LAMINATING OF STRUCTURAL WOOD PRODUCTS BY GLUING

Revised October 1948

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
FOREST PRODUCTS LABORATORY
Madison 5, Wisconsin

In Cooperation with the University of Wisconsin
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Historical background</td>
<td>2</td>
</tr>
<tr>
<td>Scope</td>
<td>3</td>
</tr>
<tr>
<td>Advantages of glued laminated wood construction</td>
<td>3</td>
</tr>
<tr>
<td>Economic limitations of laminating process</td>
<td>4</td>
</tr>
<tr>
<td>Performance required of glue joints in laminated construction</td>
<td>5</td>
</tr>
<tr>
<td>Glued laminated products for service under normally dry conditions</td>
<td>5</td>
</tr>
<tr>
<td>Glued laminated products for service under moist or wet conditions including exterior exposure</td>
<td>6</td>
</tr>
<tr>
<td>Properties and use characteristics of woodworking glues</td>
<td>6</td>
</tr>
<tr>
<td>Casein glues</td>
<td>8</td>
</tr>
<tr>
<td>Urea-formaldehyde-resin glues</td>
<td>9</td>
</tr>
<tr>
<td>Phenol-formaldehyde-resin glues</td>
<td>12</td>
</tr>
<tr>
<td>Hot-setting phenol-resin glues</td>
<td>12</td>
</tr>
<tr>
<td>Intermediate-temperature-setting (modified) phenol-resin glues</td>
<td>13</td>
</tr>
<tr>
<td>Resorcinol-formaldehyde-resin glues</td>
<td>14</td>
</tr>
<tr>
<td>Melamine-formaldehyde-resin glues</td>
<td>15</td>
</tr>
<tr>
<td>Selection of glues for laminating</td>
<td>17</td>
</tr>
<tr>
<td>Selection and preparation of lumber for laminating</td>
<td>17</td>
</tr>
<tr>
<td>Species and grades</td>
<td>18</td>
</tr>
<tr>
<td>Seasoning and moisture content of lumber</td>
<td>18</td>
</tr>
<tr>
<td>Storage of lumber</td>
<td>20</td>
</tr>
<tr>
<td>Rough surfacing</td>
<td>20</td>
</tr>
<tr>
<td>Cutting out defects</td>
<td>21</td>
</tr>
<tr>
<td>Selection for grain</td>
<td>21</td>
</tr>
<tr>
<td>Cutting laminating stock</td>
<td>22</td>
</tr>
<tr>
<td>Final surfacing</td>
<td>24</td>
</tr>
</tbody>
</table>

Report No. D1635
<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layout of laminated assembly</td>
<td>25</td>
</tr>
<tr>
<td>Location of edge and end joints</td>
<td>26</td>
</tr>
<tr>
<td>Straight members</td>
<td>26</td>
</tr>
<tr>
<td>Curved members</td>
<td>27</td>
</tr>
<tr>
<td>Gluing jigs and forms</td>
<td>28</td>
</tr>
<tr>
<td>Gluing of edge and end joints</td>
<td>30</td>
</tr>
<tr>
<td>Edge joints</td>
<td>30</td>
</tr>
<tr>
<td>End joints</td>
<td>31</td>
</tr>
<tr>
<td>Gluing laminated assemblies</td>
<td>32</td>
</tr>
<tr>
<td>Mixing and preparing glue</td>
<td>32</td>
</tr>
<tr>
<td>Spreading glue</td>
<td>34</td>
</tr>
<tr>
<td>Moisture added to wood in gluing</td>
<td>35</td>
</tr>
<tr>
<td>Assembling laminations</td>
<td>36</td>
</tr>
<tr>
<td>Assembly period</td>
<td>37</td>
</tr>
<tr>
<td>Gluing pressure</td>
<td>37</td>
</tr>
<tr>
<td>Equipment for applying gluing pressure</td>
<td>38</td>
</tr>
<tr>
<td>Cauls and clamp spacing</td>
<td>39</td>
</tr>
<tr>
<td>Measuring gluing pressure</td>
<td>40</td>
</tr>
<tr>
<td>Clamping technique for straight and curved members</td>
<td>41</td>
</tr>
<tr>
<td>Curing the glue in laminated assemblies</td>
<td>41</td>
</tr>
<tr>
<td>Members glued with casein</td>
<td>42</td>
</tr>
<tr>
<td>Members glued with urea resin</td>
<td>42</td>
</tr>
<tr>
<td>Members glued with intermediate-temperature-setting phenol, resorcinol, and melamine resins</td>
<td>43</td>
</tr>
<tr>
<td>Methods of heating clamped assemblies</td>
<td>44</td>
</tr>
<tr>
<td>Heated curing chambers</td>
<td>45</td>
</tr>
<tr>
<td>Radiant heating</td>
<td>45</td>
</tr>
<tr>
<td>High-frequency heating</td>
<td>45</td>
</tr>
<tr>
<td>Rate of heating in large assemblies</td>
<td>46</td>
</tr>
<tr>
<td>Humidification of heated chambers</td>
<td>47</td>
</tr>
<tr>
<td>Operation of curing chamber</td>
<td>48</td>
</tr>
</tbody>
</table>

Report No. D1635

-11-
Plant and machinery requirements for a laminating operation

Plant space .................................................. 50
Dry kilns ...................................................... 51
Storage buildings ........................................... 51
Sawing and jointing equipment ........................... 51
Edge- and scarf-joint gluing equipment ................ 51
Surfacing equipment ....................................... 52
Glue storage, mixing, and spreading equipment ....... 52
Gluing jigs, forms, clamps, and handling equipment 52
Curing chambers ............................................ 53
Equipment for surfacing glued products ............... 55

Control instruments ........................................ 55

Methods of evaluation of product ......................... 56
Quality of materials ........................................ 56
Testing glue-joint strength and quality ................ 56
Members for continuously dry use ...................... 57
Members for exterior use ................................ 57

Preservative treatments of laminated wood and gluing 59
of treated wood ............................................... 59

Examples of laminated construction ..................... 60
European uses .............................................. 60
American uses ............................................. 61

Literature cited ............................................ 62
LAMINATING OF STRUCTURAL WOOD PRODUCTS BY GLUING

By
A. C. KNAUSS, Technologist
and
M. L. SELBO, Chemical Engineer
Forest Products Laboratory, Forest Service
U. S. Department of Agriculture

Introduction

Bonding wood with glue is an old art that has made possible the fabrication of wood products in various forms and shapes to serve many purposes. The usefulness of glued wood products has in general been dependent on the strength imparted to them by the glue and on the ability of the glue to maintain such strength in service. The development of improved glues has increased the serviceability of conventional glued wood products and provided an opportunity for using wood for many new purposes. The recently developed highly water-resistant resins have made possible the production of laminated wood suitable for use under severe service conditions, including exterior exposure. Durable glues, however, are not all that are required to produce good laminated members. Properly prepared wood, suitable equipment, technical knowledge, and skill are also important.

A glued laminated wood product is here defined as a product built up of plies or laminations of wood joined with an adhesive so that the grain of all plies is generally parallel.

Acknowledgment is made to Gamble Bros., Inc., Louisville, Ky.; Speedwall Division of Timber Structures, Inc., Seattle, Wash.; and Summerbell Roof Structures, Los Angeles, Calif., for making available for use in this report photographs of several of their laminating operations and products.

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

Report No. D1635
Historical Background

Typical examples of structural glued laminated members are laminated wood arches and trusses in some auditoriums, gymnasiums, hangars, and other buildings. The first examples of this construction are found in Europe, where it is reported that, as early as 1907, casein glue was used in laminating arches from dry softwood lumber (1). Many of the early European installations are in satisfactory condition and use today.

Following the further development of commercial casein glues during World War I, laminating of structural arches and trusses by gluing was undertaken in the United States in 1934, when a number of three-hinged arches were fabricated and installed in a building erected for the Forest Products Laboratory at Madison, Wis. (fig. 1). This installation was followed by many others in gymnasiums, churches, halls, factories, shops, and hangars, in which arches of softwood lumber were glued with casein. In both Europe and the United States such glued construction was used satisfactorily where protected from weather and moisture. The present excellent condition of many such installations demonstrates the suitability of glued laminated construction where the glue and the wood are durable under the service conditions to which they are exposed.

The tremendous demands of World War II for heavy timbers for military and industrial use hastened the development of laminated wood products (fig. 2), 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, such as boat keels and framing, bridge timbers, spuds for dredges, and truck-body framing, were needed for use under exterior or wet exposure conditions where casein glue would not be durable.

