress for the member as a whole by the ratio of the number of laminations in the inner group to the total number of laminations in the member.

(d) If the stress calculated in step c is higher than that calculated in step b, the working stress for the member as a whole must be reduced to that point where the stress of step c is equal to or less than that of step b.

11. Strictly speaking, the survey and computations just indicated should be made for each standard width of stock for each grade. It is probable that no excessive error will be encountered if some median width, say 8 inches, is surveyed and the results applied to any width. It may be expected that the results will be somewhat unconservative for narrower widths and somewhat conservative for wider widths. It should be understood also that a change in the grading rules will invalidate the results and necessitate a resurvey and recomputations.

The procedure explained above provides a method by which a manufacturer may sample the stock he uses in his product and develop data from which he may establish strength ratios for use in design. Also commercial grades, in addition to those for which data are given, may be similarly studied.

It is recognized that beams may be made of species and grades other than those studied, and that estimates of applicable strength ratios may be desired. No feasible means of extending current data to additional grades is apparent. Figure 56 presents ratios of values of I_K/I_G by the method outlined, as determined from the grades studied, to those which would result if the largest knot permissible in the grade were assumed to be in every lamination. For the grades studied, the range in this ratio is not excessive. It seems feasible, for preliminary estimates, to assume ratios as represented by the curve of figure 56 and from these to estimate the values of I_K/I_G that may be used as a basis for design. While such a procedure appears to be reasonably conservative, its use on more than a temporary basis is not recommended.

A method of limiting the number of knots to not more than 2 of the largest permissible within 6 inches of any cross section was discussed earlier. The curves of figure 57 are for use in determining values of I_K/I_G when such limitations are observed. The equations of these curves are given below for the convenience of those who may wish to construct them more accurately or to extend them. In the equations, A indicates the number of the lamination, beginning with 1 for the outside lamination, 2 for the lamination next to the outside 1, and so on. The number of laminations is represented by N.

For $A=1$,

$$I_1/I_G=\frac{2}{N^3}(3N^2-6N+4)$$

For $A=2$,

$$I_2/I_G=\frac{2}{N^3}(3N^2-18N+28)$$

For $A=3$,

$$I_3/I_G=\frac{2}{N^3}(3N^2-30N+76) \tag{17}$$

For $A=4$,

$$I_4/I_G=\frac{2}{N^3}(3N^2-42N+148)$$

For $A=5$,

$$I_5/I_G=\frac{2}{N^3}(3N^2-54N+244)$$

Or, in more general terms,

$$I_A/I_G=\frac{2}{N^3}[3N^2-6N(2A-1)+4(3A^2-3A+1)] \tag{18}$$

LAMINATION GRADES

The principal determinants of the strength of a laminated beam are the slope of cross grain and the size and location of knots in the laminations. Safe and efficient design requires that cross grain be definitely limited and that the size of permitted knots be related to the width of the lamination.

Many commercial grades of lumber that might be used in laminating are based on general appearance and do not limit cross grain at all and limit knots without respect to board width. While the method of analysis described in the preceding section can be applied to such grades to evaluate the effect of knots, it is believed that considerably greater efficiency will be attained by further sorting and classification of the material with a direct view to use in laminating. In any event, sorting of such material with respect to cross grain prior to its use in structural members is a necessity.

Further, lumber is often lowered in grade by the presence of sap stain, pitch pockets, and like features that affect appearance but have little or no effect on strength. In addition, knotholes and encased knots are limited to one-half the size of sound, intergrown knots, even though they are no more detrimental to strength when of the same size and may be even less so if the grain deviates less around them.

In view of these considerations, as well as of the fact that grading with relation to laminated construction has not yet been undertaken by the lumber industry, it is believed that the fabricator of laminated construction can much more efficiently and economically utilize available strength values by sorting and classifying the lumber he uses. A system of lamination classes is therefore proposed for consideration by lumber manufacturers.

Five lamination classes, numbered from 0 to 4, are proposed, class 0 being free of significant strength-impairing features and classes 1 to 4 permitting such features in magnitudes differing between classes, with defects being limited most in class 1 and least in class 4, with classes 2 and 3 intermediate.

The classes of beams would be designated in accordance with the classes of laminations of which they are composed. Classes such as 0–0, 1–1, and 2–2 would designate beams composed throughout of a single lamination class, while classes such as 0–1, 0–2, 1–2, 1–3, 2–3, and 3–4 would designate beams with the higher class of laminations in top and bottom parts and the lower class in the remainder of the cross section.

A more complete description of the proposed lamination classes and their limitations is given on p. 138.

Combination of Laminations to Form Beams.—Advantageous use of laminations containing knots, such as classes 1, 2, 3, and 4 outlined above, requires that knots should be well dispersed and not concentrated at any one cross section. If, in forming beams from one of these grades, no attention whatever were given to the position, chance would of course provide various degrees of dispersion, as described earlier for commercial grades. Material classified in accordance with the sorting classes described could be sampled and studied by the statistical procedure outlined to take advantage of chance dispersion in evaluating working stresses. Lacking such a study, it appears necessary to assume the worst knot in the worst position in each lamination.

FLEXURAL DESIGN FOR VERTICALLY LAMINATED MEMBERS

The results of tests on vertically laminated members indicated that the design curve of figure 55 is inapplicable. The results did indicate, however, that the average of the strength ratios of the laminations as determined by the methods described in the Wood Handbook (*7*) could be used to determine the strength ratio of the vertically laminated beam. The increase in strength ratio permitted by the Wood Handbook for thin members used in dry locations is not applicable, since the effects of drying have been incorporated into the basic stresses of table 5.

DESIGN FOR COMPRESSIVE STRENGTH

Figure 93 shows a plot of the results of tests on laminated short columns containing knots. Values of the strength properties are plotted as ordinates, while the abscissae are values of K/b, where K is the average of the size of the largest knot in each lamination in the column and b is the width of the lamination.

Values are plotted in figure 93 for each specimen, with 8- and 17-lamination columns being indicated by different symbols. The same symbols with numerals alongside represent averages, with the numeral indicating the number of values averaged. Grand averages for each group of specimens having knots of similar size are indicated by dots with numerals of similar significance alongside.

The plots of figure 93 show a definite decrease for each of the three properties with increase in K/b. In each plot, also, the points representing grand averages are very nearly in linear relation. In each

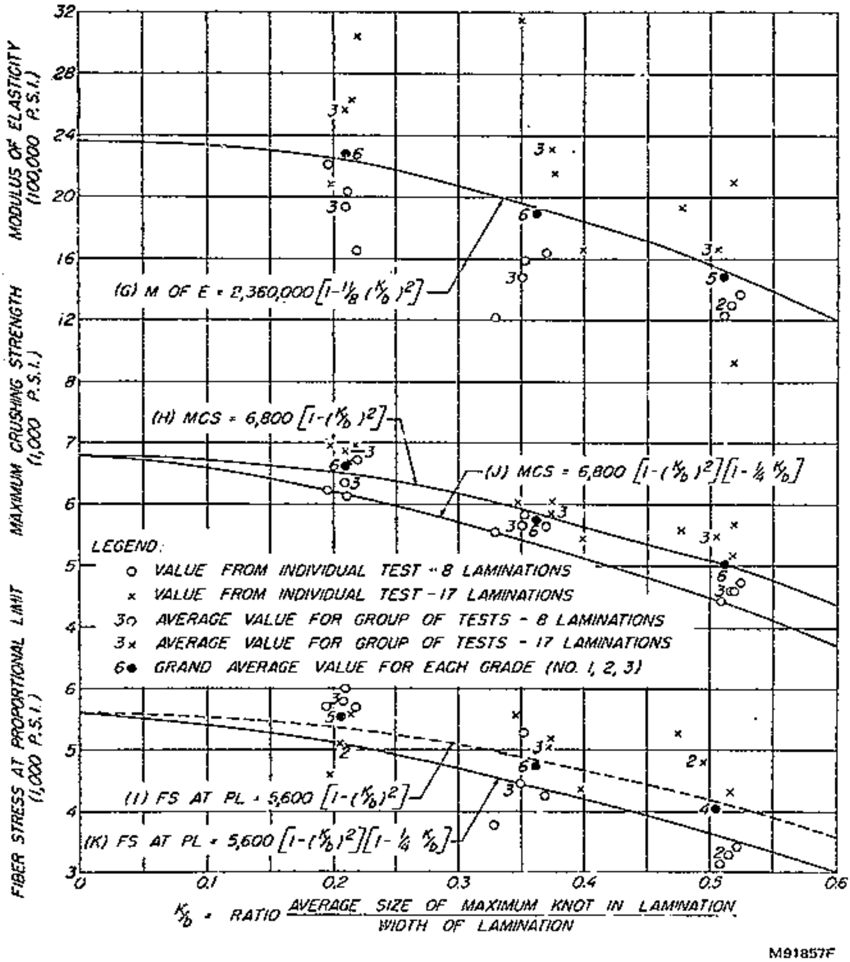


FIGURE 93.—Relation of properties of columns with knots in laminations to K/b.

instance, however, straight lines averaging the grand averages would intersect the left-hand scale at values higher than are to be expected from material of the same density but free from knots, and hence such lines cannot be considered as being representative of the effect of knots. Shown as curves *G*, *H*, and *I* are the parabolic curves that best fit the three grand averages in each plot.

