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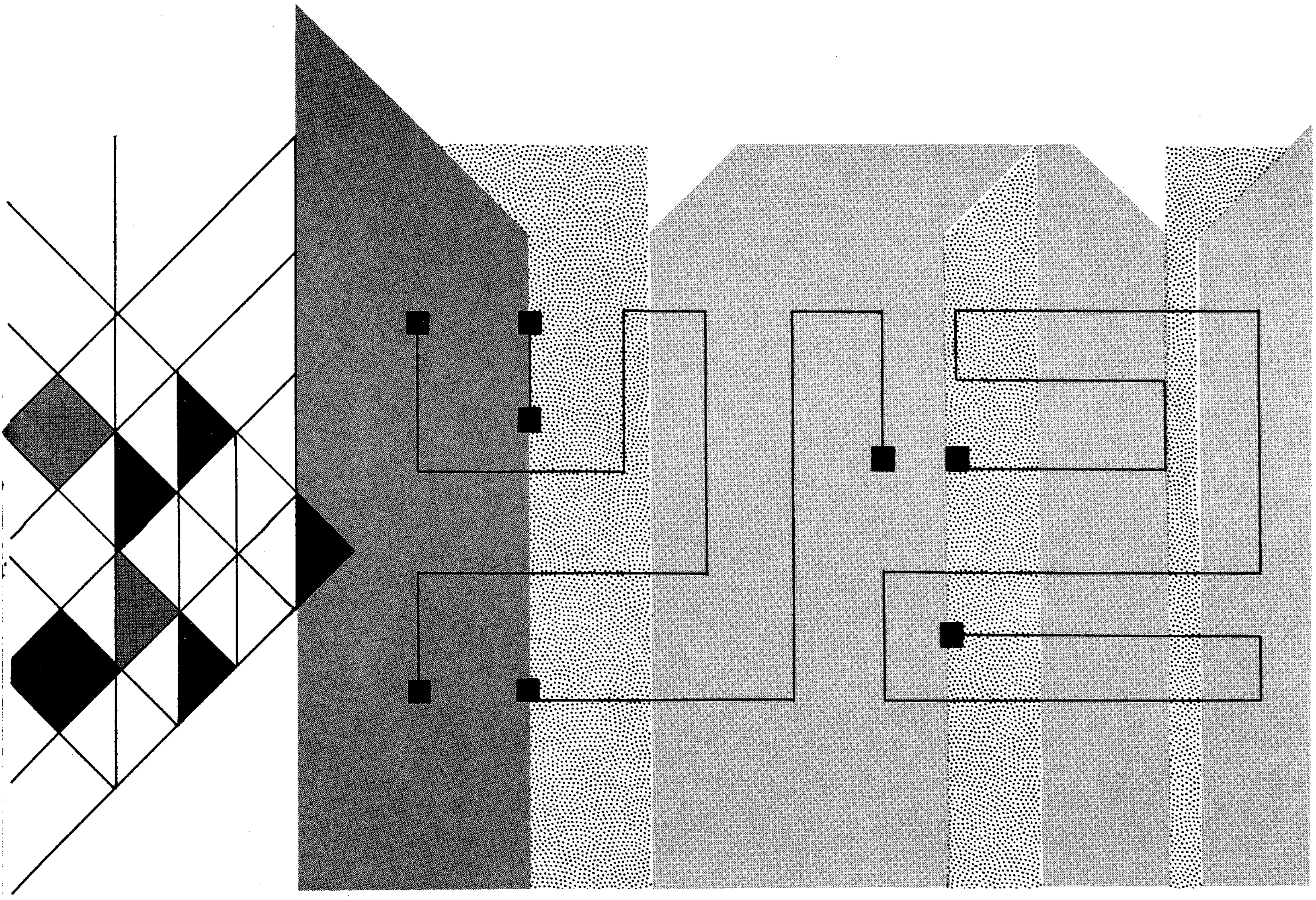
Experimental Techniques for Determining Mechanical Behavior of Flexible Structural Adhesives in Timber Joints



U. S. DEPARTMENT OF AGRICULTURE | FOREST SERVICE | FOREST PRODUCTS LABORATORY | MADISON, WIS.

SUMMARY

This report describes three experimental techniques for determination of specific mechanical properties of the adhesive layer between two pieces of lumber. The properties are stress relaxation, modulus of rigidity, and creep. They are measured in a small joint segment when loaded in compression shear so that the strain in the adhesive film can be measured at each level of stress without the usual complications of strain in the wood itself. The apparatus and procedures are described for each determination, but no actual test data are reported.

Experimental Techniques for Determining Mechanical Behavior of Flexible Structural Adhesives in Timber Joints

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INTRODUCTION

Information on the mechanical properties of an adhesive as a material is one of the two essential parts of a rigorous adhesive joint design. The other essential part is a satisfactory stress analysis. This paper is concerned only with methods for obtaining material properties. At present most conventional wood glues are rather rigid materials when cured in the joint. Most glue joints, such as in laminated timbers or plywood, are designed to use such glues satisfactorily. However, there are a number of joint types, such as joints of lumber oriented at large angles to the grain, where a somewhat less rigid and more deformable glueline may be a distinct advantage. An extreme example is gluing deck boards to runners in a wood pallet. In this instance, some movement within the glue film might prevent excessive damage in the wood, oriented at 90° when subjected to significant moisture changes as well as impact loading. Many flexible adhesive systems are available outside the wood industry. These systems have adequate initial strength to be considered useful for such special wood–bonding applications, although they sometimes do not meet the standards of conventional structural wood glues. Whether these systems have the other necessary properties, including permanence, is not yet known.

Some typical examples of flexible adhesive systems are the many epoxy–polysulfide systems, epoxy–amine systems, and the polyurethanes. Such an adhesive can be cast into a finite–thickness glue film in a joint so that the adhesive's function is not only to transfer shear but also to act as a structural component with predictable mechanical behavior. These structural units can then be effective composites of the plastic adhesive layer and the wood.

In most structural applications, a wood adhesive is required to transmit a constant external shear stress resulting from a dead load on the component. This stress may continue indefinitely. In addition to a dead load, some form of short–term live load is usually applied. These loads can be shock type, vibratory, or sustained and may produce an additive stress or completely reverse the direction of stress from that of the dead load. Compounding these effects are the internal stresses induced by swelling and shrinking of the wood as a result of moisture content changes in the adherends. Such internal stresses are partic–

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

ularly severe in joints where the angle of the grain of wood in adjacent plies approaches 90° The worst condition is at 90° when high-density species are involved.

It is necessary to completely definethe stress-strain-time relations of the material to determine if an adhesive is satisfactory for such structural joints under cyclic moisture changes, as well as being mechanically functional under the actions of external loads. These relations must be defined under conditions of changing relative humidity and temperature as well as cyclic loading. Finally, the durability of the system must be determined under the action of destructive environmental conditions.

For some- years, engineers have studied the mechanical properties of the glueline and their relationship to the design of a glued joint. Most work has been concerned with metal-to-metal bonds, particularly in simple lap joints. This is because structural bonding in aircraft and missiles has been of great concern and interest. Some work has included determinations, either directly or indirectly, of the modulus of rigidity of the glueline.[2,3,4] One particularly promising method for measuring stress-strain conditions in metal-to-metal joints is a torsion method[4] which introduces essentially true shear. However, torsion evaluations on wood itself are not well developed and torsion of glued-wood joints was not considered in the present study.

PURPOSE

The purpose of this report is to present an experimental method, consisting of three techniques developed recently at the U.S. Forest Products Laboratory for determining the mechanical properties of an adhesive. The techniques provide a quantitative determination of stress-strain-time characteristics for any type of flexible adhesive system that can be used as a wood adhesive without complications from deformations in the wood itself.

The techniques used are: (1) modified relaxation at essentially constant strain; (2) shear modulus (G) at specified rates of load; and (3) creep at constant stress. All three techniques use the same specimen design, which is a small isolated segment of the glue film in a joint. The strain-recording aspect of the creep and. modulus evaluation is accomplished by a photographic procedure.