Synthetic resins of the urea-formaldehyde type had been developed in the 1930's. Since some of the urea-formaldehyde adhesives could be used at room temperatures and were superior to casein glues in water resistance, they were believed to be applicable to laminating. When they were tried for laminating oak lumber into boat keels, however, they did not withstand the service conditions imposed. In 1942 attention was turned to the use of the newly developed intermediate-temperature-setting phenol resins for laminating white oak ship keels and frames. Sponsored by the Bureau of Ships in the Navy Department and by the Office of Production Research and Development in the War Production Board, experimental work on the application and performance of these glues was undertaken at the Forest Products Laboratory and at two commercial pilot plants, Gamble Bros., Inc.,

\[2\]

The numbers in parentheses refer to the Literature Cited at the end of this report.

Report No. D1635 -2-
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 of this work, procedures have been developed for fabricating laminated members the bonding of which is capable of withstanding all exposures that the wood itself can withstand.

Scope

The purpose of this report is to describe 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 best-known procedures for the laminating operation.

This report is intended for producers, users, and others interested in structural laminated wood members and products such as glued arches, truss members, rafters, beams, and posts used for the interior framing of buildings; in glued stems, keels, sternposts, shaft logs, frames, stringers, knees, and transoms for the construction of wood boats; in glued stringers, caps, and posts for bridges; and guides for mineshafts. In general, the report also applies to glued core stock, furniture parts, hammer boards, vehicle frames, parts for agricultural implements, and other glued wood products.

The information presented in this report is based on research and technical experience in the manufacture of glued laminated lumber. Such information may be modified as additional adhesives and techniques for using them become available.

Advantages of Glued Laminated Wood Construction

The more important advantages of laminated construction may be described as follows:

a. When laminated members are glued from dry lumber, such members will not generally undergo further drying and shrinkage in use under normally dry conditions. Hence, there is little opportunity for development of loosened fastenings and connections, checking, splitting, and other defects that accompany shrinkage during seasoning of green solid timbers. Use of dry members will reduce shipping weight and maintenance cost.

b. Laminated members can be produced in thoroughly dry condition in a relatively short time, whereas dry solid timbers, depending upon their size, require weeks or months of seasoning.
c. Laminated members can be produced from relatively narrow lumber by edge gluing to increase width, and from short lengths of lumber by end jointing to increase length. Thus, laminated members can be built to larger cross sections and greater lengths than are otherwise readily available or than can be conveniently shipped over long distances. The use of wood in short lengths and narrow widths permits more complete utilization of saw timber and of smaller and otherwise unmerchantable trees.

d. Laminated members can be produced in special shapes, such as those of curved arches, top chord members for bowstring trusses, and curved boat framing, to provide generally improved strength properties. Compared to timbers of solid wood, they usually reduce the weight and volume of wood required for such uses, and the glue sometimes replaces much hardware and connections that are necessary when using solid timbers. In curved form and other special shapes, laminated members permit a more versatile and effective application of wood to architectural design in building construction.

e. Laminating permits the use of high-strength lumber, as determined by species, density, and grade, in the portions of a member that require special strength and appearance, and weaker and less costly lumber in the low-stressed portions of the member.

f. The use of laminated members in prefabricated buildings sometimes permits their quicker and easier erection.

Economic Limitations of Laminating Process

Laminating wood products by gluing involves certain economic considerations and fabricating techniques not involved in producing solid timbers. Several of these may be described as follows:

a. The preparation of lumber for gluing and laminating usually raises the cost of the final product above that of solid green timbers.

b. For constructions in which green timbers are satisfactory, more time is required to cut and season lumber and to laminate the timber than is required to cut solid green timbers.

c. Since the value of a laminated product depends upon the strength of the glue joints, the laminating process requires special additional equipment, plant facilities, and fabricating skill not required for producing solid green timbers.

d. Large curved members are difficult to ship by common conveyances.
Performance Required of Glue Joints in Laminated Construction

The glues in laminated wood products must furnish sufficient original bonding strength to enable the glued member to perform as a structural unit and be durable enough to maintain such strength throughout its service life.

The service life of wood is usually determined by its resistance to decay and other deteriorating conditions. The glue bond must be equally resistant under the same conditions to enable the glued wood product to furnish maximum service. Any superior resistance offered by the glue bond in these respects, however, cannot be expected to extend the normal service life of the wood in the laminated product.

Glues used for bonding wood must not damage or weaken the wood, and they should permit machining of the laminated product without serious damage to surfacing equipment.

Glued Laminated Products for Service Under Normally Dry Conditions

Laminated glued products that are used either in the construction of buildings or in the equipment inside of buildings are usually protected from exposure to moisture so that there is little danger of their deterioration by decay or weathering. Under these conditions, the mechanical strength of the wood and of the glue joints and other conditions of use determine the useful life of the product.

A glue should be as permanent as the wood in the member to be suitable for use under dry exposures. 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 throughout the life of the product. Some ordinarily dry exposures may involve temporary high-humidity conditions, so that some water resistance in the glue is desirable. There is little opportunity under dry exposure conditions for bacteria, molds, or other decay organisms to damage either glue or wood, but if the moisture content of the wood is temporarily raised higher than about 20 percent, such organisms can cause deterioration of glues containing either protein or starch. Such glues, however, can 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.

Report No. D1635 -5-
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 (4, 14) most used in woodworking included the animal, vegetable-starch, casein, vegetable-protein, and blood-albumin types. Within recent years, however, an increasing number of synthetic-resin glues of various types have been made available (6). 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 bridge timbers, laminated ship keels, and other laminated members for use under severe service conditions are among the products whose manufacture has been facilitated or whose performance has been improved by synthetic-resin glues.

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 is rapidly increasing. In a limited amount, 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 resins do not soften appreciably even though subsequently 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. A thermoplastic resin, in contrast to the thermosetting glues, must first be heated to the point where it flows and then usually be cooled under pressure. Subsequent heating above the softening range will weaken the glue and permit the joints to open.
For the purpose of this report, the glues described are classified according to curing temperatures as follows:

<table>
<thead>
<tr>
<th>Classification</th>
<th>Required Temperatures for Satisfactory Curing within Practical Time Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-setting</td>
<td>Require higher temperatures than those commonly attained in heated chambers, for which the maximum is about 210° F.</td>
</tr>
<tr>
<td>Intermediate-temperature-setting</td>
<td>Require heating in excess of normal room temperatures (about 65° to 80° F.), but do not require temperatures above 210° F., the maximum that can ordinarily be attained in heated chambers.</td>
</tr>
<tr>
<td>Room-temperature-setting</td>
<td>Require no heating above normal room temperatures (about 65° to 80° F.), but do not cure satisfactorily at lower temperatures.</td>
</tr>
<tr>
<td>Cold-setting</td>
<td>Set or cure below normal workroom temperatures (minimum about 65° F.), and some may set satisfactorily at temperatures as low as 32° F.</td>
</tr>
</tbody>
</table>

This classification is made merely for the sake of 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, as different types of glues vary in minimum curing temperatures. Since it has been established that an adhesive may require different curing temperatures when used with different species for the same type of construction, certain glues may fall under one classification when used with some species and under another when used with other species. By allowing different times for curing, the temperature requirements may also vary from the range of one class to that of another.

Since blood-albumin, vegetable-protein, vegetable-starch, and animal glues are not well suited for the gluing of laminated structural members, a discussion of these glues is not included in this report.

---

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

Report No. DL635
Casein Glues

Casein glue is classed as water resistant because of its relatively high resistance to moisture compared to that of vegetable and animal glues. Its basic constituent is dried casein of milk, which, combined with alkaline chemicals, usually lime and one or more sodium salts, is water soluble. Prepared casein glue is supplied in powder form, and, when mixed with water in the correct proportions, it is ready for use. It sets as a result of chemical reaction and of loss of moisture to wood and air. If the joints are well made, casein glue will develop the full strength of the wood, especially in softwood species (14), and will retain a considerable portion of its 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. Under continuous exposures involving high humidity, casein-glue joints weaken so rapidly that these glues are not recommended where the relative humidity is 90 percent or higher for appreciable periods. The relatively recent introduction of casein glues containing sufficient toxic chemicals to retard mold and other micro-organisms, has considerably improved the durability of casein-glue joints at high humidities. Casein glue joints have demonstrated good resistance to dry heat. Results of exposures to temperatures as high as 158° F. for periods up to 4 years (duration of test period) 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 will take place only immediately adjacent to burning wood.

Casein glue will produce adequate bonds with wood from approximately 2 to 18 percent moisture content. A range of 6 to 12 percent, however, is usually preferred, as it approximates the moisture content of the glued member in service. It is also desirable to have all laminations for one assembly at approximately the same moisture content (allowable differences between boards up to 5 percent) to avoid their 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. The glue should meet the requirements of the specifications listed at the end of this section.