The intercept of curve *G* on the left-hand scale is at a value of 2,360,000, which is approximately 30 percent higher than the average value found from tests of control columns. No adequate explanation is available for this discrepancy, inasmuch as the method of measuring strains was essentially the same in all instances. The presence of knots and severe cross grain hidden within the columns, but near the strain gages, may have affected the distribution of strains to an unknown extent, and thus accounted for the discrepancy. The intercept of curve H is in good agreement with the results of tests of columns without knots, but the intercept of curve I is somewhat higher than the average fiber stress at proportional limit for the controls.

Curve J is suggested as a basis for design. It was derived in a manner analogous to that used in deriving the design curve for the effect of knots on bending stress. The strength ratio, or factor y, by which to multiply the basic stress to determine the allowable compressive stress for a column with knots would have the equation

$$y=[1-(K/b)^2][1-\tfrac{1}{2}(K/b)] \qquad (19)$$

where y is the ratio of allowable stress in compression to the basic stress, or the strength ratio, K is the average of the maximum knot size in the several laminations, and b is the width of lamination.

The term in the first bracket represents the average effect of knots, and that in the second the allowance made for increased variation in strength that accompanies increase in size of knots.

Estimation of K/b.—As has just been indicated, the factor K/b is the determinant of the effect of knots on column strength. With random assembly of laminations, some assumption must be made as to the value of K for use in design. The relations from test are based on the average of the largest knots in the various laminations of 3-foot-long columns. A conservative assumption would be, therefore, that in at least one 3-foot length of any column, each lamination would contain a knot of maximum permissible size. General experience, as well as the results of the statistical study on beams discussed earlier in the appendix, indicate that such a concentration is unlikely to occur. Accordingly, statistical procedures for estimating, from the knot distribution characteristics of a grade, an appropriate value of K/b for use in design has been developed. The step-by-step procedures are described below.

1. Obtain data on knot size and location. The procedure is, of course, exactly the same as described earlier for beams.

2. Tally the largest knots occurring in the 3-foot lengths in the sample. Since the relations from test are based on 3-foot columns, it seems necessary to use 3-foot lengths as the basis for tallying. Since any 3-foot length in any piece could be located at any point in a column, it is necessary to tally largest knots in 3-foot lengths beginning more frequently than at 3-foot intervals on the grid of the record sheet. Trials at various intervals indicate that it is sufficient to tally knots in the 3-foot lengths beginning at 6-inch intervals. To take into account the knots near the end of a piece, consider that the piece is bent to form a circle, and tally the largest knots occurring in the 3-foot lengths thus formed. Table 17 gives a sample tally for the 12 pieces shown in figure 90. The method of recording the tallies is similar to that described earlier for bending members. The number of 3-foot lengths in each piece is equal to twice the length of the piece in feet, since the beginnings of the lengths are taken at 6-inch intervals.

3. Summarize the data on occurrence of the various maximum knot sizes as tallied in step 2. A sample summary is shown in table 18. The particular sample shown in figure 90 and table 17 is shown in the summary as sample 4.

TABLE 17.—*Sample tally of maximum knot sizes in 3-foot lengths*

Piece No.	Number of 3-foot lengths [1]	Maximum knot size in 3-foot lengths in ¼-inch units							
		0	1	2	3	4	5	6	7
1	28	5+5= 10				6= 6	6= 6	6=6	
2	30	2+5+1= 8		6= 6		6+4=10	6= 6		
3	28	5+6= 11		6= 6		1+4= 5	6= 6		
4	28	6+1= 7			6+6+3=15	4+2= 6			
5	28	2= 2		14+12=26					
6	28	13+4= 17		5= 5			6= 6		
7	28	5+5+6= 16	6= 6						6=6
8	28	2= 2	5= 5	5= 5		10=10	6= 6		
9	28	28= 28							
10	30	6+11+1= 18			6= 6		6= 6		
11	28	19+3= 22				6= 6			
12	28	28= 28							
Total	340	169	11	48	21	43	36	6	6

[1] Length of piece in feet multiplied by 2.

TABLE 18. *Sample summary of distribution of maximum knot sizes in 3-foot lengths*

Maximum knot sizes in ¼-inch units	Frequency of occurrence of maximum knot sizes in sample number—								All samples	
	1	2	3	4	5	6	7	8	Total	Percentage of whole
0	474	206	404	169	192	183	86	589	2, 303	36. 72
1	54	0	12	11	0	10	5	53	145	2. 31
2	178	38	58	48	20	82	20	149	593	9. 46
3	254	33	36	21	46	33	26	251	700	11. 16
4	531	111	156	43	35	30	81	164	1, 151	18. 35
5	234	46	51	36	57	34	70	103	631	10. 06
6	226	60	53	6	30	6	34	53	468	7. 46
7	64	24	24	6	0	6	42	18	184	2. 93
8	25	42	6	0	0	0	0	6	79	1. 26
9	0	0	0	0	0	0	0	0	0	0
10	6	0	0	0	0	0	0	0	6	. 10
11	0	0	0	0	0	0	0	0	0	0
12	6	0	0	0	0	0	0	6	12	. 19
Total	2, 052	560	800	340	380	384	364	1, 392	6, 272	100. 00

4. Compute the mean of the distribution summarized in step 3 and certain other statistical characteristics. A sample computation for the distribution shown in table 18 is given in table 19. Column 1 of this table represents simply the array of maximum knot sizes in 3-foot lengths found for the grade. Column 2 represents the last column of table 18 divided by 100. The meanings of other columns are self-evident. The mean maximum knot size (m) is represented by the total of column 3. The factors m_2, m_3, and m_4 are the totals of columns 6, 8, and 10, respectively. These values, and the quantities computed from them, are useful in later steps. They are also statistical measures of the distribution. The factor $\sqrt{m_2}$, for example, is the standard deviation of the distribution about the mean, a measure of the scatter of the various knot sizes. For a normal distribution, the factor $m_3/m_2\sqrt{m_2}$ would be exactly zero and the factor m_4/m_2^2 would be exactly three. The closeness of these factors to these values indicates whether or not the actual distribution approximates a normal distribution.

Steps 1 through 4 provide data on the characteristics of the distribution of the maximum-size knots in 3-foot lengths of the grade. Subsequent steps will illustrate the application of these characteristics to particular members.

5. Compute, from the data of step 4, certain statistical characteristics of the average of the largest knot sizes occurring in a member.

(a) The mean value of the largest knot sizes will, of course, be the same as the mean value for the grade computed in step 4 for a member composed of only one grade. Other characteristics will be dependent

TABLE 19.—*Sample of calculation of statistical characteristics of the distribution of maximum-size knots in 3-foot lengths*

Maximum knot size (i) (1)	Frequency (f_i) (2)	if_i (3)	$(i-m)$ (4)	$(i-m)^2$ (5)	$(i-m)^2f_i$ (6)	$(i-m)^3$ (7)	$(i-m)^3f_i$ (8)	$(i-m)^4$ (9)	$(i-m)^4f_i$ (10)
0	0.3672	0.0000	−2.5704	6.6070	2.4261	−16.9826	−6.2360	43.6524	16.0292
1	.0231	.0231	−1.5704	2.4662	.0570	−3.8729	−.0895	6.0821	.1405
2	.0946	.1892	−.5704	.3254	.0308	−.1856	−.0176	.1059	.0100
3	.1116	.3348	.4296	.1846	.0206	.0793	.0088	.0341	.0038
4	.1835	.7340	1.4296	2.0438	.3750	2.9218	.5362	4.1771	.7665
5	.1006	.5030	2.4296	5.9030	.5938	14.3419	1.4428	34.8454	3.5054
6	.0746	.4476	3.4296	11.7622	.8775	40.3396	3.0093	138.3493	10.3209
7	.0293	.2051	4.4296	19.6214	.5749	86.9150	2.5466	384.9993	11.2805
8	.0126	.1008	5.4296	29.4806	.3715	160.0679	2.0169	869.1058	10.9507
9	0	.0000	6.4296	41.3398	.0000	265.7984	.0000	1708.9791	.0000
10	.0010	.0100	7.4296	55.1990	.0552	410.1065	.4101	3046.9296	3.0469
11	0	.0000	8.4296	71.0582	.0000	598.9922	.0000	5049.2678	.0000
12	.0019	.0228	9.4296	88.9174	.1689	838.4555	1.5931	7906.3040	15.0220
Total	1.0000	2.5704			5.5513		5.2207		71.0764

$m=2.5704$; $m_2=5.5513$; $m_3=5.2207$; $m_4=71.0764$

$\sqrt{m_2}=2.3561$; $m_3/m_2\sqrt{m_2}=0.3992$; $m_4/m_2^2=2.3064$

upon the number of laminations in the member. These may be computed from the following formulas for members composed only of one grade.

$$\sigma=\sqrt{m_2}/\sqrt{n} \tag{20}$$

$$a_3=(m_3/m_2\sqrt{m_2})/\sqrt{n} \tag{21}$$

$$a_4=3(n-1)/n+(m_4/m_2^2)/n \tag{22}$$

For example, for a member containing 16 laminations and of the grade illustrated by table 19,

$$\sigma=2.3561/4=0.5890$$

$$a_3=0.3992/4=0.0998$$

$$a_4=3 \text{ x } 15/16+2.3064/16$$

$$=2.8125+0.1442$$

$$=2.9567$$

For a normal distribution, the latter 2 factors would be exactly zero and exactly 3, respectively. There is no method of evaluating the effect of the differences in the values of these factors from zero and from three on the validity of the method of computation. Computations by other methods, however, indicated that even where sizable differences occurred, the computations were satisfactory.