The specimen design described in the original presentation of this method for determining the modulus of rigidity[5] is also used in these evaluations. Since the original work, the method has been modified to utilize a photographic recording of strains instead of a laborious microscopic technique. There are some improvements in the equipment and procedure for this modulus of rigidity technique, along with the addition of the relaxation and creep evaluation.

All the techniques are relatively rapid and provide sufficiently accurate data for adhesives intended for structural wood applications, when the shear modulus of the adhesive does not exceed 50,000 pounds per square inch. With more rigid adhesives the amounts of strain are too small to be readily measured precisely by the photographic method used.

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[2] Eickner, H. W. Basic shear strength properties of metal-bonding adhesives as determined by lap-joint stress formulas of Volkersen, and Goland and Reissner. Forest Prod. Lab. Rpt. 1850. 1955.

[3] Goland, M., and Reissner. E. The stresses in cemented joints. Jour. of Appl. Mech. 11(1):A-17-A-27. 1944.

[4] Kuenzi, E. W., and Stevens, G. H. Determination of mechanical properties of adhesives for use in the design of bonded joints. U.S. Forest Serv. Res. Note FPL-011, Forest Prod. Lab., Madison, Wis. 1963.

[5] Krueger, G. P. A method for determining the modulus of rigidity of an adhesive in a timber joint. Materials Res. and Stds. 2(6):479. 1962.

CRITERIA FOR COMPARISON OF ADHESIVES

The information obtained from the three evaluations results in both design data and comparative data.

The relaxation technique is usually completed first for elimination purposes. An adhesive, to be structurally useful, must have a relaxation limit as well as a creep limit. If the relaxation evaluation shows that a definite limit in the drop of stress is reached in a reasonable length of time, such as 24 hours, it is considered worthy of further evaluation. At the present stage of design for wood adhesives, it is not possible to define specific limits for such stress relaxation to a high degree of certainty.

For the present, it can be arbitrarily assumed that to be suitable for certain structural applications in wood, an adhesive, when first loaded to 50 percent of its ultimate stress, shouldnot relax to more than half of this value. This evaluation permits comparison of the performance of different adhesives and improvements in a given formulation with respect to amount of relaxation and length of time to a limit.

The modulus of rigidity evaluation primarily provides design data, an independent function. It also, however, provides a comparison of the relative flexibility of adhesives through definition of the function G = Stress/Strain. These criteria are explained in more detail in the section describing the modulus test.

The creep evaluation is probably most important from the standpoint of long–time behavior of the adhesive. From a design standpoint, the importance of retaining a specified load over a long period of time is self evident. From a comparative standpoint, the amount of creep expressed as a percentage of an initial strain at a given stress level provides a comparison. The length of time to reach a creep limit is also important, but no performance standard can be put on minimum acceptable values at present. The demands of a particular application are usually unique.

EXPERIMENTAL PROCEDURE

Specimen Description and Design

The same design of specimen was used for all three techniques. The specimen consists of an isolated glue segment cut from a two–ply laminated assembly of 1–inch lumber with the grainparallel to each piece. (fig. 1).

Several different assembly and bonding conditions may be used to obtain a joint of sufficient size to permit slicing of an appropriate number of specimens (fig. 1). It has been foundthat approximately 100 of the 0.09–inch–wide slices are required for a complete evaluation. A hollow–ground table saw produces a clean accurate slice for most wood species. A high–speed jigsaw is suitable for cutting saw kerfs to isolate the adhesive test segment.

This particular specimen design was chosen to obtain a shear stress condition in the adhesive segment without complications of excessive tensile or compressive stresses. This is achieved by cutting the cantilever segment and inserting a wedge at the free end. Thus, the specimen is analogous to a structural beam fixed at one end and simply supported at the other. The load is then applied very near the wall end (just above the adhesive film) to produce a stress which is primarily shear in the adhesive. Most of the applied load $\underline{P}$ is transmitted directly through the adhesive to produce the wall shear $\underline{V}$. Attempts have been made to measure the percent of $\underline{P}$ which is carried by the simple support $\underline{R}$. A calibrated load cell was mounted on the specimeninplace of the wedge.

In all instances, for adhesives with shear moduli from 150 pounds per square inch to 25,000 pounds per square inch, the reaction $\underline{R}$ was found to be less than 1 percent of the applied load $\underline{P}$. Thus, in the present method, the observed load applied to the segment $\underline{A}$ is considered as the shear load on the joint area.

In both the creep and shear modulus evaluations, the applied load and the shear strain are the only quantities measured. In these evaluations, shear strain parallel to the glueline is considered to be independent of any normal tensile or compressive stresses so that the magnitude of the normal stresses is of little concern. However, average shear stresses as high as 1,500 pounds per square inch have been developed in the specimen without a peeling–type failure. This is good evidence that the normal stresses are very low.

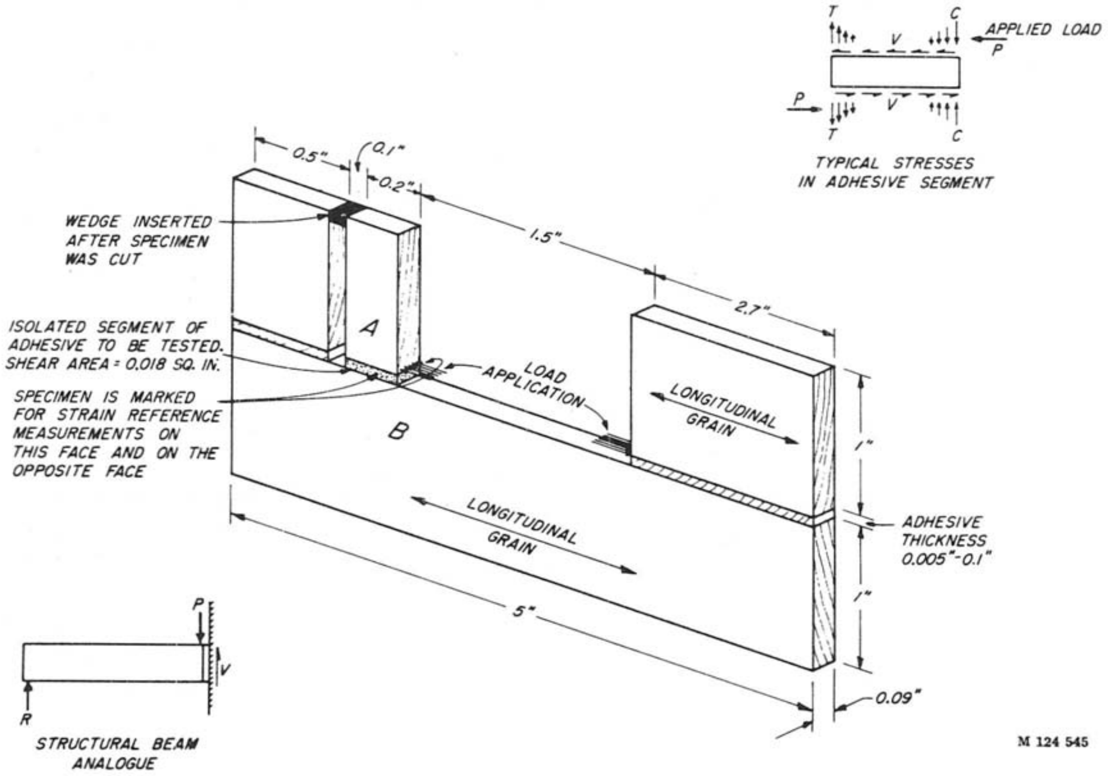

Figure 1.––Wood specimen showing dimensions and points of load application. The actual joint area under evaluation is shown between pieces A and B.

Contrary to the usual behavior of a beam with one end fixed and the other hinged, the normal tensile and compressive stresses developed in the specimen with a very flexible adhesive (G=100 to 500 pounds per square inch) will be as shown in the upper right–hand insert in figure 1. The normal stress directions were obtained by observing the Poisson effects through a high–powered stereo microscope for many different adhesive specimens.

It was concluded that the stress condition obtained is one of nearly pure shear, at least sufficiently so for measurements of surface strains on the adhesive film, independent of strains in the wood. The conclusion was reached after many evaluations of this type of specimen.