Casein glue may be spread on small areas by brush or serrated paddle, but for best control of the spread and uniformity of application, mechanical spreaders are required. The amount of 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 per 1,000 square feet of
joint area is usually adequate when single spreading is employed, and of 75 to 110 pounds when both contact areas of the joints 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 single or double spreading is employed. 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 (15-18 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 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, to develop strong joints at such temperatures. 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 pressing 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 per square inch are recommended for species of higher densities. Glue lines produced with such pressures on well-surfaced laminations will be relatively thin and strong. Thick glue lines indicate low gluing pressure and usually are weaker. When thin glue lines of good strength can be produced uniformly with pressures below the foregoing ranges, such pressure will be adequate. After removal of pressure, a conditioning period of about a week at room temperature is required for development of maximum joint strength.

To assure high quality, casein glue should meet the requirements of Federal Specification C-G-456,2 and mold-resistant casein glue should pass the performance tests of U. S. Army Air Forces Specification No. 14122.6

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

6 Obtainable from the Air Materiel Command, U. S. Army Air Forces, Wright Field, Dayton, Ohio.

Report No. D1635
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 employed. In general powdered urea-resin glues with a separate catalyst have longer storage lives than do the liquid or 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 some weakening of urea-resin glue joints occurs under dry conditions at 80° F. and more rapid weakening at 160° F., 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 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 amount of glue spread required may vary somewhat, depending upon the species glued and type of construction, but 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 below 6 percent 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° F. (2). 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° F. 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.


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 carried to completion 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 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, the durability of phenol-resin glue joints properly glued and cured is equal to the durability of the wood.

Hot-setting 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, be 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 grade) hot-pressed plywood, and the excellent performance of such glue joints under exposures involving moisture and heat indicates the performance that may be expected of phenol-resin glues requiring less heat for curing.

Intermediate-temperature-setting (Modified) Phenol-resin Glues

Several phenol-resorcinol-resin combinations that set at substantially lower temperatures than those required for hot-setting phenols have been developed. These glues are generally 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, although some phenol resins are formulated to set at low temperatures with highly acid catalysts. Either type cures at temperatures of 80° to 200° F., depending upon the particular formulation, the time allowed for setting, the species of wood glued, and the type of construction.

Results of weathering tests and cyclic soaking-drying tests on white oak glued with a highly acid intermediate-temperature-setting phenol cured at elevated temperatures, have indicated that the glue caused damage to the wood adjacent to the glue lines that resulted in reduced strength and shallow wood failures. Acid damage has also been observed in yellow birch plywood and hard maple block joints. Approximately neutral or slightly alkaline intermediate-temperature-setting phenol-resin glues did not show this deteriorating effect. Highly alkaline glues of this type have not been offered for laminating purposes.

Glues of the phenol-resorcinol-combination type have a relatively short storage life, often only 2 to 6 months at ordinary room temperature, depending upon their specific formulation, but cold storage (30° to 50° F.) prolongs their useful life.

The usual working life of this type of glue is between 2 and 8 hours at 75° F. Maximum assembly periods vary considerably among these glues, but most of them permit 1 to 2 hours of closed assembly at 75° F. The amount of glue spread required depends upon 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 10 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.

Report No. D1635
The curing requirements for these glues vary with the species of wood used, the type of material being glued, and the service conditions to which the products may be exposed. For such severe uses as ship timbers, a curing period of 10 hours at 190°F. at the innermost glue line is considered necessary for gluing white oak, a 20-hour period at 110°F. for southern yellow pine, and a 20-hour period at 80°F. for Douglas-fir. 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 these glues with low-density hardwoods and most softwood species. When gluing dense woods, pressures of 150 to 250 pounds per square inch are generally recommended.

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


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 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.

These resins are of rather recent development, so that extended service records on their performance are not available, but test data covering a period of 3 years with some resorcinols 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 phenols, these glues produce a satisfactory bond on wood at moisture-content values 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 it is usually from 2 to 5 hours at 70° to 75° F. and is considerably reduced as the temperature increases.

Assembly periods vary for the different glues, according to the temperature and to the type of assembly, whether open or closed. At 75° F., 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 one of the contacting surfaces of the joint 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 are usually satisfactory; 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, are often not so satisfactory as somewhat longer ones. Glue spreads and pressure requirements are similar to those recommended for intermediate-temperature-setting phenol-resin glues, although somewhat higher spreads and lower pressures are sometimes recommended by the manufacturers of resorcinols.

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° F. will develop joint strengths equal to the strength of the wood when relatively long pressing periods (several days to several weeks) are used. Higher temperatures 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 have indicated that for several of the resorcinol glues, curing for 10 hours at a glue-line temperature of 140° F. with white oak and 10 hours at 80° F. with southern yellow pine and Douglas-fir, with at least 1 week 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.


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. The concentrations of the glue mixtures when ready for use are generally within the range of 60 to 70 percent 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 3 years indicate that the durability of their joints, when set at about 190° F., is similar to that of joints made with phenol 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 indicate that the durability of these resins is somewhat inferior to that of melamine resins made without added catalyst.

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 phenol 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 phenols, although when used with softwoods, such as Douglas-fir and southern yellow pine, somewhat higher temperatures may be required for the melamines than for the intermediate-temperature-setting phenols. 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° F. 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. Soap suds or 30 percent calcium-chloride solution have also been recommended.

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. Urea resins should not be used if exposures to temperatures appreciably higher than room temperatures are expected; and, as previously indicated, their durability over a long term of years at ordinary temperatures and relative humidities has not been fully established, a fact that makes their suitability for permanent structures somewhat uncertain, especially where dense hardwoods are involved. Where atmospheric conditions are such that the moisture content of the wood will exceed 20 percent, neither casein nor urea-resin glue is recommended.

For service in continuous immersion in water or intermittent wetting and drying, such as in exterior exposure, or in buildings where high humidities are encountered for a considerable length of time, highly water-resistant adhesives, such as phenol-, resorcinol-, or melamine-resin glues, should be used. Within this group the choice will depend on which type is most readily available, storage life required, curing facilities, convenience of use, and cost. Intermediate-temperature-setting phenols have a relatively short storage life at ordinary room temperatures and require application of considerable heat for curing. The resorcinols have long storage life and cure adequately at 70° to 80° F. for many purposes. The cost of the resorcinol glues is at present considerably higher than that of the phenols. The melamines have a reasonably long storage life and require nearly the same cure as the phenols, but are not so convenient to use as resorcinols or some phenols because with them 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 Grades

The gluability of various species of wood under favorable gluing conditions is shown in figure 3 (3, 14). Block-shear-test values show that glue joints of high strength comparable to the shear strength of the wood can be produced with most commercial species of wood by 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, due to the more favorable cost and availability of the lumber and the suitability 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.

For most laminated members, the quality, kind, and grade of lumber required to provide the desired strength is usually prescribed in the specification or order covering the item. 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 avoided or limited in laminated members when a high-quality product and maximum durability are required. Medium to large-sized knots and knotholes aggravate glue-joint delamination when the exposure involves alternate wetting and drying. Lower grades of lumber are less adapted to laminating timbers for exterior use than for an interior use in which they are kept dry and undergo less severe moisture-content changes.

Sapwood is as durable as heartwood under continuously dry conditions, but when used under conditions developing more than 20 percent moisture content, sapwood, even of durable species, is readily susceptible to attack by wood-destroying fungi and often by insects. When placed in a glued laminated assembly with durable heartwood, the decay of a single board of sapwood may cause failure of the entire member. When it is required that the laminated product be durable under moist exposures, durable heartwood must be selected and sapwood be eliminated from any lamination unless the wood is treated with a suitable preservative.

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 may develop stresses 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 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 could be expected. In moist, wet, and exterior exposures, laminated members may develop higher moisture contents than the maximum at which good glue bonds can be produced. Consequently, lumber with a moisture content range of 12 to 15 percent is most desirable for such gluing. Members glued at 8 to 10 percent will experience 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 the consequent development of stresses in the glue line, of possible separation of laminations, and of distortion of the finished member. A range in moisture content of not more than 5 percent between laminations in a single assembly is recommended. Stresses will also be created if the interior portion of any one board differs greatly in moisture content from the outer portion or shell (fig. 4), and it is recommended that such differences not exceed 5 percent.

The most practical method for seasoning lumber to these moisture content requirements is by kiln drying, which lends itself to control of the humidity and of the final dryness of the stock (13). Air-dried lumber is equally suitable when it meets these moisture-content limitations (10).

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
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, 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 oil-borne 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. 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 for gluing is taken from unheated storage during cold weather, it is desirable to allow it to warm up to approximate room conditions before spreading. 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 always be sufficient to allow it to warm up appreciably.

Rough Surfacing

Preliminary rough surfacing of the lumber to be used for gluing, although not always necessary, is advantageous in obtaining 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 the 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 cut 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. In many cases this is done in the sawmill operation, so that the finished boards may be used by grades without further cutting out of defects, as in the case of pine and fir lumber where relatively long lengths may be available in suitable grades. In other cases, such as with most hardwoods, only short lengths can usually be cut from available lumber when clear grades are required, so that further cutting is necessary at the laminating plant.