(b) When the member is composed of two grades, the methods of computation are somewhat different. For example, consider a member having a total of n laminations made up of n_a laminations of grade a having a mean maximum knot size m_a and standard deviation σ_a and n_b laminations of grade b having a mean maximum knot size of m_b and standard deviation σ_b. Then

$$m=\frac{n_a m_a+n_b m_b}{n} \tag{23}$$

$$\sigma=\frac{1}{n}\sqrt{n_a\sigma_a^2+n_b\sigma_b^2} \tag{24}$$

where $n=n_a+n_b$.

For example, for a member consisting of 20 laminations, of which 8 are of the grade for which the data were worked out in step 4 and 12 are of a grade for which the mean is 4.3596 and the standard deviation 3.1399, the computations would be as follows:

$$m_a=2.5704,\ \sigma_a=2.3561$$
$$m_b=4.3596,\ \sigma_b=3.1399$$
$$m=\frac{8\times2.5704+12\times4.3596}{20}$$
$$=3.6439$$
$$\sigma=\frac{1}{20}\sqrt{8\times(2.3561)^2+12\times(3.1399)^2}$$
$$=0.6378$$

TB 1069 (1954) USDA TECHNICAL BULLETINS UPDATA
FABRICATION AND DESIGN OF GLUED LAMINATED WOOD STRUCTURAL MEMBERS
FREAS, A.D., SELBO, M.L. 3 OF 3

(c) When one of the grades in the combination contains no knots, m_a and σ_a both become zero, and equations (23) and (24) reduce to

$$m=\frac{n_b m_b}{n} \tag{25}$$

$$\sigma=\frac{1}{n}\sqrt{n_b \sigma_b^2} \tag{26}$$

6. Compute, from the data of steps 4 and 5, the average maximum knot size at an exclusion limit of ½ percent. This knot size equals the sum of the mean and a multiple of the standard deviation. Thus,

$$K(½\%)=m+2.575\sigma \tag{27}$$

The factor 2.575 is taken directly from the mathematical properties of a normal distribution. At other exclusion limits, the factor is different—for a 2-percent exclusion, the factor would be 2.054, and for a 1-percent exclusion, 2.326.

For the example of step 5 in which all laminations are of one grade,

$$\begin{aligned} K(½\%) &= m+2.575\sigma \\ &= 2.57+2.575\times0.5890 \\ &= 4.09 \text{ units of } ¼ \text{ inch} \\ &= 1.02 \text{ inches} \end{aligned}$$

For the second example of step 5,

$$\begin{aligned} K(½\%) &= 3.64+2.575\times0.6378 \\ &= 5.29 \text{ units of } ¼ \text{ inch} \\ &= 1.32 \text{ inches} \end{aligned}$$

7. Compute the value of K/b for use in design. For the examples of step 6, the lamination width was nominally 8 inches. Thus, for the two examples,

$$K/b=1.02/7.5=0.136$$
$$K/b=1.32/7.5=0.176$$

8. With the value of K/b computed in step 7, enter the curve of figure 62, p. 122, to determine the corresponding strength ratio. For the examples of step 7, the strength ratios are 0.95 for $K/b=0.136$ and 0.93 for $K/b=0.176$. For convenience in design, strength ratios for various grades or grade combinations may be computed at suitable intervals and plotted. Strength ratios for a member containing any number of laminations may then be picked off the curve without the necessity for computing each case. Such curves would be set up in a form similar to that shown in figure 92.

9. As has been indicated earlier, in the discussion of bending members, the analysis just described should be carried out for each standard width to be used. Reasonable results may be expected, however, if the analysis is based on some median width such as 8 inches. A change in grading rules will require a complete reanalysis.

10. The procedure for tension members will be exactly the same as just described for all steps, including calculation of K/b. Strength ratios for tension will be taken from figure 64, p. 126.

As was true for bending members, there appears to be no feasible way to extend the results of an analysis such as that outlined above to other species or other grades. Figure 63 presents ratios of the values of K/b determined by the method outlined above for several grades to the value of K/b derived on the assumption that all laminations contain a knot of maximum permissible size in every lamination in at least one 3-foot length. Again, the range of values of this ratio is not excessive. Therefore, it seems feasible, for preliminary estimates of values of K/b that may be used as a basis for design, to use ratios as represented by the curve of figure 63. The use of this procedure on more than a temporary basis is not recommended.

Effect of Form and Height of Beams

FORM AND HEIGHT FACTORS

Beams and eccentrically loaded compression specimens develop in test higher computed stresses in compression than are obtained when compression members are uniformly or concentrically loaded. This is true also of beams of circular section and of square beams placed with a diagonal vertical instead of with the normal orientation, both of which develop higher computed flexural stresses than rectangular pieces. On the other hand, beams of I or box section show lower stress values than do rectangular beams. Also, among beams of rectangular section the computed unit strength decreases as the height increases.

All available test results are in agreement with the hypothesis (*5*, *15*) that the minute elements of the wood structure behave as long, slender columns subject to buckling under load and that, in any instance of nonuniformly distributed compressive stress, as in a beam or an eccentrically loaded compression specimen, the more highly stressed elements are restrained from buckling by those that are less highly stressed. This may be termed the hypothesis of supporting action. In the case of the circular and diagonal-vertical sections, the support is increased by the increase in width of section with increase in distance from the outermost fiber. I and box sections are inferior because, as compared to rectangular sections, part of the support is lacking. High or deep beams give lower values than shallow ones because less support results from the smaller rate of decrease of stress with distance from the outermost elements.

The conclusion from this hypothesis is that flexural unit stresses are not actual properties of wood but are manifestations of behavior in compression under varying circumstances. Obviously, however, such a conclusion is modified somewhat when defects are present that reduce the tensile strength below the compressive.

The form-factor formula (*5*, *15*) for I and box sections was developed from the concept that the modulus of rupture of such a section consists of two parts that can be added together. These are:

1. The compressive strength of the material.
2. The excess of modulus of rupture of a rectangular section of the same height over the compressive strength multiplied by a factor that

expresses the ratio of the support afforded the outer fibers in the I or box section to the support afforded them in a rectangular beam.

This concept may be expressed in symbols as follows:

$$R_F = C + (R - C)S \tag{28}$$

where R is the modulus of rupture, C is the compressive strength, and S is the support factor.

Since R varies with the height of the beam, the manner of that variation must be considered. The formula originally presented (*5*, *7*) is

$$F_h = 1.07 - 0.07\sqrt{\frac{H}{2}} \tag{29}$$

where F_h is the ratio of the strength of a beam of height H to that of a beam 2 inches high.

It is now recognized that this formula is inconsistent with the hypothesis presented, inasmuch as it implies that, at large values of H, R is less than C, whereas the hypothesis put C as the lower limit of R. Furthermore, the formula is not consistent with recent data. Consideration of these data has resulted in a new formula for F_h. The data and graphs of the new formula are shown in figures 94, *A* and *B*, and the corresponding relation of R to C is shown in figures 95, *A* and *B*.

The data are from tests on Douglas-fir beams. Obviously, whichever curve is taken in figure 94, *A*, or figure 95, *A*, it should be coordinated with that in figure 94, *B*, or figure 95, *B*, and inasmuch as the data do not justify differentiation between proportional limit and ultimate, the curves in the four graphs are essentially identical. There are noticeably large departures of plotted points from the curve in each graph, but with all four graphs considered together, points below the curve are reasonably well-balanced by points above the curve and the fit of the curves is as good as may be expected. The fact that R, as found from tests of 2- by 2-inch air-dry specimens of Douglas-fir, has averaged about $1.6C$ (or $C=0.625R$), was made use of in correlating and locating the curves.