Stress and Strain Measurements

In order to give quantitative meaning to the data resulting from the evaluation techniques, all shear loads must be carefully applied, and the intensity and the resulting shear strains carefully measured.

Stress determination.––The directionof the load applied to the specimen is shown in figure 1. The basic equipment for applying this shear load is illustrated in figure 2.

A steel cantilever arm has two temperature–compensating foil strain gages mounted on the narrow faces. This armis mounted on analuminum base and has a matching lever attached to it with screws. This device operates like a draftsman's compass. By turning one or both of the thumb screws, the arms separate or approach each other, thereby exerting a force on anything fastened between them. The strain gages are connected to a standard SR–4 strain indicator unit. The loading unit was calibrated on an Instron testing machine so that microinches of strain in the arms represent the specific load P applied to the specimen.

Figure 3 illustrates a typical specimen, for all the tests, mounted on the load applicator. The specimen is loaded adjacent to the glueline (fig. 1), and the wood wedge is inserted at the bottom of the sawcut as previously described (fig. 3).

An increment of applied force divided by the shear area of 0.018 square inch results in the average applied shear stress increment $\Delta\tau$.

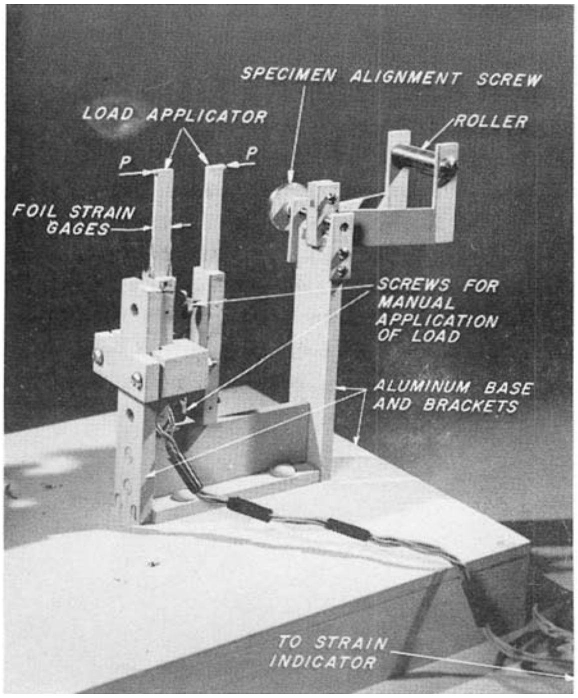

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Figure 2.--Basic equipment used for application of shear load in all adhesive evaluations.

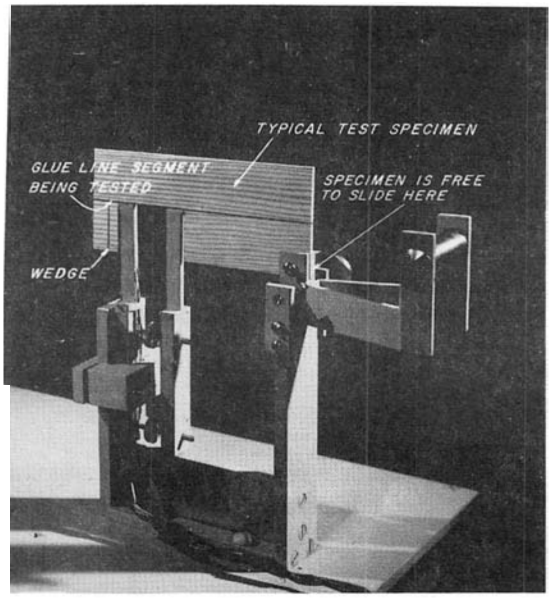

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Figure 3.--Typical specimen mounted on loading device.

Strain determination.--In any subsequent evaluations when stress-strain-time relations are obtained, the strains (shear deformations at both edges of the joint) are carefully recorded for each load increment. These shear strains were determined from photographs of the relative displacements of a series of index marks placed on the surface of the adhesive film.

The two longitudinal faces of the glue joint segment that are parallel to the direction of the load are marked for strain measurements. One of these faces is shown in figure 1. This markingconsists of enamel dots, razor scribe lines, or any convenient form of distinguishable reference point or line. Figure 4 shows an enlarged view of two sides of a typical specimen with reference marks applied. One line of dots is used to establish a base line, the other is used for displacement measurements.

Figure 4 is a typical example of the technique of photographing strains corresponding to any specific load increment. Photographic records are taken on either 35-millimeter color slides or 16-millimeter color movie film, depending on the rate of load required and the recording speed required. The image is magnified approximately 1-1/2 to 2 times in the camera.

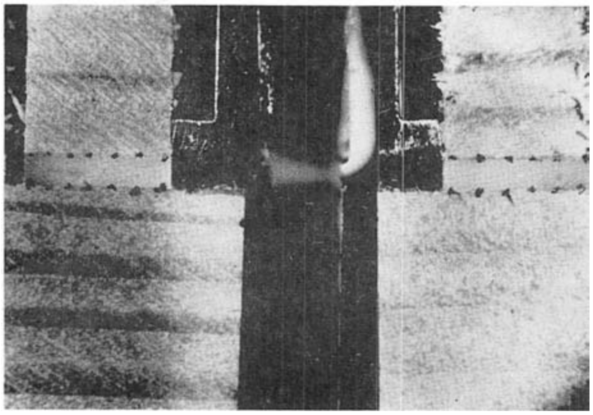

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Figure 4.--Enlarged view of adhesive segment showing strain reference points (black dots). When observed from the camera's viewpoint, both sides of the adhesive are shown, by reflection. in the two mirrors.

Figure 5 schematically represents an enlarged adhesive film segment with typical displacements that might occur under any increment of shear load.

It is assumed that the strain variation through the depth is as line $\underline{x}$ rather than $\underline{x'}$ (fig. 5). It is also assumed that the shear strain variation is linear transversely as line $\underline{Y}$ rather than $\underline{Y'}$. If the adhesive volume is assumed homogeneous and isotropic, then the deformations δ_1, δ_2, etc. (fig. 5) define the longitudinal strain at different locations in the direction of the applied load. $\underline{T}$ is the glueline thickness. The shear strain at any point is the quantity $\gamma_n = \frac{\delta_n}{T}$ or the tangent of the angle θ_n. The average strain at each of 10 locations is used for each stress level.

Measurement of strains for successive loads is accomplished by projecting onto a piece of paper the 35-millimeter slides or 16-millimeter film to about 100 times magnification. The relative longitudinal displacements and glueline thickness of each reference point are obtained on the projected image. They are obtained by manually measuring the position relative to a fixedpoint on the particular film or the position relative to the reference point positions on the film for zero load.

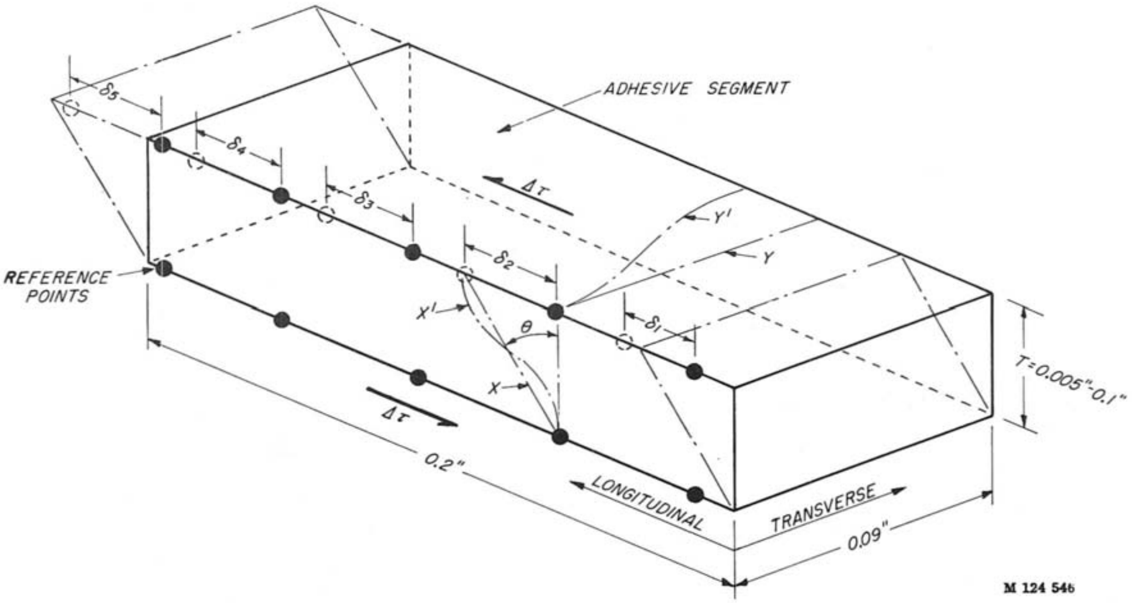

Figure 5.--Adhesive segment showing typical shear displacements resulting from an incremental shear stress. Linear displacement is represented by the δ designations and angular displacement by the θ designation