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 similar sizes of vertical-grain or quarter-sawed lumber. 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 Douglas-fir having a moisture content of 8 percent will swell about 0.3 inch when its moisture content is raised to 18 percent, while a similar vertical-grain board will swell only about 0.2 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. 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.

Laminating glues will bond plain-sawed and quarter-sawed lumber equally well, so that the segregation for grain is recommended primarily to reduce the subsequent development of stresses in members subjected 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, both to increase strength properties and 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 ordinarily 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 full-strength bonds. 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 the desired widths. 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 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 rip saw 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, when preparing nominal 1-inch hardwood lumber that is finally to be surfaced to 3/4 inch for laminating an 8-inch wide timber, the proportion of 8-inch stock would be small. The narrowest piece practical for edge gluing would probably be about 1-1/2 inches. These would then be a number of width combinations that 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; 1-1/2,5,1-1/2; 2-1/2,3,2-1/2; 4,4; and 1-1/2,4,2-1/2. If the specifications require a minimum spacing of 3/4 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 lamination in one piece. Various kinds of glued end joints used for this purpose are illustrated in figure 5. The plain scarf, hooked-scarf, finger, and serrated scarf are among those commonly used. All these joints require a relatively long slope to develop maximum tensile strength in the joint. 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 efficient. It is desirable to have the slope of the scarf with, rather than against, the grain of the wood. There is also no strength advantage in having the slope of the 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 increases somewhat 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 and 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 superior to sawed surfaces, especially with lumber of dense hardwood species. There are no high-speed machines on the market that permit a low-cost, high-volume production of glued end joints.

There is some advantage in having end joints of the plain- or serrated-scarf type cut 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 the necessity of turning them over, and will permit crosscutting 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 the lumber is case-hardened or not uniformly dry. Such cupping is a disadvantage later in applying glue in the glue spreader, and also in applying gluing pressure by clamping. Cupping in resawn lumber can be minimized by using uniformly dry stock, relatively free from case-hardening (2). 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.

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, with the wood fibers undamaged. Intentional roughening of wood surfaces by tooth planing, scratching, or sanding with coarse sandpaper has been practiced to some extent, but tests of joints made with such surfaces under good gluing conditions showed this practice of no benefit to the glue bond.

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, not more than 1/16 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) of an 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 of an 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 3/4 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 both at edges and center 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 1/96 of the ratio of width to thickness of boards. For laminations 6 inches wide, this will allow 1/4-inch cup in a board 1/4 inch thick, 1/8-inch cup in a board 1/2 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. Periods of storage after final surfacing may permit the lumber to change in moisture content, resulting in nonuniform dimensional changes, and the lumber may thus become less satisfactory for gluing into laminated assemblies. 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 shipping to the laminating plant should be resurfaced just before gluing.

Sawed surfaces have not been used to any great extent in gluing laminated wood products. Sawed lumber surfaces are generally those produced when the green lumber is cut from the log, but after it dries, planing is the most practical means of dressing the stock. 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 the use of a greater glue spread. Sanded surfaces have no advantage over well-planed lumber surfaces in producing glue joints of high strength and durability. 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 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.

Location of Edge and End Joints

When beams are made of laminations containing edge joints, such 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 applied normally 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. The location and spacing of scarf joints must be controlled to produce laminated members of maximum strength and durability. For this purpose, 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. 6). Whenever practical, all scarf joints in the surface lamination should slope in one direction to obtain best results in machining the finished product. Butt joints are not considered end-glued joints.

Straight Members

Assembly lay-up should give consideration 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 grade of lumber may be the same throughout, or of mixed grades as permitted by the specifications covering the order. Mixing of 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. Wide variations of moisture content in service cause unequal shrinking and swelling of adjacent laminations where species are mixed. The higher
stresses induced by the stronger species are likely to cause the wood of the weaker species to rupture, and will thereby reduce the strength and usefulness of the member, even though the glue joint be durable.

Laminations up to approximately 2 inches thick may be used in gluing straight timbers, provided suitably dry stock is available. Within this 2-inch limit, the thickness of the lamination does not influence the strength or durability of well-glued joints, so that different thicknesses may safely be glued in the same laminated assembly. It may sometimes be desirable to use more than one thickness of stock in flat assemblies in order to attain maximum utility of the lumber supply, or to fabricate a laminated member to exact dimension. Arrangement of the different thicknesses will be 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 would be placed in the position entailing the least subsequent face machining.

As a result 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 lay-up 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 a 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 laminating high-strength curved members from boards, 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 lumber at a moisture content of about 10 percent when laminating white oak, Douglas-fir, or southern yellow pine.

Table 2 applies to both flat- and vertical-grained lumber at a moisture content of about 10 percent. For drier lumber, and especially fast-growing
material, somewhat longer radii may be required. In any curved laminated member, the radius of curvature of the inner or concave face will be 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.

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. 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 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 male or female type of jig or form. The jig may be constructed in fixed position for a single curvature, or to permit adjustment in setting up to various curvatures (fig. 7). The general laminating procedure with such jigs is to lay the individual laminations in approximate bent position and hold them by a series 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 hold it there while gluing pressure is applied (fig. 8, B).
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 serve this purpose very satisfactorily in many cases.

The spacing and setting of adjustable arms on the bed of bending jigs 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 heating 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 caul 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 one operation requiring gluing pressure to be applied simultaneously in two planes, or in two operations requiring gluing pressure in one 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. 9).

**Gluing of Edge and End Joints**

It is highly important in the production of laminated material that the sequence of operations be carefully planned and the various steps be carried out in the proper order. Edge gluing must occasionally be employed 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 where maximum-strength members are required. Whether edge gluing should precede end gluing or vice versa, depends upon 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 saved 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 enable handling full-width laminations during the laminating process, 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 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 for applying 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 strengths that will permit handling the edge-glued stock without damaging the glue.
bond. The carrier should be properly aligned to assure straight glued boards. This type of clamp can be enclosed and heat 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.

Clamping edge-glued stock can also be accomplished with piling clamps (fig. 10), 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 usually provides an adequate cure for edge joints.

If the edge-glued boards are planed too soon after removal from clamps, sunken joints will probably result. If sunken joints are to be avoided, the edge-glued boards must be conditioned for a period sufficient to permit the water added with the glue to diffuse away from the joint.

End Joints

The choice of glues for end joints involves the same considerations as 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 gluing end joints, it might sometimes be of advantage to use a different type of glue for the end joints than for the laminating. Resorcinol glues, having moderate curing requirements, set comparatively rapidly, and 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. By the latter method, however, it is extremely difficult to produce joints of uniformly high quality. 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 possible 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, such as are certain to develop adjacent to butt joints in curved assemblies.
Plain scarf and serrated end joints, that require a slight overlap to insure adequate gluing pressure on the joint (fig. 11), 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. 12) 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.

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.

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

Gluing Laminated Assemblies

Much of the success in fabricating satisfactory laminated members depends on following a proper procedure when gluing the assembly. Good practice requires that attention be given to arranging the laminations 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. 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 joined (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 used. Directions for mixing (furnished by the manufacturer) give the amount by 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. 13), equipped with a mechanism for turning the paddle in a double rotary motion at two or three 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 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 13, 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.

Some resins tend to develop heat when mixed with the hardener, so that the manufacturer's instructions for keeping the materials cool during mixing should be followed. Precociling of the resin in refrigerated storage just before mixing has been found 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 then 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.

For urea resins supplied in powder form, probably the most generally applicable procedure for mixing 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 phenols 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, more rapid stirring may be used. 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, so that a high degree of cleanliness should be exercised in their use. Where toxic fumes are involved, good ventilation should be provided and suitable exhaust fans may be desirable. The use of rubber gloves, aprons, and goggles is helpful in preventing direct contact with the glue. Information on precautionary measures to be taken for any particular glue used 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 in which the rolls are rubber-covered and which is fitted with "doctor" rolls to control the glue spread. 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 glue one surface only; otherwise, the outer faces of the surface laminations should be covered with wax paper to prevent adhesion to the cauls.

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.

Report No. D1635 -34-
<table>
<thead>
<tr>
<th>Glue</th>
<th>Pounds per 1,000 square feet of joint area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single spread</td>
</tr>
<tr>
<td>Casein</td>
<td>60 to 90</td>
</tr>
<tr>
<td>Resin</td>
<td>40 to 60</td>
</tr>
</tbody>
</table>

The higher range of spreads should be used under conditions such as 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 enable checking of glue spreads quickly and frequently. For this purpose, test pieces of the same thickness as the material being laminated should be employed. If a test piece 6 inches wide and 26-1/2 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 two to obtain the rate in pounds per 1,000 square feet of joint area.

The adjustment of the glue spreader and checking of glue spread should be done 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 due to 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 spread will be greater with species of low specific gravity than with those of high specific gravity.