The curve in figure 94, *B*, has the equation

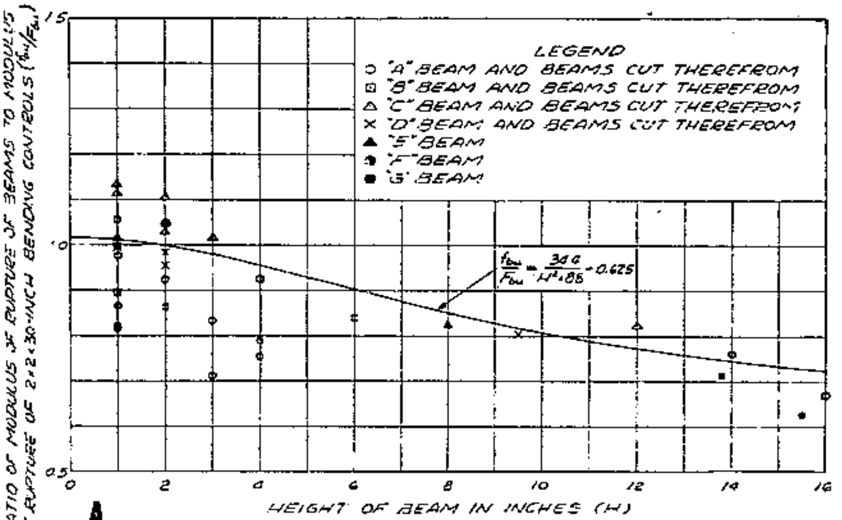
$$F_H = 5/8\left(\frac{55}{H^2+88}+1\right) = 5/8\,\frac{H^2+143}{H^2+88} \tag{29}$$

and is asymptotic to 5/8, the value of C/R_2, the ratio of the compressive strength of Douglas-fir to the modulus of rupture as found from tests of 2- by 2-inch air-dry beams. Then

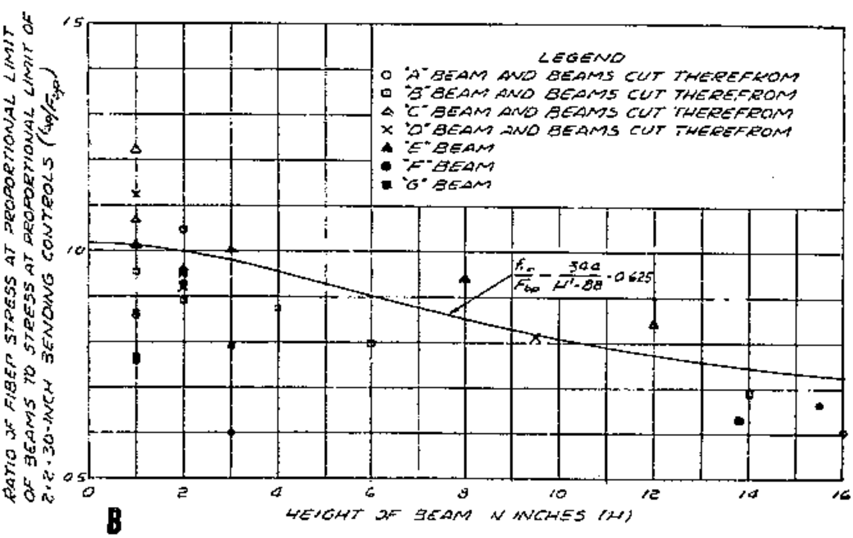
$$R_H = 5/8\,\frac{H^2+143}{H^2+88}\,R_2 \tag{30}$$

where R_2 is the modulus of rupture for height of 2 inches and R_H is modulus of rupture for height H. Also from figure 95:

$$R_H = \frac{H^2+143}{H^2+88}\,C \tag{31}$$



A



B

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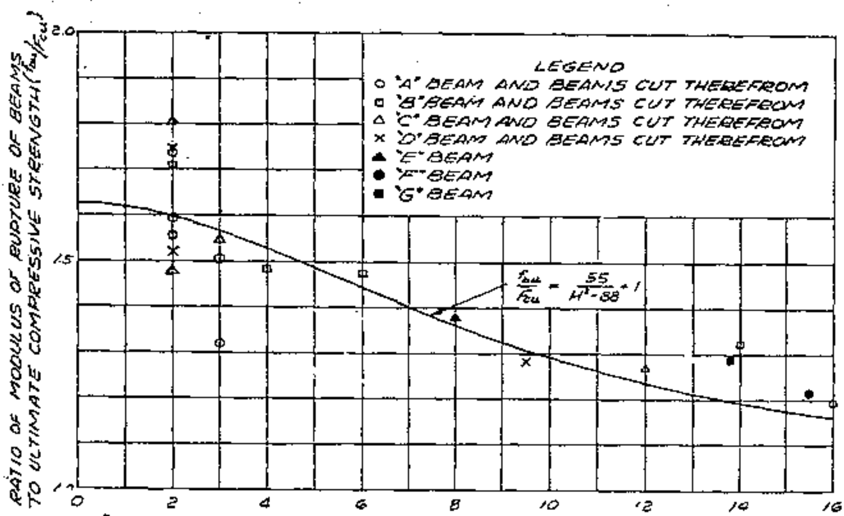
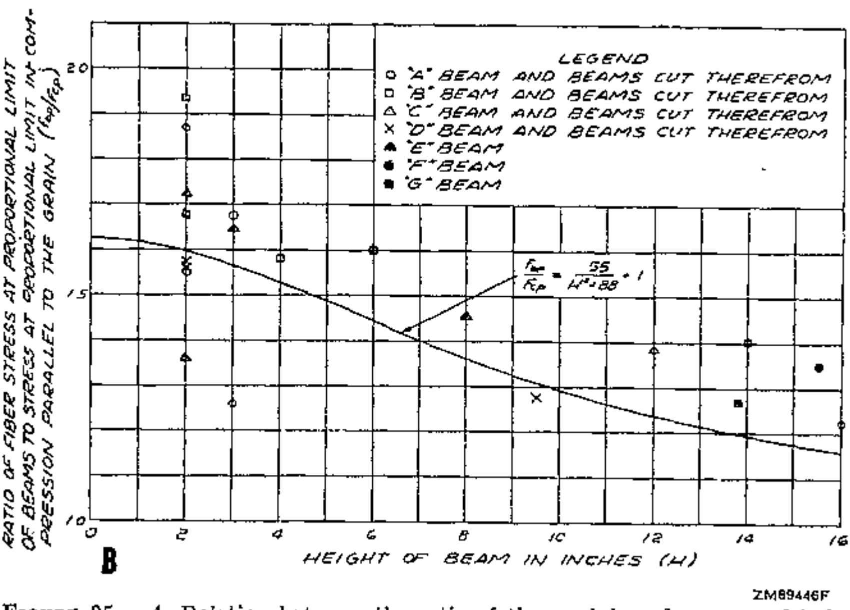
FIGURE 94.—*A*, Relation between the ratio of modulus of rupture of individual beams to the modulus of rupture of 2- by 2- by 30-inch matched bending control beams and the height of the beam. *B*, Relation between the ratio of the fiber stress at proportional limit for the individual beams to the fiber stress at proportional limit of 2- by 2- by 30-inch matched bending control beams and the height of the beam.



A



B

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FIGURE 95.—*A*, Relation between the ratio of the modulus of rupture of individual beams to the compressive strength parallel to the grain of matched control specimens and the height of the beam. *B*, Relation between the ratio of fiber stress at proportional limit for the individual beams to the fiber stress at proportional limit in compression parallel to the grain in matched control specimens and the height of the beam.

This expression for R_H in terms of H and C can be used in the form-factor equation, which becomes

$$R_{HF}=C+(R_H-C)S \tag{32}$$

where R_{HF} is the modulus of rupture of an I- or box beam of any height.

Dividing by R_2,

$$\frac{R_{HF}}{R_2}=\frac{C}{R_2}+\left(\frac{R_H}{R_2}-\frac{C}{R_2}\right)S=F_{hf_2} \tag{33}$$

where F_{hf_2} is the form and height factor for an I- or box beam of height H and R_{HF} equals F_{hf_2} multiplied by R_2.

Using the values of R_H/R_2 and C/R_2 as derived above from the curve of figure 94, the resulting equation is

$$F_{hf_2}=5/8+\left(5/8\,\frac{H^2+143}{H^2+88}-5/8\right)S=5/8\left[1+\left(\frac{H^2+143}{H^2+88}-1\right)S\right] \tag{34}$$

where, as previously stated, F_{hf_2} is the form and height factor for an I-beam or box beam of height H and is the ratio of the modulus of rupture of such a beam to that of a rectangular beam 2 inches high.

The basic flexural stress of table 5, p. 100, is for a height of 12 inches. Hence for use with these stresses a value of F_{hf12} is needed.

By analogy with equation (33)

$$\frac{R_{HF}}{R_{12}}=\frac{C}{R_{12}}+\left(\frac{R_H}{R_{12}}-\frac{C}{R_{12}}\right)S=F_{hf12} \tag{35}$$

From equation (31), $\frac{C}{R_{12}}=\frac{232}{287}$

From equation (30), $\frac{R_H}{R_{12}}=\frac{232}{287}\,\frac{H^2+143}{H^2+88}$

Substituting these values,

$$F_{hf12}=\frac{232}{287}\left[1+\left(\frac{H^2+143}{H^2+88}-1\right)S\right] \tag{36}$$

which is seen to be identical with equation (34) except that 5/8 is replaced by $\frac{232}{287}$, which can without significant error be taken as 0.81, and

$$F_{hf12}=0.81\left[1+\left(\frac{H^2+143}{H^2+88}-1\right)S\right] \tag{37}$$

It may be noted that, for a rectangular beam, S equals 1 and equation (34) reduces to equation (29). Likewise, equation (37) reduces to

$$F_h=0.81\,\frac{H^2+143}{H^2+88}.$$

Inspection of equations (32) and (34) shows that:

1. When S becomes very small, as with shallow flanges, R approaches C as a limit.

2. When H becomes very large, the fraction in which it appears becomes nearly equal to unity and R approaches C as a limit. Thus, because of height and form factors, the value of flexural stress to be used in design never becomes less than the compressive strength.

The formulas for height and form factor and for height factor are based on the assumption of failure in compression, whereas the factors for end joints and for knots provide for any deficiency in tensile strength. Hence, there is no need to apply factors of the two types consecutively.

SUPPORT FACTOR FOR I-BEAMS AND BOX BEAMS

The supporting action that the fibers at various levels give to the extreme fiber in compression has been empirically represented (*5*). A close approximation to this original relation is given by the curve of figure 96 which has the equation

$$\begin{aligned} Y &= (1-x)^2 x \\ &= x - 2x^2 + x^3 \end{aligned} \tag{38}$$

where Y equals the support given to the extreme compression fiber by a fiber at a distance x from the extreme fiber.