METHODS

In this section each of the three determinations is described. The results are illustrated by hypothetical curves, based on actual studies of adhesives using these techniques. It should be emphasized that most of the present experimental determinations of adhesives in the present study were made using rather unusual adhesives. Most of the adhesives were experimental laboratory formulations obtained from chemical manufacturers. The exact compositions of these adhesives were not disclosed. These adhesives were quite different from conventional wood glues. Some were actually sealants rather than structural adhesives. They were studied primarily because of a current interest at the Laboratory in partially deformable gluelines from a rather basic viewpoint without specific applications in mind. Adhesives studied to date had moduli of rigidity from 150 to 50,000 pounds per square inch as determined by the method described. Creep characteristics varied from only a few percent of the initial strain to 100 percent unrecoverable strain.

Since the adhesives used could not be adequately identified in this report, the only data reported, therefore, are illustrative or hypothetical curves showing general performance. These curves are based on actual experimental data from the study and are not unusual, except as the adhesives themselves are unusual as wood glues.

Modulus of Rigidity

The modulus of rigidity is commonly termed "shear modulus" and may be considered as the slope of the shear stress-strain curve. For this evaluation, the strains are recorded photographically on 35-millimeter color film for various load increments.

The equipment used for this technique is shown in figures 6, 7, and 8. Figure 6 shows the specimen in the loading apparatus, the strain indicator used to determine stresses applied as described previously, and the camera and lighting system mounted on the aluminum base.

Figure 7 shows two small mirrors mounted over the glue segment in a special frame. These mirrors are oriented at 45° to each side of the specimen so that the camera records the closeup of both sides of the glue segment on one slide. A closeup of the camera's view is shown in figure 8. Figure 4 illustrates the typical photograph produced by this method.

The significance of this modulus of rigidity data depends on the rate of load used during the evaluation. It has been customary in this work to run a series of three stress-strain-time curves for each adhesive using three separate matched specimens. If the relaxation evaluation shows that the drop of load occurs in a matter of seconds, it is practical to determine a lower boundary of the stress-strain-time behavior by loading at a slow enough rate so that no drop of load results during the evaluation. All relaxation then occurs while the load is being applied. In the second evaluation, the specimen is loaded at a standard rate of load of 25 pounds per square inch per second or 1,500 pounds per square inch per minute for comparison of adhesives. In the third evaluation, if it is desirable to determine more nearly the true elastic modulus, the load can be applied manually at a maximum rate of 1,100 pounds per square inch per second. This rate of load was determined by recording the strain indicator dial movement with a high-speed 16-millimeter movie camera (8,000 frames per second). The corresponding strains are also measured by means of this same camera.

Hypothetical data from this modulus of rigidity determination are shown in figure 9. Ordinarily the stress-strain relationship of a given adhesive is time dependent. Curve A represents the lower boundary or least modulus stress-strain curve

Figure 6.--Equipment for modulus of rigidity evaluation.

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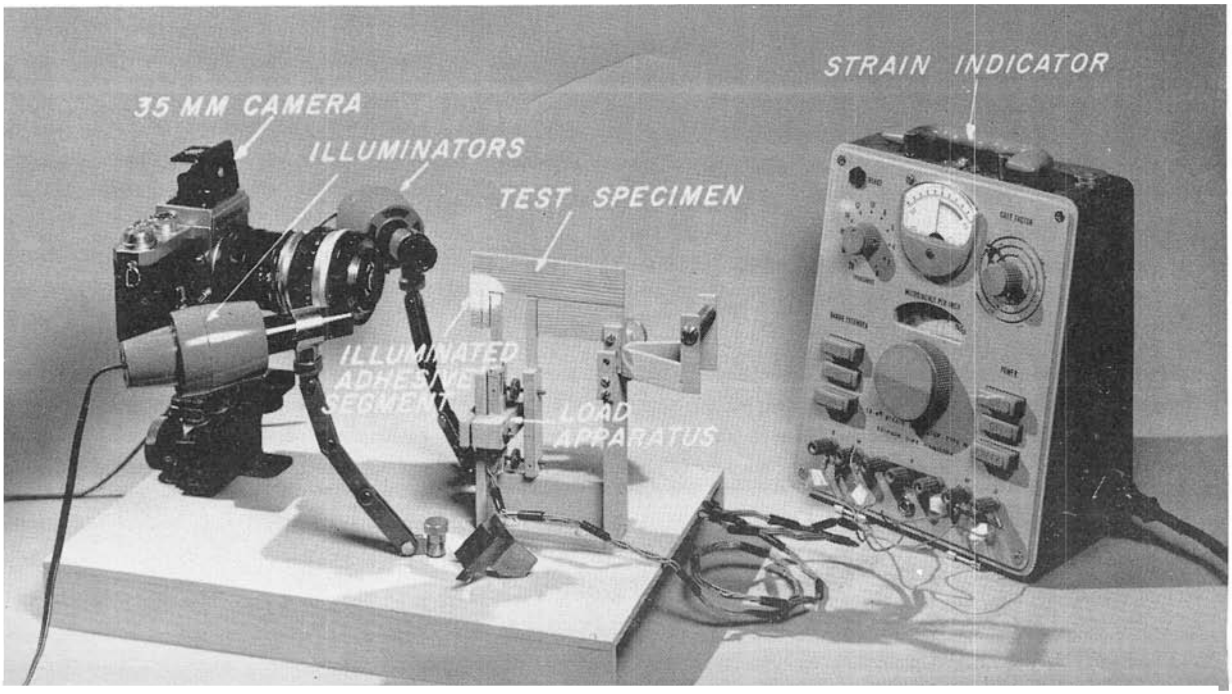

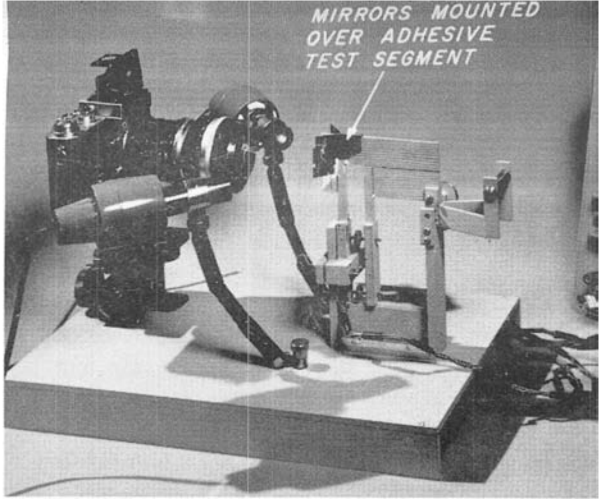

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Figure 7.--Mirrors mounted on the specimen for modulus of rigidity evaluation.

