

Summary
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LAMINATED WOOD CONSTRUCTION

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Summary :

STUDIES OF THE STRENGTH OF GLUED LAMINATED

WOOD CONSTRUCTION¹

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Introduction

Glued laminated construction has had a long history in Europe, particularly in Germany, Sweden, and Switzerland. A wide variety of applications were observed by a member of the Forest Products Laboratory staff on a European trip during which he inspected some 50 structures varying in age up to 25 years, all laminated with casein glue. He reported that members used in buildings in which normal atmospheric conditions prevail had not seriously deteriorated even after considerable periods of service. Casein-glued members used under more severe conditions, such as locomotive-repair shops, chemical plants, footbridges, and railway-platform structures, also were reported to have given good performance.

The use of glued laminated construction in the United States is much more recent, so that examples of extended service are not available. While definite information on the first uses of glue in structural members in this country is lacking, it appears that no extensive development in this field occurred prior to the installation of glued laminated arches in a building on the grounds of the Forest Products Laboratory in 1935. Since that time, however, the number and variety of applications have grown so remarkably that a new industry has developed.

Arches were among the first forms of glued laminated construction to find wide use in this country. The inherent structural efficiency of this form of support, together with the fact that it made available unobstructed floor area usable to a considerable height, resulted in the use of arch structures in industrial buildings, gymnasiums, and aircraft hangars. The possibility of varying the form to give the necessary pleasing and traditional effects, resulted in the application of considerable numbers of laminated arches in church architecture. The farm market in the past few years has absorbed an increasing amount of glued laminated construction in the form of curved rafters, particularly for barns, but for machine sheds, brooder houses, and other farm buildings, as well.

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Military requirements during World War II gave considerable impetus to the laminating industry. Not only did these requirements cover buildings of various types, but many other uses as well, including parts for aircraft and for wood vessels.

Exterior applications in the United States are less common. There are, however, a few instances of such applications. A footbridge in Madison, Wis., has given satisfactory service over a period of about 9 years. Laminated dredge spuds in use on the Columbia River have apparently performed satisfactorily over a period of 3 or 4 years. The railroads have installed a number of experimental bridges with a view to gathering service experience as to the suitability of laminated members because of the increasing difficulty of obtaining suitable one-piece members.

Advantages of Glued Laminated Construction

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

(a) Ease of fabricating large structural elements from standard commercial sizes of lumber. Laminated arches have already been erected that provide buildings with clear spans up to 170 feet, and, also, laminated beams of 80-foot span. Arches with sections as deep as 7 feet have been projected.

(b) Achievement of excellent architectural effects, and the possibility of individualistic interior decorative styling.

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

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

(e) The opportunity to design structural elements that vary in cross section along the length in accordance with strength requirements.

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

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

On the other hand, there appear to be no disadvantages of laminated construction as such. Modern glues and gluing techniques provide both adequate and effective means of bonding laminations into an assembly equal or superior in strength to a single-piece member of equivalent section. They may be selected to provide a laminated assembly that is water-resistant or waterproof,

as conditions of use may dictate. When properly glued, laminated members may be given preservative treatment by pressure methods much as solid members are treated, which will improve their resistance to decay when used under adverse exposure conditions.

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

(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) Since considerably more operations are involved in manufacturing laminated members than in manufacturing solid members, there are more possibility for error, and special care must be exercised in each operation to insure a product of high quality.

(e) Large curved members are difficult to ship by common conveyances.

Background of Research

The first research at the Forest Products Laboratory on the strength properties of glued laminated construction was begun in 1934 on curved members. This research, which covered a period of several years, studied a number of factors affecting strength, including the effect of curvature, end joints, and defects. It culminated, in 1939, with the publication of U. S. Dept. of Agriculture Technical Bulletin No. 691, "The Glued Laminated Wooden Arch." This bulletin not only presented the results of an extensive series of tests, but presented also recommendations on working stresses and design procedures. It has had extensive use, since its publication, as a basis for design and specification of this type of construction.