The support given to the extreme compression fiber by all the fibers down to a level p will be given by

$$\begin{aligned} \text{Support} &= \int_o^p (x - 2x^2 + x^3) \\ &= \frac{p^2}{2} - \frac{2p^3}{3} + \frac{p^4}{4} \end{aligned} \tag{39}$$

The support given by all the fibers over the full depth, considering the depth equal to unity, will be given by

$$\begin{aligned} \text{Full support} &= \int_o^1 (x - 2x^2 + x^3) \\ &= \frac{1}{2} - \frac{2}{3} + \frac{1}{4} \\ &= 1/12 \end{aligned} \tag{40}$$

$$\begin{aligned} \text{Support factor} = \frac{\text{support}}{\text{full support}} &= \frac{\frac{p^2}{2} - \frac{2p^3}{3} + \frac{p^4}{4}}{\frac{1}{12}} \\ &= 6p^2 - 8p^3 + 3p^4 \\ &= p^2(6 - 8p + 3p^2) \end{aligned} \tag{41}$$

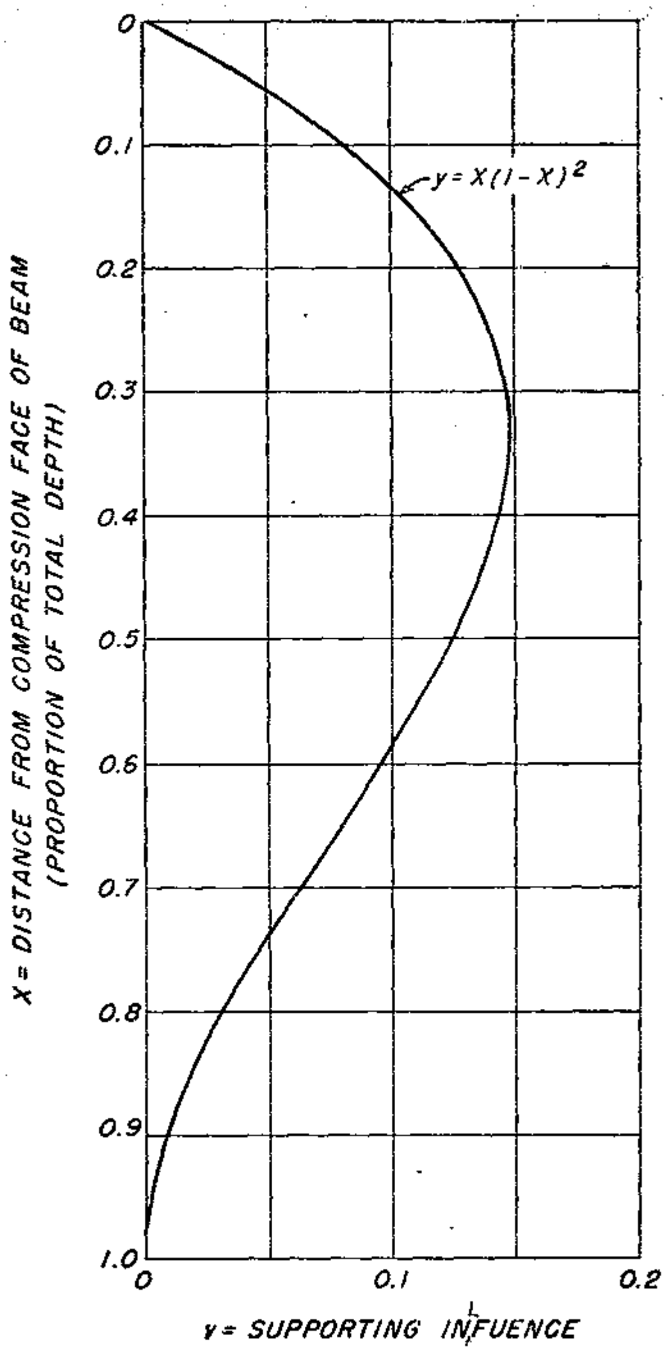

FIGURE 96—Curve of relative supporting influence on extreme fiber in compression of fibers at various points in the depth of a rectangular beam.

In the case of an I-beam (fig. 97), full support will be given over a width equal to that of the web, while partial support, as represented by equation (41), will be given over a width equal to the width of the beam minus the width of the web. Therefore, the support factor for the I-beam (or for a box beam, taking the thickness of the two webs as that over which full support is available) is given by

$$S=p^2(6-8p+3p^2)\ (1-q)+q \tag{42}$$

where S is the support factor, p the ratio of depth of the compression flange to the full depth of the beam, and q the ratio of thickness of the web (or webs) to the full width of the beam.

Relation of Strength Properties to Curvature

Figure 98 presents results from tests of curved laminated members (*28*) plotted against the relative curvature of the laminations. The plotted points represent average and minimum values as determined from end-thrust tests of members built of southern yellow pine and individual results of tests of halves of two large building arches, also of southern yellow pine.

Figure 99 presents the data of figure 98 reduced to a percentage of the strength of straight members, and includes also the results of similar tests of Sitka spruce and Douglas-fir members. The results for the smallest relative curvature (0.00125, fig. 99) were taken as the base for the southern yellow pine members, while the results for straight members matched to the curved members were taken as the base for the Sitka spruce and Douglas-fir members.

The curves shown in figures 98 and 99 are essentially identical. In placing them, consideration was given to the plotted points of these figures, to the number of tests represented by each plotted point, and to other pertinent information. Furthermore, more weight has been given to the values at the proportional limit than to those at the maximum moment. It had been found that the full ultimate bending strength at the section of maximum curvature had not been developed in the tests of the half-arches. Consequently, the points representing these arches in the upper part of figure 98 are too low.

If half-arch D–2 alone is considered, the curve for the proportional-limit values in figure 98 would seem to be too high. The value for arch D–2 is counterbalanced, however, by values representing nearly as great curvature and lying, in general, well above the curve in figure 99.

The arches were of various heights, so that the results would have been somewhat more comparable if each value had been divided by its appropriate height factor. In many of the tests, however, the variation in height was small enough for such a procedure to make no large differences. For the half-arches, an upward adjustment of about 10 percent would make the results more comparable to those from the other tests and would bring the points representing such tests considerably nearer the curve.

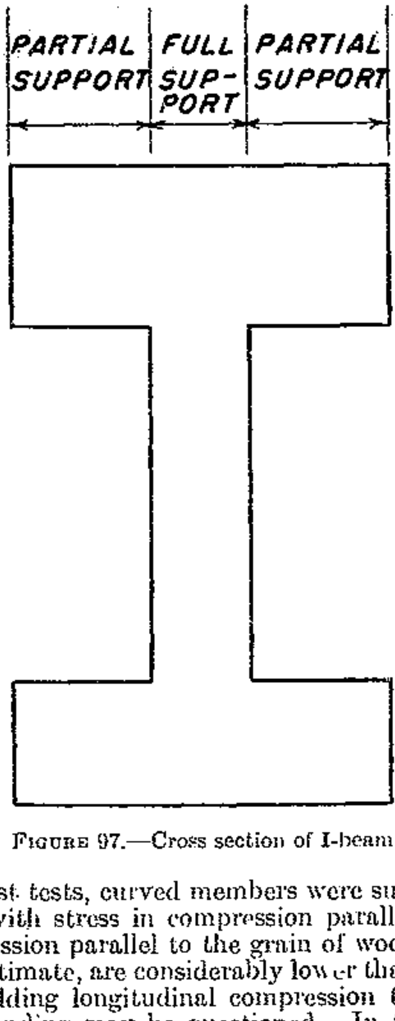

FIGURE 97.—Cross section of I-beam

In the end-thrust tests, curved members were subjected to bending stress combined with stress in compression parallel to grain. Since stresses in compression parallel to the grain of wood, both at proportional limit and ultimate, are considerably lower than bending stresses, the validity of adding longitudinal compression to the compression resulting from bending may be questioned. In the tests, however, the bending stress had been from 78 to 98 percent of the total; and a previous investigation has shown that within this range the combined stress is not significantly lower than bending stress alone at either proportional limit or ultimate.

Some share of the increased deficiency of strength with increased curvature has come from the use of equations for computing stress that are applicable to straight members, but which give results somewhat in error when applied to deep, sharply curved members. The indications are, however, that this has been a relatively small factor in the tests reported, so that the larger share of the deficiency shown results from stresses induced in bending the laminations to form.