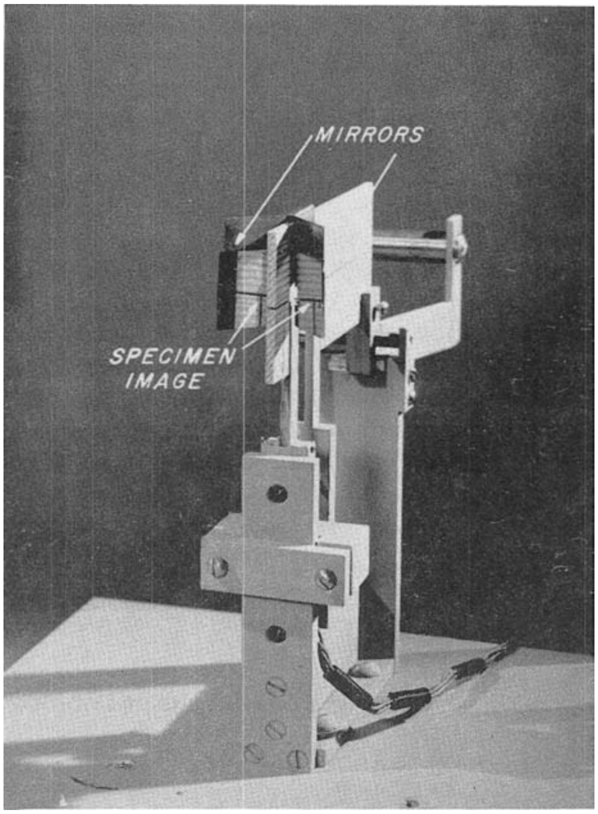

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Figure 8.--Closeup of camera's view. The specimen image is reflected by the mirrors.

typical of a slow rate of loading. Curve B is a standard rate of load curve. Curve C is very nearly the true elastic shear modulus as measured at a high rate of loading. Of course, if the response is independent of time, all three curves will coincide.

This information is used for predicting the stress-deformation behavior of the adhesive in any practical application. The stress-strain determination can also be conducted under a variety of temperature and humidity conditions. The criterion for comparison of adhesives is the modulus of rigidity or the slope of the stress-strain curve.

$$G = \tau / \gamma = \text{pounds per square inch}$$

where τ = average shear stress previously defined, and γ = average strain previously defined. It is not unusual to have nonlinear stress-strain curves, in which case the modulus can be defined as a nonlinear function:

$$G = \tau / \gamma^{n} = \text{pounds per square inch}$$

or by the slope of a secant to the curve, providing a secant modulus for a specified intensity of stress or strain.

Stress Relaxation

A true stress relaxation determination is one in which the specimen is quickly stressed and the resulting strain is held constant. The initial load is allowed to decrease with time as a result of rheological changes in the adhesive. This is carried out at constant temperature.

The equipment for this technique consists of the load applicator, the strain indicator bridge, and a paper recorder (fig. 10).

An initial load is applied to the specimen at a rate of 1,100 pounds per squareinchper second to minimize unmeasured relaxation. This rate of load is the fastest that can be obtained by manually turning the load applicator screws. The exact load is determined by initially unbalancing the strain indicator by an amount equivalent to the desired load. When the needle in Dial A on the SR-4 recorder reaches the balanced position, the load has been applied. The paper recorder records the stress values as shown on Dial A.

Zero load and full load limiting points are plotted on the recorder paper before the test. Thus, even though there is an instrument lag in the paper recorder, the full amount of load relaxation is recorded. There is a small amount

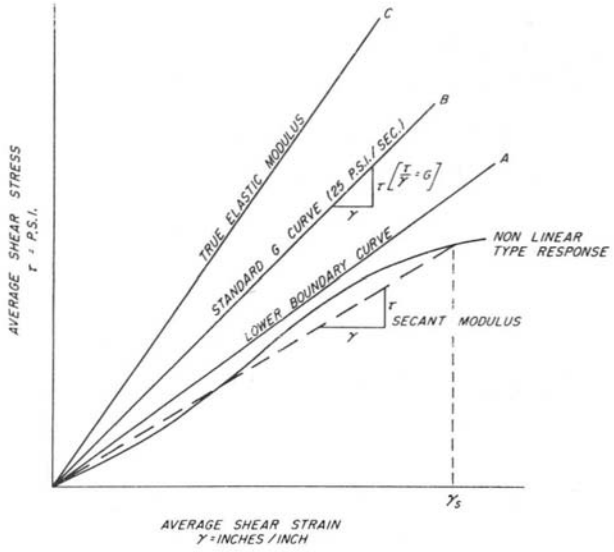

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Figure 9.--Hypothetical data resulting from the modulus of rigidity evaluation.

of play in the screws of the load applicator. To evaluate this play, specimens of Douglas-fir without adhesive were studied, and this loss was found to average 0.16 pound, or 6 microinches per inch, for Douglas-fir of average specific gravity. Hypothetical data from this evaluation are given in figure 11. Curves A and B would represent relaxation data for the same adhesive loaded initially to two different levels. The difference $(t_a - t_b)$ between times when stress relaxation levels out at each stress level (relaxation limits) indicates the time dependence, and $(\Delta\tau_a - \Delta\tau_b)$ indicates the load dependence of the relaxation limit. It is not unusual to have an adhesive relax almost completely as shown by curve C.

The technique, which is a part of this evaluation series, is a modified relaxation determination in that the applied strain increases simultaneously as the initial load drops off. This increase in strain results from the elastic deflection of the load applicator (fig. 2). The ratio of increased strain from elastic deflection of the applicator to initial strain is independent of load level, but is a function of the elastic modulus of the adhesive and glueline thickness.

If an adhesive that was 0.030 inch thick, with a G equal to 100 pounds per square inch, would relax 100 percent of an arbitrary initial stress, the corresponding percentage increase in strain over the initial strain would be 3.8 percent. The formula used to give this value for the particular applicator used here is:

$$\text{Percent} = 0.00114 \; G/T$$

where G = elastic modulus of rigidity of adhesive; T = glueline thickness.[6] For a given G and T, the percent increase of strain is also in direct pro-

Figure 10.--Equipment used for modified relaxation evaluation.

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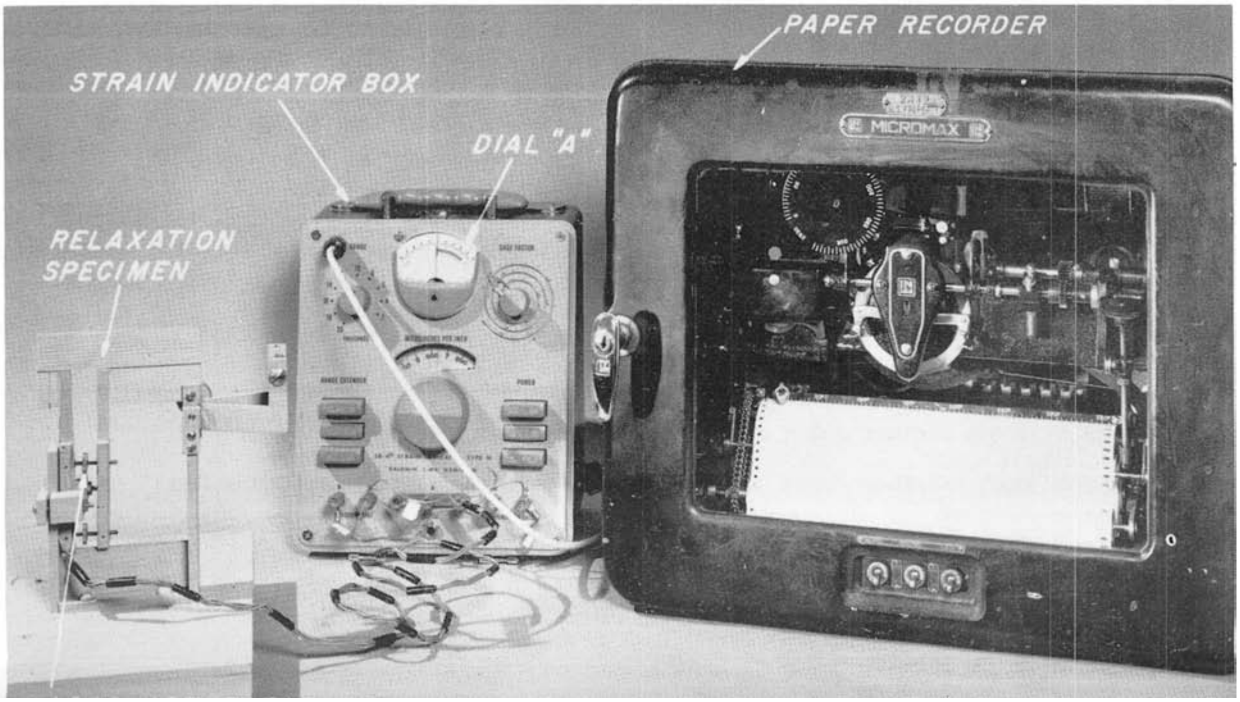

portion to the drop in load. As another example, if an adhesive has a G of 1,000 pounds per square inch and a glueline thickness of 0.010 inch, the average creep for 100 percent relaxation is 11.4 percent of the initial average strain. If the relaxation determination shows a stress relaxation of 10 percent of the initial average stress, then the average flow has been one-tenth or 11.4 percent of the initial average strain. As a result of this modification from a true relaxation technique, the technique is used for purposes of preliminary evaluation or elimination.