During World War II, it became increasingly apparent that additional research was necessary to answer the questions that arose with the development of this method of construction. Accordingly, with the cooperation of the War Production Board and industry, further work was undertaken at the Forest Products Laboratory, including the testing of a large number of full-size beams and columns to provide additional design data and information for technical phases of specifications. Factors investigated included the relative strength of members containing end joints of different types, the effect on strength of

defects in different laminations, the effect of varying the thickness of laminations, and like factors.

While this paper has for its major purpose the presentation of information on the strength of glued laminated construction, the author would be remiss if he did not mention the developments in glues and gluing techniques that have made this material so promising for the future. Prior to World War II, casein glue was the only adhesive reasonably acceptable for use in structural members, and its limitations under severe exposure were recognized. During World War II a number of synthetic resin adhesives suitable for use under severe exposure and capable of being set at room or intermediate temperatures (between room temperature and about 200° F.) were developed by the adhesive industry. Coincident with those developments, the Forest Products Laboratory pursued an active and continuous program of research on the properties of these adhesives and on the techniques of applying them for optimum results.

Results of Research

End Joints

Available lengths of lumber are frequently not adequate to provide full-length laminations for the larger structures. It is necessary, therefore, to join two or more lengths of lumber end to end to provide the necessary lamination lengths.

Butt joints are simple to make, since they require no special preparation of the ends of the pieces to be joined. Obviously, however, they have no strength in tension when not glued, and tests have shown that even when glued they are very low and erratic in strength, even the best gluing techniques affording no more than a fraction of the tensile strength of the wood. Further, even with the best techniques in fitting, butt joints can be expected to be only partially effective in transmitting compressive stress.

The longitudinal stress in a butt-jointed lamination is, of course, zero immediately adjacent to the joint and increases by transfer through shear from the adjacent laminations as the distance from the joint increases. Hence the excess of longitudinal stress in the continuous laminations over that in the jointed ones is a maximum at the joint and, consequently, the shear stress is a maximum at the joint, where it is very concentrated. The result is that shear failure starts adjacent to the joint and progresses as more of the length of the jointed lamination is relieved of its stress. Progressive failure of this character was observed in tests of beams containing butt joints.

Strain measurements made in the vicinity of butt joints in laminated beams indicate that the joints tend to cause considerable concentration of stress in the unjointed laminations. For example, strain in the region of a joint in the top lamination of a beam was found to reach a measured value as high as 2-1/4 times as great as the strain at the same vertical position in a cross section that was at some distance from the joint and subjected to the same moment.

Butt joints are undesirable, therefore, not only because they fail to transmit longitudinal stress, and therefore represent an ineffective area in a beam or column, but also because they concentrate both longitudinal and shear stress. Butt joints are additionally undesirable in curved laminations because of their effect on interlamination contacts in their vicinity. It is impossible to produce curvature right to the end of a square-ended piece. Hence, in the vicinity of butt joints, contact between adjacent laminations can result only from pressure sufficient to crush the wood and expel the glue, an occurrence that makes the joints between laminations locally deficient in resistance to shear.

When butt joints occur in adjacent laminations, tests have shown that the joints must be well separated if their effects are not to be additive. Even with a spacing as great as 30 times the lamination thickness, it appears necessary to consider both laminations ineffective in columns or in the compression portions of beams. When the joints are in the tension portion of a beam, at the spacing mentioned above, the strength is lower than would be estimated by considering both laminations ineffective, a fact that indicates the undesirability of using butt joints in members subject to tension stresses.

Tests have indicated that a scarfed joint, if carefully prepared, well glued, and of sufficiently flat slope, can have a considerable proportion of the strength of an uncut piece. Beams, arches, and columns containing scarf joints gave test results nearly as high as did similar members having continuous laminations. Tests of individual joints indicate considerable variability, so that some conservatism is desirable in assigning allowable stresses to jointed members. Tests of members containing scarf joints in adjacent laminations indicate the desirability of separating such joints, but have not provided a firm basis on which to establish spacing rules.