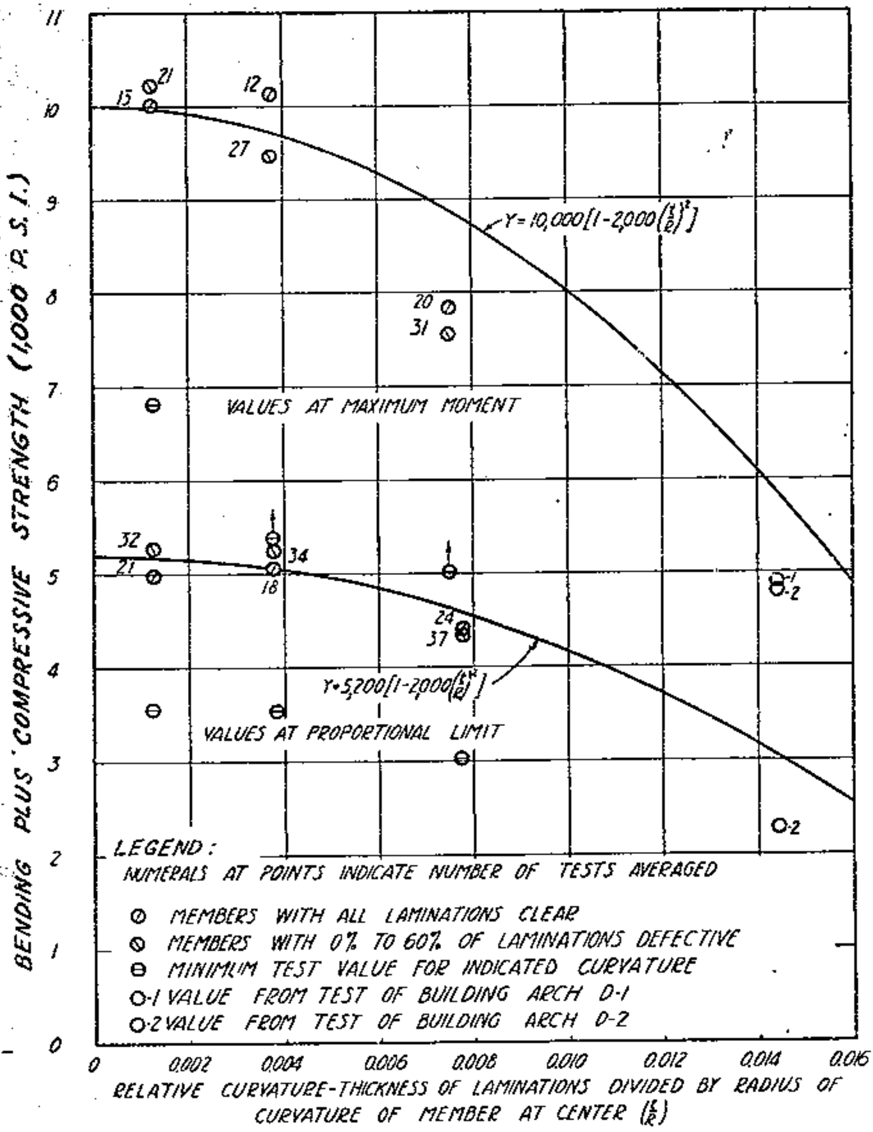

FIGURE 98.—Strength of laminated members of southern yellow pine as related to curvature.

STRENGTH OF GLUED LAMINATED CONSTRUCTION MADE OF THIN VENEERS

During World War II, the shortage of Sitka spruce suitable for solid wing spars in aircraft or for spars laminated from sawed lumber prompted an investigation (*11*) of the feasibility of laminating spars and spar flanges from veneer, so as to avoid some waste in sawdust and shavings. Included in the investigation were studies of the

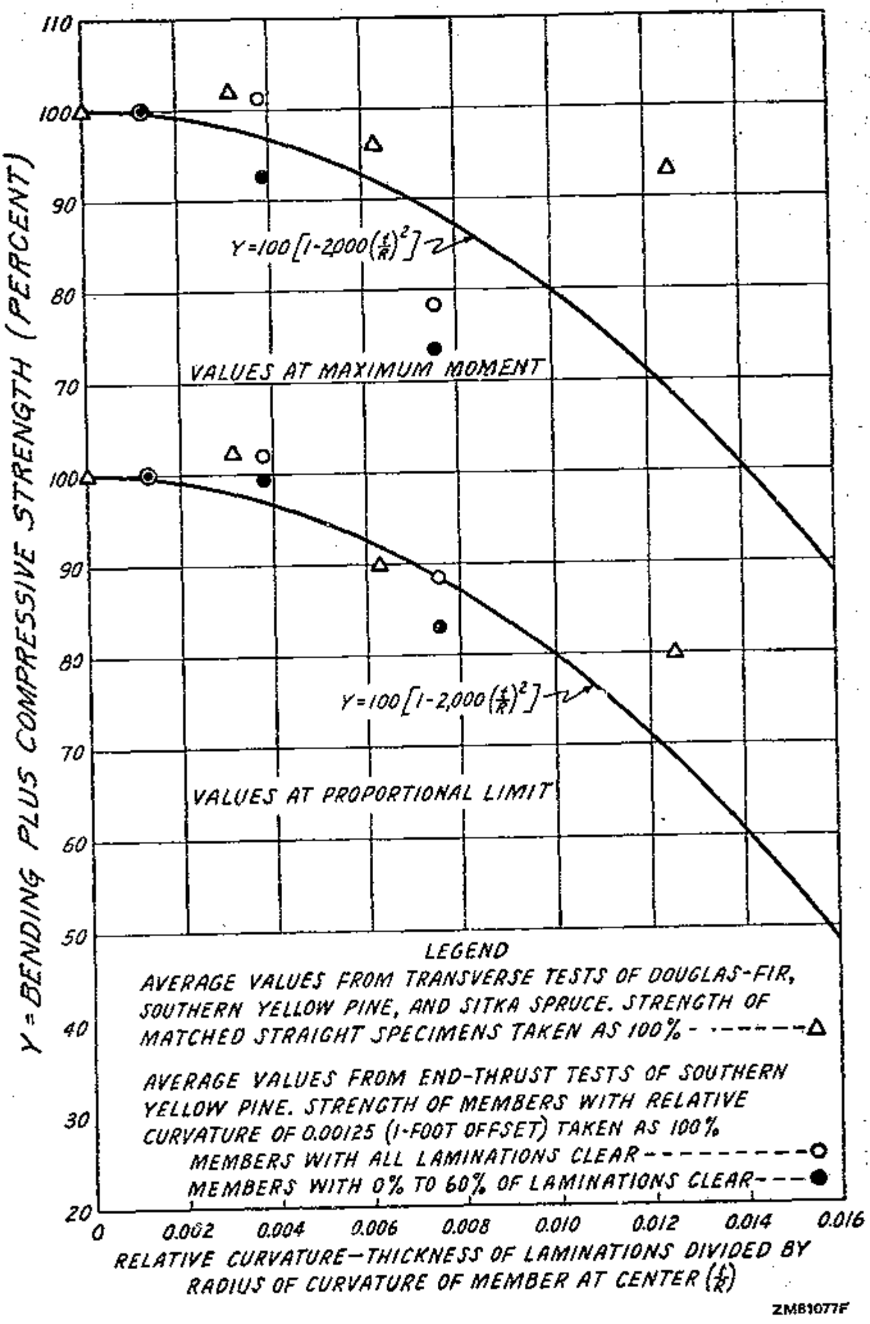

FIGURE 99.—Strength of laminated members as related to curvature

strength of such material and of the effect on strength of cross grain, scarf joints, and the orientation of laminations. The results of this investigation are presented in tables 20 through 23.

The veneer was fabricated into 2-inch-thick stock, most of which was straight-grained and made with continuous laminations. Some was purposely fabricated with the grain slopes in adjacent plies crossed, so as to make planks with grain sloping at 1 in 10 or 1 in 15. Other planks were made from straight-grained veneer with scarf joints having a slope of 1 in 15 in alternate laminations.

The liquid glue, together with possible slight densification of the wood from the pressure applied in gluing, added about 7 percent to the unit weight of the laminated material.

The tests included static and impact bending, compression parallel to grain, and toughness.

In these tests the straight-grained laminated Sitka spruce gave average values essentially similar to averages from previous tests on solid Sitka spruce (table 20), except that in work values in static bending, a measure of shock resistance, the laminated stock was definitely lower than the solid. This exception was not, however, confirmed by impact-bending and toughness tests, which are also measures of shock resistance.

Whether straight-grained or cross-grained, beams tested with laminations vertical were essentially as strong as beams tested with laminations horizontal, except for height of drop in impact bending and work in static bending (table 21), in both of which they were consistently lower. The tests, therefore, confirmed previous conclusions that a given slope of grain has the same effect regardless of the orientation of the plane in which the slope lies.

Laminated material with grain sloped 1 in 15 showed no significant deficiency, as compared to similar straight-grained material, in those strength properties used in aircraft design (table 22). Deficiency in work values in static bending is apparent, and particularly so for specimens tested with third-point loading, wherein the stress is constant between the two load points. That this deficiency is corrobated neither by toughness nor impact-bending values is very possibly due to the fact that these tests were made only with center loading.

Strength values of laminated material with grain sloped 1 in 10 were not sufficiently high to justify use of such material in parts that are highly stressed in compression, or bending (table 22), or in tension parallel to the grain (considering modulus of rupture values in table 22).

It has frequently been thought that, by interlacing the grain (reversing grain slope in adjacent laminations) in stock built up from thin laminations, the deleterious effects of cross grain on such properties as bending and tension could be overcome and wood with steep grain slopes could be made equal to straight-grained material. This was not confirmed by these tests. It was, however, definitely indicated that, under flexure (as in static- or impact-bending or toughness tests) beams with grain sloping oppositely in adjacent laminations were superior to those with grain oriented throughout at the same slope.