Report No. D1635 -35-
The percentage of moisture content added to the wood when laminations of equal thickness are used, may be calculated by using the following formula:

\[
\text{Increase in moisture content (percent)} = \frac{W/100 \times G \times (L - 1)}{\frac{T \times L}{12} \times 1,000 \times S \times 62.5} \\
= \frac{0.000192 \times W \times G \times L}{T \times S \times \frac{L - 1}{L}}
\]

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 the percent of moisture content in the wood resulting from the addition of water from the glue used in typical constructions.

**Assembling Laminations**

Normally, the lumber should be at room temperature before spreading the glue, especially when glues not requiring elevated curing temperatures are used. Since sizeable assemblies heat rather slowly, minimum pressing periods are obtained when 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 for gluing should be clean and free from crayon marks, grease, oil, or other contaminating 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
that might upset the predetermined pattern for end-joint spacing. It is advantageous in handling long laminations that the workmen be assigned to definite stations to avoid confusion and delay in laying up the assembly. 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 the evaporation of solvent and permits the use of 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 strengths. 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 for 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, pressure must be applied progressively along the assembly to permit slippage of laminations, so that retaining clamps serve to best advantage. 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 effect of high temperature and humidity, where such conditions are required for curing, also renders the use of expensive presses unsuitable.

Use of nails for applying gluing pressure has not been thoroughly investigated. In general, however, nailing provides low and inadequate pressures for most gluing operations. Hence, based on existing knowledge, nailing as a means of applying pressure in gluing is not recommended for high-strength laminated members.

A frame type of retaining clamp with rocker head (fig. 8A) for equal distribution of pressure across the width of the assembly has 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 less loss is suffered by breakage. For narrow members, a yoke-type, single-bolt clamp (fig. 14) 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 in use and do not give so satisfactory service over long periods of use as the square-threaded bolts.

Air-operated or electric nut runners will speed production and have been used to advantage for tightening nuts on retaining clamps (fig. 15).

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. 16). The pressure in the hose may be read by means of a hydraulic pressure gage, and the total load be computed from the following relationship:

Total load equals the gage pressure times area of contact between hose and caul. If, for example, for each hose shown in figure 16 it is assumed that 2 inches of circumference of the inflated hose bear on the caul, and the gage shows 100 pounds 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 four hoses shown in figure 16 would, accordingly, deliver \( \frac{4 \times 2,400}{60} = 160 \) pounds per square inch.

Gluing pressure = \( \frac{2,400}{60} = 160 \) pounds per square inch.

A heavy, rigid caul would be 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.

In general, it is advantageous to use thick cauls except when curved members of short radius are made. In this case, the use of two or more thin cauls on each face of the assembly will distribute the pressure more evenly than if only one 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 \( \frac{3}{4} \)-inch wood cauls may permit a clamp spacing of 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, to a certain extent, governed 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 3/8 inch or less in thickness.

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. 17,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 17,F and 18. Torque wrenches are generally calibrated in foot-pounds. When the compressometer is placed within the clamp and the clamp nuts are tightened by use of 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 the 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:

\[ FL = \frac{WR}{\sqrt{\frac{\pi}{4}D+K}} \]

\[ = \frac{WD}{2} \left( \frac{\pi}{\sqrt{D-fK}} \right) \]

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 (diameter at root outside diameter)
- \( K \) = pitch of thread, in inches
- \( f \) = coefficient of friction (may be assumed as 0.20)
- \( \pi \approx 3.1416 = 22/7 \), 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, so that determination of the load developed by the clamps when a known torque is applied, should be carried out at reasonable 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**

The application of clamp pressure to a straight assembly should be done by tightening the clamps progressively from one end to the other, 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 apply full pressure progressively along the assembly. If the clamps are tightened to full pressure in the first application, a slight bend in the member is often likely to be produced by the clamping. When the assembly is clamped on a solid bed (fig. 19) and pull-down clamps are used to insure straightness in the member, the foregoing precautions becomes 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, 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. Then, on each side of the central point, retaining clamps may be progressively applied toward each end, and each pull-down clamp be tightly drawn to the form as the application of retaining clamps reaches that point. This procedure enables the bent laminations to slip endwise where necessary to produce uniformly tight joints. Where male forms are used, the same technique generally applies, except that application of pressure may begin either at one 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. While 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° F. 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, amount of curvature in the glued timbers, and water-absorptive power of the wood.

The setting of glues that will cure adequately when held under pressure for a sufficient period at room temperature, is sometimes appreciably accelerated when heating is employed. When heating 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 an increased pressing time is recommended. There is little advantage in heating casein-glued laminated assemblies of appreciable 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. Spreading the glue on warm lumber will accelerate the setting, but 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 at least at 70° F. before gluing, or heat should be applied to the glued member to reach this temperature at all parts of the glue line. Straight members glued with urea resins at 70° F. 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° F., a pressing period of 6 to 8 hours is
recommended. Members laminated with urea resins and cured at room temperature require a conditioning period similar to that of casein-glued members 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, and Melamine Resins

Intermediate-temperature-setting phenols 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 do not become completely cured.

These glues are expected to provide 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, species of wood, and probably also with type of construction. When gluing white oak with intermediate-temperature-setting phenols for exterior use, a curing temperature of 190° F. maintained for 10 hours at the innermost glue line has been found necessary to develop adequate resistance to delamination. To meet this requirement, the clamped assembly should be heated until all portions of the glue joints have reached this minimum temperature, and 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 phenols develop satisfactory bonds in straight timbers when cured at a glue-line temperature of 110° F. for 10 hours. Curing at 80° F. (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° F. in order to hasten the curing of the glue. Southern yellow pine members require heating to 110° F. (glue-line temperature) or higher for 10 or more hours to produce durable joints.
For Central American mahogany, curing at 140° F. for 10 hours has been found adequate. Lower temperatures for curing than those given have not been found adequate with these glues.

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 at 140° F. for a similar period 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° F. with some of these glues.

Members laminated with resorcinol-resin glues will develop joint strengths adequate for many purposes when cured at temperatures from 70° to 80° F. When gluing softwood species, such as Douglas-fir and southern yellow pine, glue bonds cured at these temperatures for 10 hours are durable under weather exposure. 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, however, such as white oak, heating of the glue joints to 140° F. or higher for 10 hours is necessary to provide similar durability.

Since with some glues of the foregoing types, curing may be delayed as much as a week after spreading and clamping have been completed, and 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 120° to 130° F. with proper humidification may be accomplished in a warm room in the plant. A canvas canopy, dropped over the assembly to enclose automatically controlled heating and humidification equipment, involves a relatively low expenditure and may serve satisfactorily for temporary purposes. Among other means of heating are high-frequency generators and radiant heating. Where heating is required at temperatures higher than 130° F., 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.

Report No. D1635 -44-
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° F. At temperatures much above 215° F., it is difficult to maintain the proper relative humidity, and the use of such temperatures is not recommended. Whenever assemblies of an appreciable size are to be heated in a curing chamber, it is usually most practical to maintain the chamber temperature about 20° F. 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 heating 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 due to the difficulty in maintaining a properly controlled humidity. Infrared lamps and strip heaters might be useful in laminating small members in constructions that are subject to relatively little checking when appreciable changes in moisture content are encountered.

High-frequency Heating

By the use of high-frequency heating all parts of the glue lines in a large assembly may 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 shortwave broadcasting range or higher, heating occurs throughout the mass, thus making it possible to introduce heat at a rate dependent on the material to be heated and the power capacity of the equipment available. Further, 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.

Report No. D1635 -45-
Although this method has been introduced only within the last 5 or 6 years in the United States, it is gaining favor for the rapid setting of the class of adhesives that sets at room or slightly higher temperatures. 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.

Among the disadvantages of high-frequency heating are the necessity for special pressing equipment, nonuniformity of heating, and the need of highly skilled operating personnel.

High-frequency heating has been used to a limited extent in commercial production of flat and curved plywood, and to a greater extent in gluing edge and end joints (fig. 20), furniture panels, and similar products. Recently it has also been used on large-scale production of laminated curved rafters. Resorcinol type of glue is the adhesive used in this operation and the field is applied parallel to the glue line.

While urea, resorcinol, and melamine resins have been effectively used, results with phenol resins, that require the application of considerable heat for curing, have not shown sufficient promise to enable developing a satisfactory method of gluing structural laminated products with them by high-frequency heating.

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 under handling of the members after the pressure has been released. Several days must then be allowed for conditioning and for completing the cure at room temperature.

Arcing has probably been one of the worst handicaps in the use of high frequency for curing glues. Recently, however, certain glue manufacturers have indicated that they have succeeded in formulating glues with reduced arcing tendencies.