Creep properties are actually the most important part of the entire evaluation system. It is possible to first determine if the adhesive has a combined relaxation and flow limit. Second, it is possible to determine if the flow characteristics are load dependent as well as time dependent. Third, it provides an indication of the amount of creep under constant load that can be anticipated. These considerations are shown diagrammatically in figure 12.

Line ABF represents the true elastic stress-strain or response curve. At an initial stress of τ_2, the true relaxation test would yield line BC and the true creep test at constant stress would yield line BE. Similarly, at an initial load τ_5, FG is the relaxation curve and FI is the creep curve.

The present method yields straight lines BD and FH, both of which must have the same slope. It is assumed that the decreases in $\tau_2 - \tau_3$ and $\tau_5 - \tau_6$ are the result of combined relaxation and creep. If this combined phenomenon has a limit, it is concluded that the material will have a creep limit at constant stress. This limit is a very important requirement of the structural adhesive. The difference between $(\tau_5 - \tau_6)$ and $(\tau_2 - \tau_3)$ is an indication of the load dependence on stress relaxation.

The difference between time τ_2 and time τ_1 gives an indication of the time dependence. It can also be concluded that if the specimen is loaded at constant stress τ_2, the creep will be at least $(\gamma_3 - \gamma_1)$. Similarly, if the constant stress of τ_5 is applied, creep will be at least $(\gamma_6 - \gamma_4)$.[7]

Creep

The final evaluation is a true creep determination at constant stress. In this case, increasing strains are recorded while the load is held constant.

The specimen is loaded to a specified load level as rapidly as possible with the equipment described here, the rate being 1,100 pounds per square inch per second. The load is held constant while the increasing strains with time are recorded photographically as previously described. After the creep or increase in strain has ceased, the specimen is unloaded, and the recovery is also recorded photographically. As in the two previous evaluations, this technique can be run at any temperature or relative humidity in which the apparatus can be operated. This information supplies the designer with data necessary for predicting time-dependent deformations in any structural application.

The equipment used for this technique is shown in figures 13 and 14. The same type of record of strains at each time periodunder constant stress, as shown in figure 4, results from the photographic procedure, with photographs taken at any desired time intervals.

The creep record can be taken with a 35-millimeter camera. The specimen is loaded with a predetermined dead weight using a separate metal loading fixture attached to a nylon cord and weight (fig. 13). The calibrated lever arm of the load applicator is positioned so that it does not bear on the specimen. The load is verified with the strain indicator. The use of the strain indicator eliminates the possibility of undetected friction losses. A balanced bridge insures that

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[6] The derivation of the formula giving percent increase in strain is included in the Appendix.

[7] The relaxation limit hereafter refers to the limit obtained with the modified relaxation test subsequently described.

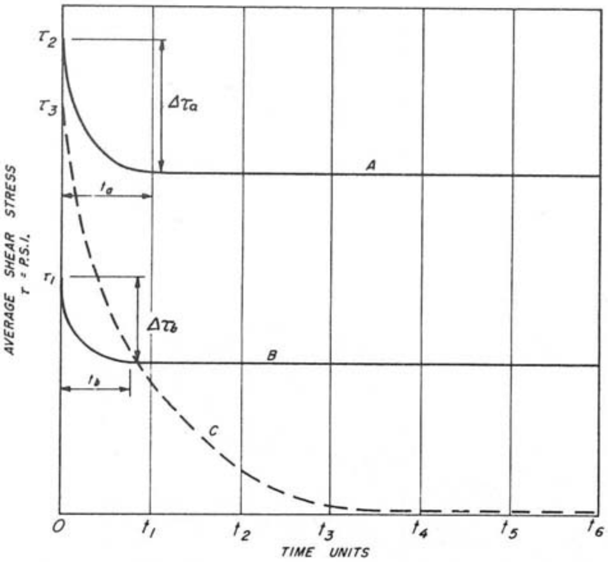

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Figure 11.--Hypothetical data from stress relaxation determination.

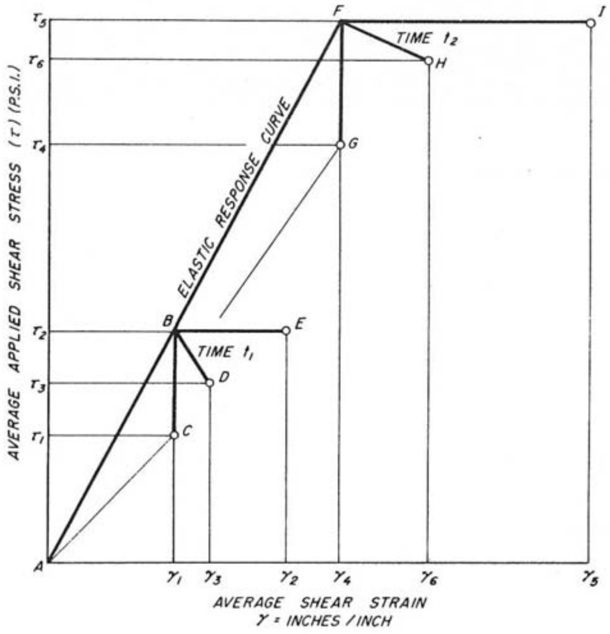

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Figure 12. --Diagram of adhesive behavior during modified stress relaxation determination.

the load is constant. As in the relaxation technique, the initial load is applied very rapidly at approximately a rate of 1,100 pounds per square inch per second by dropping the weight.

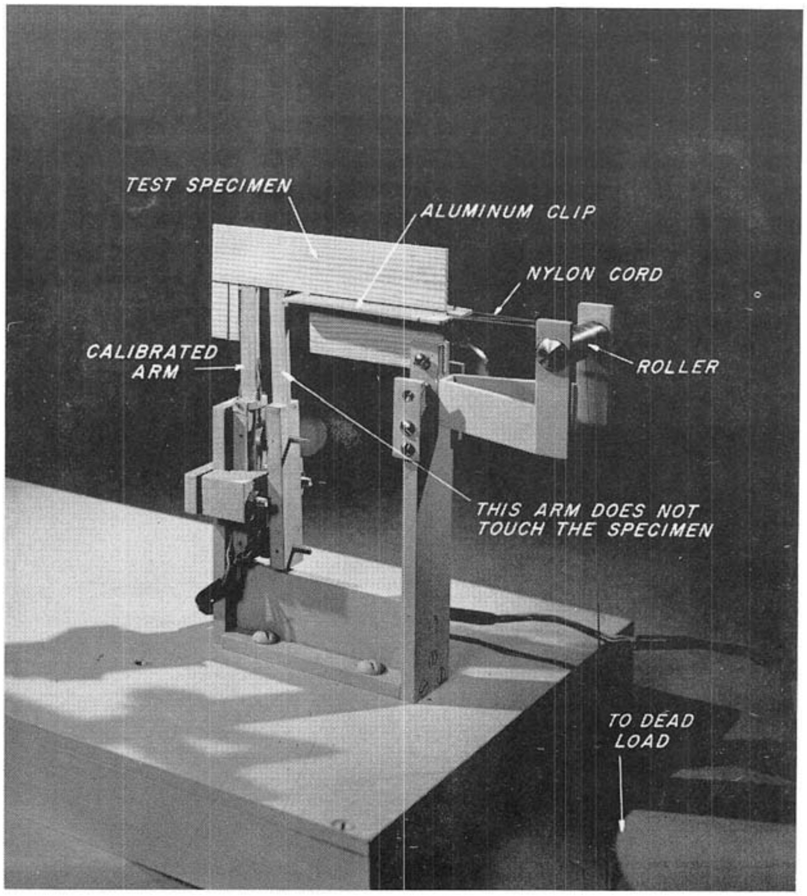

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Figure 13.--Closeup of creep specimen loaded with dead load.