Many other types of end joints have been proposed and some are in use. The data available are generally inadequate to establish the stresses that should be assigned to them. These joints generally have a form that is designed to facilitate alignment of the two pieces and to provide additional gluing area. Difficulties in accurate machining of the mating parts, and small changes in shape due to moisture changes, may actually result in less effective gluing area than in a plain joint.

Effect of Knots

In solid timbers, the position of defects within the cross section of a member is essentially fixed by the location of the defects in the tree. In laminated members, however, the location of defects can be more or less controlled. This fact opens up the possibility of producing members combining high-strength and low-strength material in a single member. It would appear that a beam of relatively high strength could be produced if the defective material were placed near the neutral axis and the high-strength material in the outer portions of the depth.

This possibility was explored in tests of curved members by combining defective and clear material in various proportions. The results indicated that up to about 60 percent of defective material in the central portion of a laminated arch would not seriously reduce the strength below that of members consisting entirely of clear laminations.

The same problem was studied in somewhat greater detail by means of an extensive series of tests on beams and columns containing knots in various combinations of size and placement. The data from these tests afforded a somewhat more complete relation between strength and knot size and placement.

Inasmuch as the strength of a beam depends upon the moment of inertia of its cross section, it seemed valid to assume that the reduction in strength caused by knots could be related to the moment of inertia of the parts of the cross section occupied by the knots. Obviously, knots that are reasonably near to each other longitudinally would have nearly the same effect as if they were at the same cross section. For each beam, there was computed a value of I_K , the sum of the moments of inertia of all knots within 12 inches of the central cross section.

A study of the data revealed a relation between bending strength and the ratio I_K/I_G , where I_G is the gross moment of inertia of the beam. Both modulus of rupture and fiber stress at proportional limit decrease with increasing values of I_K/I_G , with the rate of decrease becoming larger at the greater values of I_K/I_G . Contrary to experience from tests of solid timbers, the modulus of elasticity was found also to decrease with increasing values of I_K/I_G .

Recommendations for Design

Time limitations have permitted covering only two of the more important phases of research on this subject. A considerable number of additional phases, however, have been studied in more or less detail. Among those are: effect of lamination curvature on strength, strength of curved members in radial tension, the shear strength of members in which gluing pressure was obtained by nailing, shear strengths of both knotty and clear beams where gluing pressure was applied with clamps, and the effect of both knots and end joints on the strength of columns. The data from these studies form the basis for a manuscript currently in preparation and presenting recommendations of the Forest Products Laboratory with respect to the design of glued laminated construction. It is expected that these recommendations, together with those of the Laboratory on methods of fabrication, will be published as a technical bulletin of the U. S. Department of Agriculture.

Future Research

While the research discussed herein represents a considerable body of knowledge on the subject, which permits the designing of laminated structures with reasonable confidence, there still remain problems to be solved.

During the past year, the Forest Products Laboratory has made additional studies on the spacing of end joints in laminations. The results, while affording useful information, were not conclusive. Further, the possible combinations of joints are myriad, presenting an endless array of possible tests if all were to be investigated. Some attempt should be made to develop a theory of joint action to simplify the problem.

It has long been known that deep beams develop, in test, lower stresses than do shallow beams, and that box or I-beams develop lower stresses than do beams of solid section. Two independent investigations of the effect of depth have developed two different expressions for depth effect, which vary considerably from each other. The maximum beam depth tested was 14 inches. Yet beam or arch depths of 3 feet are not uncommon, and an arch with a depth of 7 feet has been projected. In designing at such depths the Laboratory is on uncertain ground. It needs, therefore, to investigate the effect of depth over a considerable range and to study the fundamentals of this phenomenon.

The weakness of some Douglas-fir in shear has been noted in test. If it were found that Douglas-fir were markedly stronger in shear in the radial than in the tangential plane, it might be advantageous, for cases where shear-strength requirements are high, to use laminations so cut that the plane of shear would be radial. The Laboratory proposes to study this problem and to investigate the possibilities.

The items mentioned above represent only a few of the more urgent problems still to be solved. There are many others.