Beams with glued scarf joints at a slope of 1 in 15 in alternate laminations and at the same point in the length were deficient as compared to beams with all laminations continuous (table 23). The reduction was particularly large in those properties indicative of shock resistance. The low value of joint efficiency resulting from tension tests of scarfed and unscarfed veneer strips and the consistent failure of the test specimens in the scarf joints indicated that the gluing technique could have been improved. Scarf joints are being successfully used in aircraft parts formed of sawed laminations. Rotary-cut veneers, because they are thinner, afford opportunity for better joint distribution than the thicker sawed material; and, for this reason, the effect of a jointed lamination at the tension face of a member stressed in bending would be less.

The general conclusion is that, on the basis of strength values, Sitka spruce laminated from rotary-cut veneer is satisfactory as an alternate to solid members or members laminated from sawn veneer, provided the same requirements for straightness of grain and limitation of defects are observed.

Concentration of Shear Strain Near Load Points of Beams

Strain measurements on one beam indicated that shear strain is highly concentrated in the vicinity of points of load application. Figure 100 shows the distribution of shear strain as determined both by strain measurements and from theoretical considerations. In addition to evidencing strains far higher than those that would be computed by the usual methods, the distribution is considerably different, in that the larger strains are located near the surface of the beam to which load is applied rather than at the neutral surface. In addition, the data indicate that shear exists between load points, whereas the usual theory indicates no shear in this zone.

This matter needs further exploration, but it may serve as at least a partial explanation of why failures of beams in horizontal shear are ordinarily at computed values (using the usual assumptions) much lower than are found in shear tests of small clear specimens. It may serve also to explain, in part, the results of tests of beams containing butt joints near the upper surface and close to the loading blocks (fig. 73).

Shear concentration as described above, together with that exisiting solely because of the presence of butt joints, may, in combination, result in shear failures. It appears desirable to keep butt joints, if used, well away from any concentrated load on a beam.

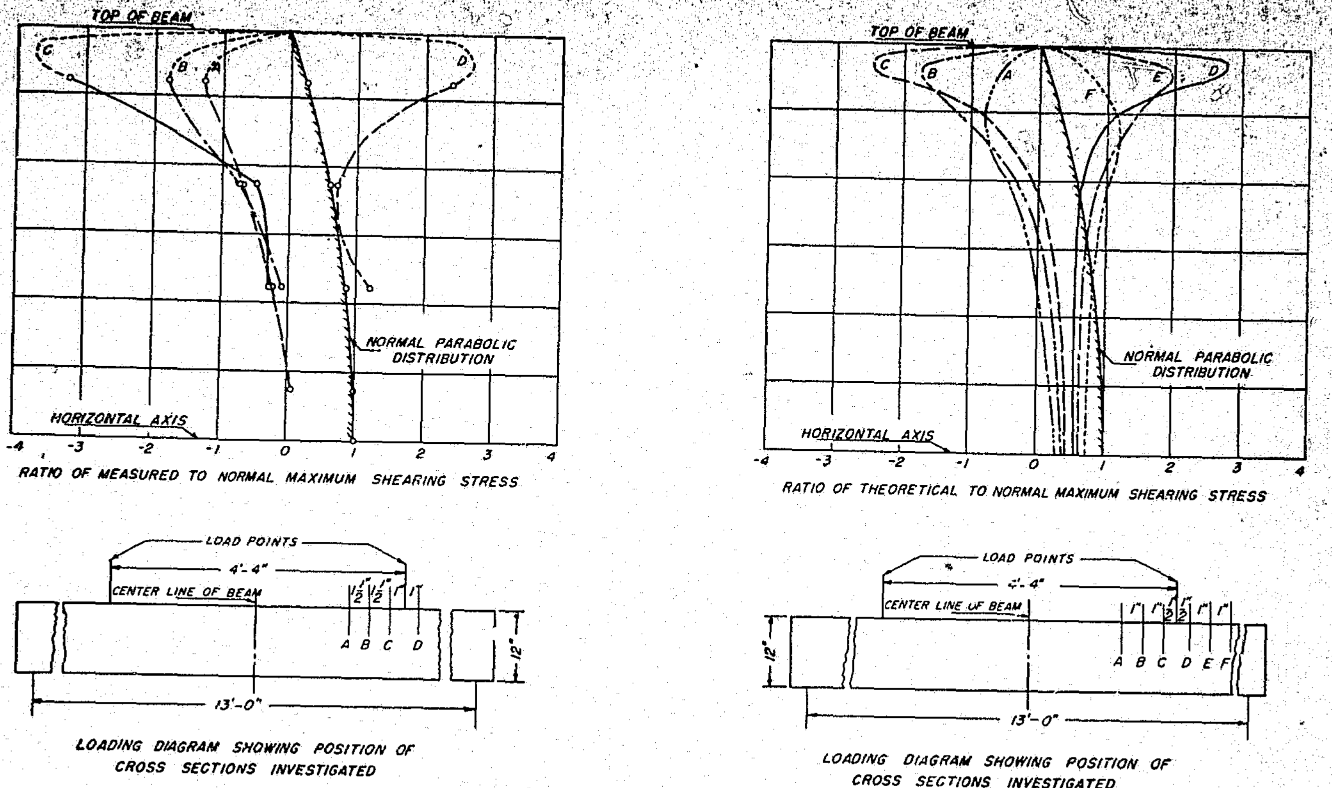

FIGURE 100.—Distribution of measured strains (left) and of strains computed from more precise theory (right) compared to the usual assumption of parabolic distribution.

TABLE 20.—*Strength of laminated Sitka spruce*[1] *compared to that of solid material*

Kind of beam	Static bending						Impact bending	Compression parallel to grain			Toughness		Shear parallel to grain
	Stress at proportional limit	Modulus of rupture	Modulus of elasticity	Work: Proportional limit	Work: Maximum load	Work: Total	Height of drop causing complete failure (50-pound hammer)	Stress at proportional limit	Maximum crushing strength	Modulus of elasticity	Loaded on radial face	Loaded on tangential face	Maximum shearing strength
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	P. s. i.	*P. s. i.*	*1,000 p. s. i.*	*In.-lb. per cu. in.*	*In.-lb. per cu. in.*	*In.-lb. per cu. in.*	*Inches*	*P. s. i.*	*P. s. i.*	*1,000 P. s. i.*	*In.-lb. per specimen*[2]	*In.-lb. per specimen*[2]	*P. s. i.*
Laminated [3]	6, 620	11, 500	1, 788	1. 36	8. 52	12. 24	24. 9	4, 520	6, 590	2, 022	86. 8	154. 5	1, 200
Solid [4]	6, 700	10, 200	1, 570	1. 62	9. 4	17. 2	25. 0	4, 780	5, 610	-------	73. 5	113. 4	1, 150
Solid [4 5]	7, 340	11, 000	1, 620	1. 88	9. 9	17. 0	25. 0	5, 260	6, 180	-------	[6] 86. 0	[6] 131. 0	1, 190
	Ratios of laminated to solid material (percent)												
	90	104	110	72	86	72	100	86	106	-------	101	118	101

[1] Based on 40 tests for static and impact bending, 37 for compression parallel to grain, 80 for toughness in each direction, 152 for shear. Moisture content at test was approximately 10 percent. Specific gravity, based on weight when oven-dry and volume at test, was approximately 0.41, excluding the weight of the glue.

[2] Specimens ⅝ by ⅝ by 10 inches, tested over an 8-inch span, center loading.

[3] Averages include values from static-bending and impact-bending specimens, irrespective of whether laminations were horizontal or vertical.

Of the 40 static-bending specimens, 26 were tested under center loading and 14 under third-point loading. Averages for work properties include only values from specimens tested under center loading.

[4] Data from U. S. Dept. Agr. Tech. Bul. 479, "Strength and Related Properties of Woods Grown in the United States," except toughness values.

[5] Adjusted to correspond to the moisture content of laminated material.

[6] Adjusted for specific gravity, assuming toughness varies as 2½ power of specific gravity. No reliable method of adjusting for moisture differences is available.