It has been found that use of time-lapse movie equipment is convenient for the creep technique. This equipment is shown in figure 14. The initial strain is recorded continuously, usually at a rate of 24 frames per second on 16-millimeter color film. At the instant the proper load is reached, the camera is stopped and set to take one frame per minute. After creep has stopped, the instantaneous release of load is photographed at the rate of 24 frames per second, and the camera is again set back to 1 frame per minute until it is estimated that the recovery has stopped.

Hypothetical data from this creep evaluation are shown in figure 15. Curve A is the initial elastic response. Curve B is the time-dependent creep at constant stress and Curve C is the recovery curve after the load has been released. Unrecoverable strain may or may not exist.

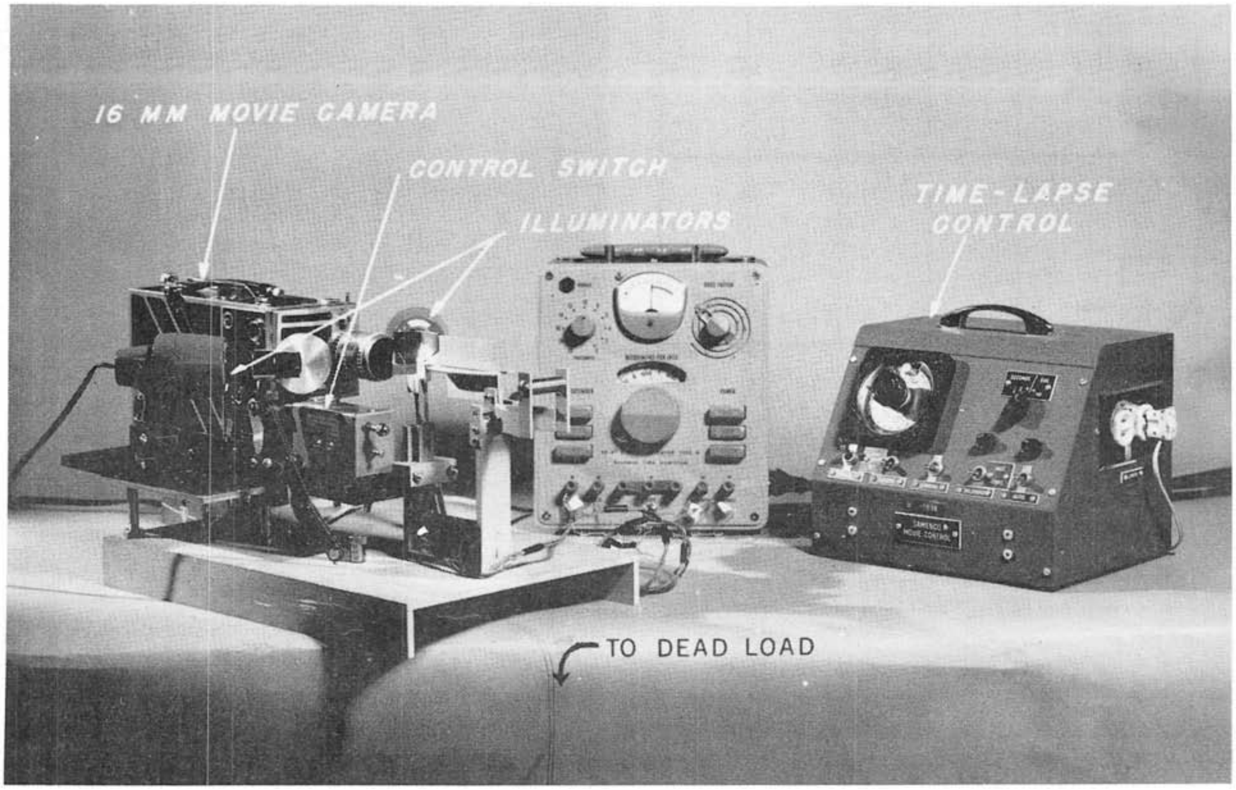

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Figure 14.--Creep evaluation equipment with 16-millimeter movie camera and time lapse control.

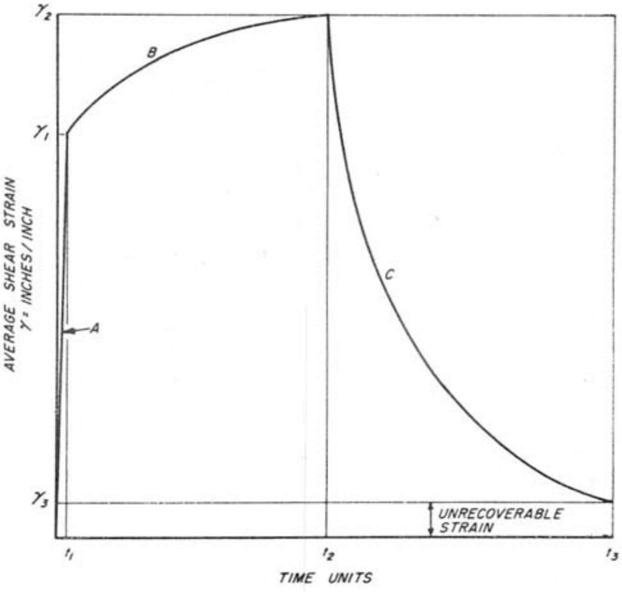

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Figure 15.--Hypothetical data from creep determination at constant stress.

CONCLUSIONS

The stress relaxation, modulus of rigidity, and creep techniques are considered to be useful for quantitative determinations of mechanical properties of gluelines in wood under the conditions described. The techniques have been under development and use at the U.S. Forest Products Laboratory for several years. Other improved techniques, for determining the basic mechanical properties of the glueline in the joint, will eventually become standardized. The techniques will thus serve as useful criteriafor specification development and acceptance of new adhesives for new future uses to supplement data from conventional failing load evaluations of joints.

APPENDIX

Modified Stress Relaxation Evaluation

The relaxation technique described in the text is slightly modified from a true relaxation evaluation at constant strain because of the elastic bending deflection in the load applicator arms.

As the load relaxes, there must be an accompanying increase in strain in the adhesive. The recorded load will not drop unless there is a decrease in elastic deformation in the lever arms. This phenomenon results from the fact that the strain gages are mounted on the lever arm and their function depends on the strain in the arm

Figure 16 shows the lever arms in place against the specimen as in both the modulus of rigidity and stress relaxation determinations. Figure 17 shows an instantaneous load applied and the accompanying elastic deflection in the lever arm and adhesive.

The applied load drops as a result of rheological changes in the adhesive. This must be accompanied by the reduction in elastic bending deflection in the lever and an increase in strain in the adhesive (fig. 18).

The derivation of the formula for increased percent strain for a given relaxation is as follows:

Initial elastic deflection in two lever arms:

$$\delta_L = 2 \times \frac{PL^3}{3EI} = \text{inches}$$

where P = 1 unit; E = 30 x 10^6 pounds per square inch (for steel); L = 2 inches; $I = \frac{1}{12} \times 0.125 \times (0.30)^3 = 0.000281 \text{ inch}^4$; and $\delta_L = 0.000633$ inch per pound.