**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 moisture content of the wood and depends a great deal upon the dimensions of the assembly. The graphs in figures 21 through 32 show the rate at which members of white oak and Douglas-fir in 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 (2). 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.

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.

(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.

While the outer area of a laminated assembly may be expected to heat rapidly as the atmosphere of the curing chamber is raised in temperature, a period of 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.

**Humidification of Heated Chambers**

When wood is heated in an atmosphere of low relative humidity for a number of hours, a drying of the wood takes place that results in a tendency toward shrinkage. 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. Drying will be avoided if a high relative humidity is provided and maintained in the curing chamber. Under these conditions, the wood will not shrink or check, and the glue joints will remain tight. It is desirable to provide a relative humidity that will maintain the equilibrium-moisture-content value of the wood in the laminated assembly. Figure 33 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° F., such a relative humidity requires a wet-bulb temperature of 199° to 202° F.

Humidity refers to the amount of water vapor in the atmosphere. Absolute humidity is expressed in terms of the weight of 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 between the amount of moisture present and 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, since the atmosphere at 70° F. will contain 8 grains of water vapor when saturated (100 percent relative humidity). 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° F. the capacity of the atmosphere rises to 255 grains per cubic foot, and a relative humidity of 80 percent requires about 204 grains per cubic foot. Obviously, in order to provide sufficient humidity in a curing chamber to avoid drying of the glued assembly, it becomes necessary to add a considerable amount of water vapor to the atmosphere. The vapor can be most 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.

Operation of Curing Chamber

The operation of a curing chamber is similar in principle to the operation of a modern lumber dry kiln, in that heat may be provided by steam coils, humidification by means of steam jets and sprays, and circulation of air by mechanically operated fans. Temperature may be controlled by a thermostat operating on the heating coils, and relative humidity by a wet-bulb thermostat operating on the steam-spray line. It is possible to obtain required control by hand-valve operation, but the use of recording-controller instruments is much preferred.

When the assemblies have been placed in the curing chamber and the heating process is begun, it is desirable to raise the chamber temperature at a rate of not more than 70° F. per hour.

In the process of curing in the heated chamber, both the metal retaining clamps and the wood will increase in dimensions due to thermal expansion. The coefficients of expansion for steel and wood are given as follows:

Thermal expansion of steel -- 0.000006 inch per °F. (Marks' Mechanical Engineering Handbook).

Thermal expansion of oak across the grain -- 0.000030 inch per °F. (Wood Handbook) (7).

The thermal expansion across the grain for oak lumber is approximately five times that of steel. Thus, in heating the clamped assembly, the total thermal expansion of the wood (without change in moisture content) will be greater than that of the steel retaining clamps, and crushing of the cauls under the clamp heads results. The greater expansion of the wood will result in an increased pressure on the glue line, but in the early stages of heating the clamps will heat faster than the wood assembly, and there may be danger of temporarily reducing the pressure if the curing chamber is heated too rapidly. Raising the chamber
temperature at a rate of about 70° F. per hour has been found satisfactory. Upon cooling, the wood contracts more than the clamps, so that the clamps may be somewhat loose when curing and cooling have been completed. Loose clamps on cured and cooled assemblies are not necessarily an indication of inadequate pressure during the curing process.

During the heating-up period of the chamber, the steam-spray supply should be throttled to avoid bringing the humidity to the point where condensation appears on the glued members, but the humidity may be raised as fast as this limitation will permit. Rapid circulation of air in the curing chamber is helpful in attaining uniformity of curing conditions.

While recorder-controllers are useful in controlling the temperature and relative humidity in the curing chamber, they do not record the temperature inside the laminated member. Thermocouples, however, may be placed at desired points in the glue lines while laying up the assembly, and the temperature in the member at these points can be determined at any time during the curing operation by means of a potentiometer (electrical thermometer). While the curves shown in figures 21 through 32 indicate the temperature readings to be expected in the center of laminated assemblies during curing, they are subject to change whenever heating conditions in the chamber are varied, and often some correction must be made. The use of thermocouples and a potentiometer to check the interior temperatures during curing is recommended, 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 drying and checking of the surface of the wood will take place. 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 spray 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. The introduction of water spray or mist, however, should be controlled to avoid wetting glued members. Cooling of the chamber should preferably be carried to a temperature within 25° F. of the temperature outside the chamber before the members are removed and unclamped.
The fabrication of strong and dependable glued laminated wood products includes careful and accurate preparation of the lumber. Preparation of lumber for this purpose requires plant facilities and machinery 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, and adequate clamping and curing of the glue are necessary to produce dependable joints. Average woodworking machinery and hand-fitting of joints do not generally lend themselves to producing 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 upon three major factors: (a) the source of dry lumber or the facilities for kiln drying and storage of kiln-dried lumber, (b) the anticipated daily production; and (c) the size and the shape of the laminated material.

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

If the material to be fabricated is to consist largely of lengths greater than those obtainable from the standard lengths of lumber, provision must be made 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 prior to spreading the glue. 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 easily moved, but ample space is nevertheless highly desirable.
The space requirements when using fixed clamping beds or jigs are somewhat greater than for mobile equipment, but such a plant lay-out 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 equally well-dried lumber is also satisfactory where the fabricator does not dry the lumber himself. Equipment for testing 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

(a) 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.

(b) 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.

Report No. D1635 -51-
(c) 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

(a) 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.

(b) 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

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

(b) 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.

(c) 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.

Gluing Jigs, Forms, Clamps, and Handling Equipment

(a) 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
their deformation. 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.

(b) Provision should be made for the mechanical handling of heavy members by overhead hoists, by floor cranes, or by 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 of a design and size 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.

(c) 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 sometimes becomes necessary, however, to precure or fully cure the glue while the members remain in the jigs in which they are formed, due to 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 then moved to some convenient storage space and accumulated until a sufficient quantity has been assembled to charge the curing chamber.

Although laminated products, glued with adhesives that cure at room temperatures, can be cured adequately in the room in which the gluing is done, where the adhesives require elevated temperatures for adequate curing, heated chambers provided with accurate control of temperatures and humidity become 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:

Report No. D1635 -53-
(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 a
portion of the heating coils need be used after the chamber has become
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. It is
desirable that the inner face of the chamber structure be such as to
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, under which structural
openings, cracks, or permeable wall materials will permit considerable
vapor leakage.) Painting the inside faces with a good grade of
asphaltic kiln paint is very helpful. Outside faces should not be
vaportight. In addition to possessing a vaportight construction,
the chamber should also be well insulated against heat loss to
avoid condensation on the interior faces of the chamber.

The use of live-steam spray controlled by a wet-bulb thermostat is
satisfactory and practical for supplying the required humidity. The
wall construction of a dry-kiln type of curing chamber may be of
conventional hollow tile, brick, or similar material. In smaller
units, vaportight cement-asbestos-board interior lining, behind which
insulating board is applied, and interior joints sealed with asphaltic
plastic are satisfactory for use inside enclosed buildings. Require-
ments for heating, humidifying, circulation of air, cooling, and auto-
matic instrument control in such a small chamber are the same as for
large installations.

(c) Forced-air-circulation system. The uniform control of temperature
and relative humidity is much easier to maintain 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.

Another type of 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 its use may be practical
in certain instances.

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

Report No. D1635
(d) Equipment to provide high humidity during cooling. While steam sprays may be used to provide humidity during heating-up and curing, they are undesirable during cooling 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 34 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.

**Control Instruments**

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

(a) Equipment for testing 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 equal, 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 equal) measuring to 0.001 inch, which is suitable for measuring the thickness of lumber when setting up the finishing planer, and which may also be used 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 to cure the glue, are desirable for determining temperatures within the package during heating and cooling. This determination 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.

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 the contract and can be readily verified at the time of fabrication. Determination of the type of glue in a finished product may require performance tests and chemical analysis, but at this stage 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 a portion of the laminated product or from a separate sample laminated beam. The types of shear specimens used in this test are shown in figure 35. Either the stairstep or the block-shear type of 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 one shear test be made upon each glue line, and that the total number of tests per member tested be not less than five.

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 to fully 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 36. The load should be applied to the specimen at a rate of 0.015 inch per minute plus or minus 25 percent. 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 use of table 4.

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

Specimens that show strength values below the required average for the species when combined with 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 over 20 percent) should have glue joints that consistently meet the average strength requirements of 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.

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, exposure to steam, and the like, without serious delamination of the glue joints. Test 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 dry-block-shear-strength values shown in table 4 and, in addition, show average wood-failure values of not less than 75 percent.

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 of not less than 75 percent on standard shear blocks that have been boiled in water for not less than 12 hours, then thoroughly cooled by immersion in cold water, and tested wet. This test is recommended as a means 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 not more than 10 percent average glue-joint opening when tested according to either of procedures (a) or (b) that follow.