TABLE 21.—*Bending strength of Sitka spruce beams with laminations horizontal compared to that of beams with laminations vertical*

Direction of grain	Orientation of laminations	Static bending									Impact bending			
		Tests	Moisture content	Specific gravity[1] excluding glue	Stress at proportional limit	Modulus of rupture	Modulus of elasticity	Work			Tests	Moisture content	Specific gravity[1] excluding glue	Height of drop causing complete failure (50-pound hammer)
								Proportional limit	Maximum load	Total				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
		Number	*Percent*		*P. s. i.*	*P. s. i.*	*1,000 p. s. i.*	*In.-lb. per cu. in.*	*In.-lb. per cu. in.*	*In.-lb. per cu. in.*	*Number*	*Percent*		*Inches*
Straight	Vertical	8	10	0. 407	6, 720	11, 580	1, 763	1. 43	8. 39	11. 16	10	10	0. 408	24. 2
	Horizontal	6	10	. 404	6, 160	11, 480	1, 769	1. 22	8. 28	13. 66	10	10	. 405	26. 6
1:15 parallel	Vertical	8	10	. 405	6, 350	10, 710	1, 661	1. 36	6. 61	12. 01	10	10	. 407	25. 8
	Horizontal	6	10	. 405	6, 240	10, 920	1, 646	1. 33	7. 89	12. 42	10	10	. 405	26. 0
1:15 crossed	Vertical	8	10	. 415	6, 400	11, 340	1, 804	1. 27	6. 60	10. 33	10	10	. 412	23. 2
	Horizontal	6	10	. 414	6, 690	11, 730	1, 764	1. 42	9. 09	12. 51	10	10	. 401	26. 4
Straight	Vertical	7	9	. 408	6, 620	11, 850	1, 774	1. 38	8. 53	11. 76	10	10	. 408	24. 0
	Horizontal	5	9	. 412	6, 530	11, 970	1, 770	1. 35	8. 91	12. 91	10	10	. 408	24. 8

1:10 parallel	Vertical	7	9	.407	6,230	10,070	1,529	1.42	5, 19	11.04	10	10	.406	21.6
	Horizontal	5	9	.411	6,190	11,260	1,567	1.36	7.25	11.29	10	10	.405	23.2
1:10 crossed	Vertical	7	10	.413	6,780	11,080	1,765	1.46	6.28	10.30	10	10	.410	21.4
	Horizontal	5	10	.415	6,840	10,790	1,702	1.53	6.12	12.14	10	10	.403	23.6
Ratios [2] of horizontal to vertical laminations (percent)														
Straight	------	------	102	99	92	99	100	85	99	122	------	100	99	110
1:15 parallel	------	------	100	100	98	102	99	98	119	103	------	99	100	101
1:15 crossed	------	------	103	100	105	103	98	112	138	121	------	101	97	114
Straight	------	------	96	101	99	101	100	98	104	110	------	99	100	103
1:10 parallel	------	------	98	101	99	112	102	96	140	102	------	100	100	107
1:10 crossed	------	------	100	100	101	97	96	105	98	118	------	98	98	110

[1] Based on oven-dry weight and volume at test.
[2] These ratios are based on actual moisture content, not on figures rounded off to nearest percent as indicated in upper part of table.

TABLE 22.—*Sitka spruce beams composed of laminations with slopes of grain of 1 in 15 and 1 in 10, compared to beams with straight-grained laminations* [1]

Direction of grain	Orientation of laminations (static and impact bending)	Method of loading (static and impact bending)	Static bending: Stress at proportional limit	Static bending: Modulus of rupture	Static bending: Modulus of elasticity	Static bending: Work (center-load tests): Proportional limit	Static bending: Work (center-load tests): Maximum load	Static bending: Work (center-load tests): Total	Static bending: Work (⅓-point load tests): Proportional limit	Static bending: Work (⅓-point load tests): Maximum load	Static bending: Work (⅓-point load tests): Total	Impact bending: Height of drop causing complete failure (50-pound hammer)	Toughness: Loaded on radial face	Toughness: Loaded on tangential face	Compression parallel to grain: Stress at proportional limit	Compression parallel to grain: Maximum crushing strength	Compression parallel to grain: Modulus of elasticity
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
			P. s. i.	*P. s. i.*	*1,000 p. s. i.*	*In.-lb. per cu. in.*	*In.-lb. per cu. in.*	*In.-lb. per cu. in.*	*In.-lb. per cu. in.*	*In.-lb. per cu. in.*	*In.-lb. per cu. in.*	*Inches*	*In.-lb. per specimen* [2]	*In.-lb. per specimen* [2]	*P. s. i.*	*P. s. i.*	*1,000 p. s. i.*
Straight	Vertical	Center	6,720	11,580	1,763	1.43	8.39	11.16				24.2	86.1	155.5	4,820	6,670	1,981
	do	⅓ point	6,860	11,480	1,861				2.36	14.16	21.49		95.5	157.9	4,340	6,420	2,088
	Horizontal	Center	6,160	11,480	1,769	1.22	8.28	13.66				26.6	85.7	154.7	4,490	6,700	2,101
Average			6,590	11,520	1,794	1.34	8.34	12.23				25.4	87.4	155.5	4,630	6,640	2,039
1:15 parallel	Vertical	Center	6,350	10,710	1,661	1.36	6.61	12.01				25.8	93.3	158.0	4,280	6,440	1,885
	do	⅓ point	6,440	10,280	1,686				2.28	9.57	12.97		95.8	143.3	4,110	6,300	1,981
	Horizontal	Center	6,240	10,920	1,646	1.33	7.89	12.42				26.0	92.4	154.8	4,410	6,270	1,998
Average			6,340	10,640	1,664	1.35	7.16	12.19				25.9	93.3	154.5	4,300	6,360	1,942
1:15 crossed	Vertical	Center	6,400	11,340	1,804	1.27	6.60	10.33				23.2	82.6	145.6	4,910	6,660	1,960
	do	⅓ point	6,360	10,740	1,815				2.12	10.53	15.31		89.1	158.9	4,540	6,200	1,980
	Horizontal	Center	6,690	11,730	1,764	1.42	9.09	12.51				26.4	85.5	155.8	4,880	6,730	1,964
Average			6,480	11,280	1,795	1.33	7.67	11.26				24.8	84.7	151.7	4,840	6,620	1,965
Straight	Vertical	Center	6,620	11,850	1,774	1.38	8.53	11.76				24.0	87.9	162.9	4,500	6,600	1,988

	do	⅓ point	6,740	10,870	1,796				2.37	12.44	19.58		88.5	129.4	4,440	6,320	2,071
	Horizontal	Center	6,530	11,970	1,770	1.35	8.91	12.91				24.8	83.4	151.6	4,280	6,630	1,977
Average			6,650	11,490	1,782	1.37	8.69	12.24				24.4	86.2	153.4	4,420	6,540	2,006
1:10 parallel	Vertical	Center	6,230	10,070	1,529	1.42	5.19	11.04				21.6	84.8	133.2	4,520	6,210	1,765
	do	⅓ point	6,210	9,170	1,599				2.24	7.05	10.98		80.2	128.2	4,100	5,820	1,835
	Horizontal	Center	6,190	11,260	1,567	1.36	7.25	11.29				23.2	80.9	124.2	4,240	6,220	1,778
Average			6,210	10,000	1,567	1.40	6.05	11.14				22.4	82.6	128.9	4,330	6,100	1,788
1:10 crossed	Vertical	Center	6,780	11,080	1,765	1.46	6.28	10.30				21.4	84.9	140.3	4,300	6,360	1,976
	do	⅓ point	6,400	10,120	1,718				2.22	9.92	14.00		85.2	145.4	3,950	6,320	2,034
	Horizontal	Center	6,840	10,790	1,702	1.53	6.12	12.14				23.6	81.0	141.2	4,300	6,580	1,920
Average			6,640	10,620	1,730	1.49	6.21	11.07				22.5	83.4	141.4	4,210	6,430	1,971
	Ratios of sloping to straight grain (percent)																
1:15 parallel			96	92	93	101	86	100	97	68	60	102	107	99	93	96	95
1:15 crossed			98	98	100	99	92	92	90	74	71	98	97	98	105	100	96
1:10 parallel			93	87	88	102	70	91	95	57	56	92	96	84	98	93	89
1:10 crossed			100	92	97	109	71	90	94	80	72	92	97	92	95	98	98

[1] Each value based on from 5 to 18 tests. Moisture content at test approximately 10 percent; specific gravity, based on weight when oven-dry and volume at test, approximately 0.41, excluding the weight of the glue.

[2] Specimens ⅝ by ⅝ by 10 inches, tested over an 8-inch span, center loading.

Table 23.—*Sitka spruce beams with scarf joints (slope 1:15) in alternate laminations compared to beams with all laminations continuous* [1]

Type of specimen	Orientation of laminations	Static bending [2]						Impact bending [2]
		Stress at proportional limit	Modulus of rupture	Modulus of elasticity	Work: Proportional limit	Work: Maximum load	Work: Total	Height of drop causing complete failure (50-pound hammer)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
		P. s. i.	*P. s. i.*	*1,000 p. s. i.*	*In.-lb. per cu. in.*	*In.-lb. per cu. in.*	*In.-lb. per cu. in.*	*Inches*
With scarf joints	Vertical	6, 160	10, 380	1, 745	1. 21	5. 71	7. 61	20. 0
Without scarf joints (matching one end). [3]	do	6, 270	11, 120	1, 771	1. 24	7. 93	11. 13	24. 8
Without scarf joints (matching other end).	do	6, 560	11, 000	1, 775	1. 35	7. 49	10. 66	24. 4
Average		6, 420	11, 060	1, 773	1. 30	7. 71	10. 90	24. 6
With scarf joints	Horizontal	5, 940	8, 910	1, 738	1. 14	4. 05	7. 95	20. 4
Without scarf joints (matching one end). [3]	do	6, 170	11, 040	1, 793	1. 19	7. 31	13. 01	27. 6
Without scarf joints (matching other end).	do	6, 350	11, 240	1, 762	1. 27	8. 61	12. 27	26. 4
Average		6, 260	11, 140	1, 778	1. 23	7. 96	12. 64	27. 0
	Ratios of jointed to continuous laminations (percent)							
	Vertical	96	94	98	93	74	70	81
	Horizontal	95	80	98	93	51	63	76

[1] Five specimens of each type were tested at about 10-percent moisture content, and at 0.39 specific gravity, based on oven-dry weight and volume at test.

[2] Failures at scarf joints were very largely in the wood.

[3] A control specimen adjacent to each end of each beam containing scarf joints was tested.

INDEX

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END