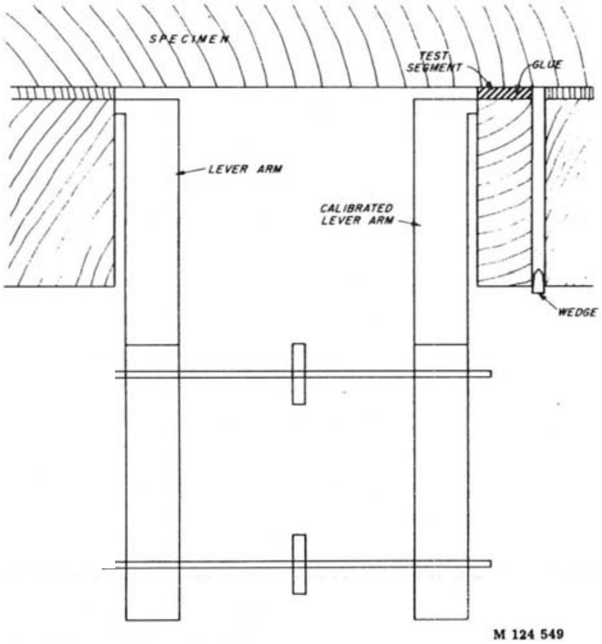

Figure 16.--Lever arms of load applicator in position against specimen. No load applied.

Corresponding initial average elastic shear strain of the adhesive

$$G = \frac{P/A}{\delta_{A/T}} \qquad \gamma_A = \frac{P/A}{G}$$

where P = 1 unit; G = elastic modulus of rigidity:

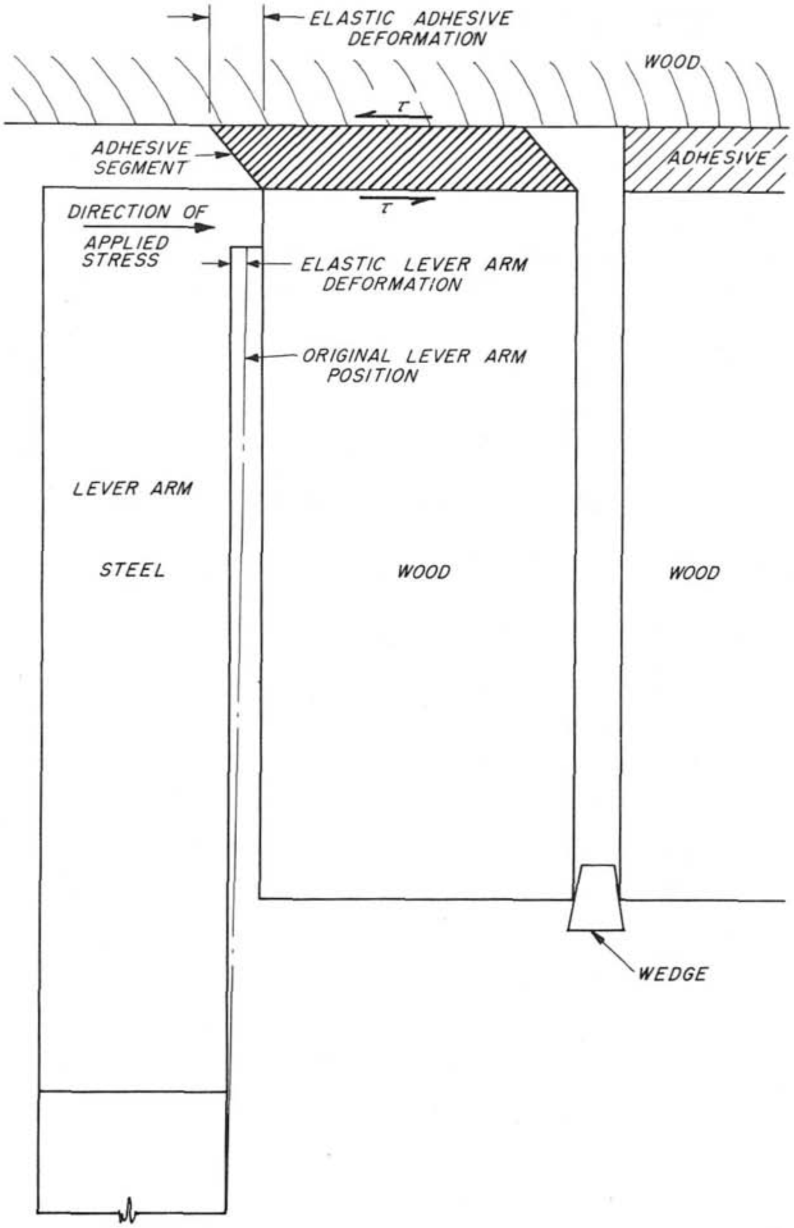

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Figure 17.--Relation of lever arm and adhesive under action of instantaneous load.

A = 0.018 inch^2; and $\gamma_A = \frac{1}{0.018\ G} = 55.6/G$ inches per inch per pound.

If the wood relaxes a given percent of initial stress, there must be an equivalent elastic deflection decrease in the lever arm equal to $\Delta\delta = 0.000633$ x Percent relaxation/100 inches per pound. This deformation results in an increased adhesive strain of $\Delta\gamma = 0.000633$ x Percent relaxation/100 x $\frac{1}{T}$ inches per inch per pound where *T* is glueline thickness. The percent increase in adhesive strain over the initial strain is equal to:

$$\text{Percent} = \frac{\Delta\gamma}{\gamma} =$$

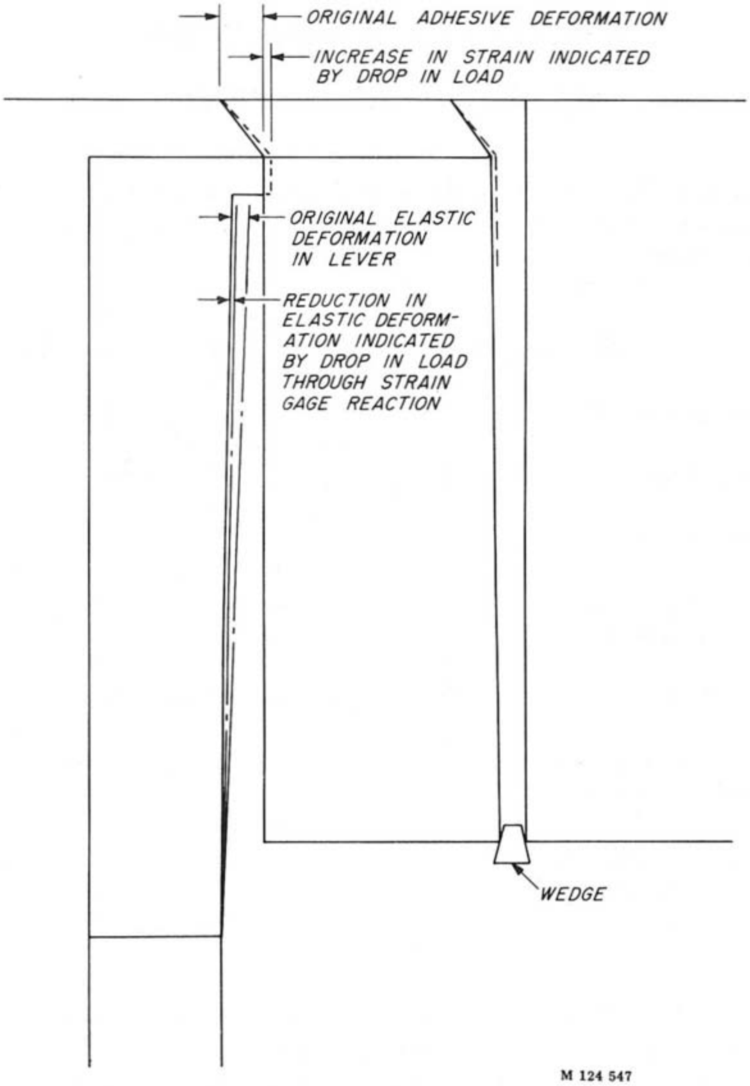

Figure 18.––Relation of lever arm and adhesive after relaxation and drop in load.

$$\frac{0.000633 \text{ x Percent relaxation}/100 \text{ x } \frac{1}{T} \text{ x } 100}{55.6/G} = 0.000114 \, \frac{G}{T} \text{ Percent relaxation}$$

For 100 percent relaxation the percentage increase in creep = 0.00114 $\frac{G}{T}$, the formula given in the text.

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