For either test, cut three cross sections, each with a length (along the grain) of 3 inches, from the laminated member or sample beam, or preferably one section from each of three different beams. The end-grain surfaces of the sections should be cut or sanded to a smooth condition.

(a) Place the sections in an autoclave or other type of pressure vessel, immerse them in water at room temperature, and weight down the specimens to keep them submerged. Draw a vacuum of 20 to 25 inches and hold it for 2 hours. Release the vacuum and apply air pressure of 75 pounds per square inch to the immersed specimens for 2 hours. Repeat the vacuum-pressure cycle once, with the specimens remaining immersed. Continue the soaking for an additional 16 hours at room temperature and atmospheric pressure. Expose the soaked specimens in a room maintained at 80° F. and 30 percent relative humidity and provided with brisk circulation of air, with the specimens placed at least 2 inches apart and with end-grain surfaces parallel to the stream of air, and dry for 6 days to complete one soaking-drying cycle. Repeat the soaking-drying cycle twice for a total test period of 21 days. Measure the total length of open glue joints (delamination) on the end-grain surfaces of the sections during the part of the drying period in the third or final cycle when the checking of the wood and open glue joints are most in evidence (usually during the third or fourth day of drying). Failure in the wood, due to checking or other causes, is not regarded as delamination.

(b) Soak the specimen by immersing in water at room temperature for not less than 15 days and then dry as in (a). After three soaking-drying cycles, measure delamination as in (a).

The total length of open glue joint on the end-grain surfaces of a section is expressed as a percentage of the entire length of glue joints exposed on these surfaces, and this value is referred to as the percentage delamination.

Report No. D1635 -58-
As a substitute for an autoclave or other suitable pressure vessel, the
type of equipment shown in figure 37 has been used successfully at the
Forest Products Laboratory in carrying out the test described under 3(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 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 would
depend 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 due to the action of the water and subsequent
drying. Where pressure impregnation with water-borne chemicals is
required, it is recommended that exterior-type resins be used.

The wood in members used under wet conditions in either interior or
exterior exposure is subject to decay, and its useful life may be
appreciably prolonged by the application of preservatives (8). 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 timbers treated with wood-preserving and fire-retardant chemicals is limited to weather-exposure tests and service tests extending over a period of about 3 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 often be inconvenient, and sometimes impossible, due 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 modified phenols will adequately bond southern yellow pine when the treatment is not sufficiently heavy to cause bleeding in subsequent surfacing and gluing operations. Very limited tests have indicated that red oak also can be glued satisfactorily under similar conditions of treatment. Surfacing after treatment and before gluing is necessary, 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 portions of the lumber that have the highest preservative retention. Surfacing of the lumber before treatment is also desirable, since it facilitates the use of a lighter cut that will remove less of the highly treated material in the final surfacing of the lumber after treatment.

When treatment with water-borne chemicals is used, the moisture content of the wood is appreciably increased. 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, however, is limited, 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 variations in procedures used for untreated lumber may become necessary when gluing treated lumber. For instance, it has been found that use of higher curing temperatures are often required when gluing treated wood.

Examples of Laminated Construction

European Uses

The most extensive use of glued laminated construction has been in Europe, especially in Switzerland and the Scandinavian countries. European uses
include roof supports in airplane hangars, auditoriums, bandstands, bath-
houses, chemical and other factories, churches, concourses of important
railway stations, exhibit halls, engine houses, garages, greenhouses,
gymnasiums, planetariums, residences, riding academies, schools, stock
barns, tennis halls, theaters, and warehouses. In addition, laminated
construction has been used in a few foot and vehicle bridges and in
erection forms for stone and concrete-arch bridges.

American Uses

The use of laminated construction in America received a decided impetus
in 1934 when a service building containing glued laminated arches was
erected at the Forest Products Laboratory. Subsequently, hundreds of
structures employing glued laminated construction have been erected
throughout the United States. Some typical American applications are
illustrated in figures 38 to 49.
(1) DUNLAP, M. E.
1939. ELECTRICAL MOISTURE METERS FOR WOOD. Forest Products Laboratory Report No. R1146.

(2) EICKNER, H. W.

(3) 1942. THE GLUING CHARACTERISTICS OF 15 SPECIES OF WOOD WITH COLD-SETTING UREA-RESIN GLUES. Forest Products Laboratory Report No. 1342.

(4) FOREST PRODUCTS LABORATORY
1941. GLUES FOR USE WITH WOOD. Technical Note No. 207, revised.

(5) 1940. THE DETECTION AND RELIEF OF CASEHARDENING. Technical Note No. 213, revised.

(6) 1941. SYNTHETIC-RESIN GLUES. Forest Products Laboratory Report No. 1336.

(7) 1940. WOOD HANDBOOK. U. S. Dept. Agr. (Unnumbered pub.)

(8) HUNT, G. M. and GARRATT, G. A.

(9) MacLEAN, J. D.
1943. RATE OF TEMPERATURE CHANGE IN LAMINATED TIMBERS HEATED IN AIR UNDER CONTROLLED RELATIVE HUMIDITY CONDITIONS. Forest Products Laboratory Report No. R1434.

(10) MATHEWSON, J. S.


(12) 1937. MOISTURE FLUCTUATIONS IN LUMBER WITHIN CLOSED STORAGE SHEDS CONTROLLED WITH ELECTRICAL EQUIPMENT. Forest Products Laboratory Report No. R1140.

Report No. D1635
(13) THELEN, ROLF

(14) TRUAX, T. R.

(15) WILSON, T. R. C.
Table 1. Use characteristics of laminating glues

<table>
<thead>
<tr>
<th>Glue type</th>
<th>Exposure: Storage</th>
<th>Working: Maximum</th>
<th>Permissible moisture:</th>
<th>Setting characteristics</th>
<th>Laminating pressure:</th>
<th>Conditioning period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>suited life at 60° F.</td>
<td>70° to: assembly time</td>
<td>at 70° F. of wood</td>
<td>Cold:</td>
<td>Room temperature:</td>
<td>:Intermediate Minimum:Maximum:</td>
</tr>
<tr>
<td>Casein</td>
<td>Normal interior:</td>
<td>12</td>
<td>5</td>
<td>15</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>Urea, powdered with catalyst interior:</td>
<td>12</td>
<td>2-6</td>
<td>10</td>
<td>20</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>Intermediate-temperature setting phenol</td>
<td>Interior: 2-6</td>
<td>2-8</td>
<td>30-60</td>
<td>60-120</td>
<td>6</td>
<td>17</td>
</tr>
<tr>
<td>Resorcinol</td>
<td>Interior: 12 or more: 2-5</td>
<td>15</td>
<td>50</td>
<td>6</td>
<td>17</td>
<td>No (except with:</td>
</tr>
<tr>
<td>Molamine</td>
<td>Interior: 6-18</td>
<td>2-36</td>
<td>30-60</td>
<td>60-120</td>
<td>7</td>
<td>15</td>
</tr>
</tbody>
</table>

1 The values given in this table are approximations; for more exact information consult the text.

2 Where glue is completely cured by application of heat accompanied by adequate humidification before pressure is removed, merely cooling to room temperature is sufficient; where no heat is applied, a 5- to 7-day conditioning period is desirable.

3 Approximate temperature ranges designated as cold, room temperature, and intermediate temperature are given on page 7.

4 Includes glues both with and without separate catalyst.

Report No. D1635

Z M 79139
Table 2.—Minimum bending radius recommended for different thicknesses of clear straight-grained lumber of white oak, Douglas-fir, or southern yellow pine.

<table>
<thead>
<tr>
<th>Thickness of lamination</th>
<th>Recommended minimum radius of curvature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>White oak</td>
</tr>
<tr>
<td>Inches</td>
<td>Inches</td>
</tr>
<tr>
<td>1/4</td>
<td>18</td>
</tr>
<tr>
<td>5/16</td>
<td>24</td>
</tr>
<tr>
<td>3/8</td>
<td>36</td>
</tr>
<tr>
<td>7/16</td>
<td>43</td>
</tr>
<tr>
<td>1/2</td>
<td>58</td>
</tr>
<tr>
<td>5/8</td>
<td>73</td>
</tr>
<tr>
<td>3/4</td>
<td>73</td>
</tr>
<tr>
<td>13/16</td>
<td>79</td>
</tr>
<tr>
<td>1</td>
<td>105</td>
</tr>
<tr>
<td>1-1/4</td>
<td>140</td>
</tr>
<tr>
<td>1-1/2</td>
<td>178</td>
</tr>
<tr>
<td>1-3/4</td>
<td>217</td>
</tr>
<tr>
<td>2</td>
<td>256</td>
</tr>
</tbody>
</table>

Report No. D1635
Table 3.--Calculated percentages of moisture added to wood in gluing (five-ply construction)

<table>
<thead>
<tr>
<th>Kind of glue</th>
<th>Glue</th>
<th>Lamina</th>
<th>Hard maple</th>
<th>White oak</th>
<th>Mahogany</th>
<th>Douglas-fir</th>
<th>Southern yellow pine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>spread</td>
<td>:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casein</td>
<td>65</td>
<td>3/4</td>
<td>1.4</td>
<td>1.3</td>
<td>1.8</td>
<td>1.9</td>
<td>1.8</td>
</tr>
<tr>
<td>Do</td>
<td>95</td>
<td>3/4</td>
<td>2.1</td>
<td>2.0</td>
<td>2.7</td>
<td>2.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Do</td>
<td>65</td>
<td>3/8</td>
<td>2.8</td>
<td>2.7</td>
<td>3.6</td>
<td>3.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Do</td>
<td>95</td>
<td>3/8</td>
<td>4.2</td>
<td>3.9</td>
<td>5.3</td>
<td>5.5</td>
<td>5.1</td>
</tr>
<tr>
<td>Urea-resin</td>
<td>45</td>
<td>3/4</td>
<td>.6</td>
<td>.6</td>
<td>.8</td>
<td>.8</td>
<td>.7</td>
</tr>
<tr>
<td>Do</td>
<td>65</td>
<td>3/4</td>
<td>.9</td>
<td>.8</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Do</td>
<td>45</td>
<td>3/8</td>
<td>1.2</td>
<td>1.1</td>
<td>1.5</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Do</td>
<td>65</td>
<td>3/8</td>
<td>1.7</td>
<td>1.6</td>
<td>2.2</td>
<td>2.2</td>
<td>2.1</td>
</tr>
<tr>
<td>Resorcinol or intermediate-temperature-setting phenol</td>
<td>45</td>
<td>3/4</td>
<td>.4</td>
<td>.4</td>
<td>.6</td>
<td>.6</td>
<td>.5</td>
</tr>
<tr>
<td>Do</td>
<td>65</td>
<td>3/4</td>
<td>.6</td>
<td>.6</td>
<td>.8</td>
<td>.8</td>
<td>.8</td>
</tr>
<tr>
<td>Do</td>
<td>45</td>
<td>3/8</td>
<td>.9</td>
<td>.8</td>
<td>1.1</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Do</td>
<td>65</td>
<td>3/8</td>
<td>1.3</td>
<td>1.2</td>
<td>1.6</td>
<td>1.7</td>
<td>1.6</td>
</tr>
</tbody>
</table>

1Calculated upon following basis:

<table>
<thead>
<tr>
<th>Species</th>
<th>Specific gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard maple</td>
<td>0.63</td>
</tr>
<tr>
<td>White oak</td>
<td>0.67</td>
</tr>
<tr>
<td>Mahogany</td>
<td>0.49</td>
</tr>
<tr>
<td>Douglas-fir</td>
<td>0.48</td>
</tr>
<tr>
<td>Southern yellow pine</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Glue mixture: Casein - 1 part solids to 2 parts water (33 percent solids)
Urea resin - 1 part solids to 0.65 part water (61 percent solids)
Resorcinol and intermediate-temperature-setting phenol - 70 percent solids

Report No. DL635
Table 4.--Shear strength of glue joints in laminated construction of different species at various moisture content values

<table>
<thead>
<tr>
<th>Species</th>
<th>Moisture content</th>
<th>Increase in shear strength for each 1 percent decrease in moisture content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8%</td>
<td>12%</td>
</tr>
<tr>
<td>Redwood</td>
<td>910</td>
<td>850</td>
</tr>
<tr>
<td>Douglas-fir</td>
<td>1,100</td>
<td>1,030</td>
</tr>
<tr>
<td>Western hemlock</td>
<td>1,160</td>
<td>1,050</td>
</tr>
<tr>
<td>Pine, southern</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(shortleaf)</td>
<td>1,360</td>
<td>1,180</td>
</tr>
<tr>
<td>White oak</td>
<td>1,940</td>
<td>1,700</td>
</tr>
<tr>
<td>Sugar maple</td>
<td>2,450</td>
<td>2,100</td>
</tr>
</tbody>
</table>

Report No. D1635
Figure 1.—Laminated arches in service building at Forest Products Laboratory.
Z 70556 P
Figure 3.—Results of joint strength tests for various woods glued with casein, urea resin, resorcinol resin, and intermediate-temperature phenol resin glues.
Figure 4.—Methods of cutting sections from lumber for moisture-content and moisture-distribution determinations.
Figure 5.—Typical end joints which are glued and used in laminating.
Figure 6.—Spacing of scarf joints in a laminated assembly.
Figure 7.—Adjustable jig for laminating curved timbers.
Figure 8.--(A) Rocker-head type of 2-bolt retaining clamp used to apply pressure to a laminated assembly. (B) Curved laminated timbers in adjustable jigs.
Figure 9.--Laminated boat bilge stringers formed to a pattern including compound curvature and twist.
Figure 10.—Edge-gluing lumber laminations in piling clamps.

Z X 70562 F
Figure 11.—Aligning scarf joints for gluing. (A) correct with slight overlap, (B) incorrect, too much overlap, (C) incorrect.
Figure 12.--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.
Figure 13.—Three-speed electric mixer with 3- and 8-quart bowls and two sizes of paddles for mixing glue.

Z M 70663 F
Figure 14.—Yoke-type, single-bolt clamp used to apply pressure to two narrow assemblies.

ZN 70864 F
Figure 15.--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 16.—Cross sectional view of a fire hose press.
Figure 17.--Devices for measuring pressure applied to retaining clamps, (A) torque wrench and (B) compressometer.
Figure 18.--Detailed drawing of a compressometer used to measure gluing pressure.

Z M 70887 F
Figure 19.—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 phenol resin.
Figure 21.—Glue-line temperature at center of laminated timbers of 4-inch width and various thicknesses; curing chamber held at 210°F. and 80 percent relative humidity.
Figure 22.--Glue-line temperature at center of laminated timbers of 6-inch width and various thicknesses; curing chamber held at 2100 F. and 80 percent relative humidity.

Z M 51749 y
Figure 23.—Glue-line temperature at center of laminated timbers of 8-inch width and various thicknesses; curing chamber held at 210°F. and 80 percent relative humidity.
Figure 24.—Glue-line temperature at center of laminated timbers of 12-inch width and various thicknesses; curing chamber held at 210°F. and 80 percent relative humidity.

2 M 51751 P
Figure 25.—Glue-line temperature at center of laminated timbers of
4-inch width and various thicknesses; curing chamber held at 160° F.
and 80 percent relative humidity.
Figure 26.—Glue-line temperature at center of laminated timbers of 6-inch width and various thicknesses; curing chamber held at 160°F. and 80 percent relative humidity.
Figure 27.--Glue-line temperature at center of laminated timbers of 8-inch width and various thicknesses; curing chamber held at 160° F. and 80 percent relative humidity.
Figure 28.--Glue-line temperature at center of laminated timbers of 12-inch width and various thicknesses; curing chamber held at 160°F and 80 percent relative humidity.

2 M 70873 F
Figure 29.--Glue-line temperature at center of laminated timbers of 4-inch width and various thicknesses; curing chamber held at 125°F and 75 percent relative humidity.
Figure 30.--Glue-line temperature at center of laminated timbers of 6-inch width and various thicknesses; curing chamber held at 125°F. and 75 percent relative humidity.
Figure 31.—Glue-line temperature at center of laminated timbers of 8-inch width and various thicknesses; curing chamber held at 125°F and 75 percent relative humidity.

2 x 709/6 F
Figure 32.—Glue-line temperature at center of laminated timbers of 12-inch width and various thicknesses; curing chamber held at 1250°F and 75 percent relative humidity.
Figure 33.--Relation of dry-bulb temperature, relative humidity, and equilibrium moisture content of wood.
Figure 34.—Portable planer used for surfacing straight or curved timbers.
Figure 36.—Shearing tool and testing machine used in glue joint testing.
Figure 37.--Pressure tanks suitable for use in accelerated soaking and drying test of laminated sections.

3 X 70580 F
Figure 38. -- Laminated barn rafters (1-5/8 by 5-1/2 inches in cross section) continuous from foundation to roof peak. Spacing of rafters, 2 feet.
Figure 39.--Laminated hammerboards. Hard maple glued with urea resin.
Figure 40 — Laminated gun mount platform. White oak glued with intermediate-temperature-setting phenol resin.
Figure 41.--Laminated stem, keel, and stern assembly for 26-foot boat. Oak glued with intermediate-temperature-setting phenol resin.
Figure 42.—Railway trestle made of laminated pine timbers. Stringers, posts, and caps were glued from southern pine with intermediate-temperature-setting phenol resin glue and were pressure treated with creosote.

25W 70862 P
Figure 43—Laminated cross arm of Douglas-fir glued with intermediate-temperature-setting phenol resin.
Figure 47.--Glued laminated arches for cow barn.