Abstract

Recommends a system for evaluating adhesives to supply required data on both performance and permanence of adhesive bonding in building construction. A main problem in selecting and using any adhesive to meet specific performance requirements has been the lack of suitable information for the architect and design engineer.

This evaluation system provides data for specific design situations that can be related to anticipated levels of stress and deflection, as well as the critical nature of each adhesive application. Involved are mechanical property measurements, duration of loading, variability, quality control, and effects of service environments.

The system involves also accelerated aging to forecast durability properties for 50 years and longer.

The resulting broad, integrated approach involves information needed by adhesive formulators, raw material manufacturers, and architects and design engineers to secure dependable adhesive bonding in building construction.
EVALUATING ADHESIVES FOR BUILDING CONSTRUCTION

by

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Many people recognize that adhesive bonding of assemblies in building construction has great promise. Adhesive bonding can lead to more efficient use of materials with prospects of lower costs and better performance. But what do we really require of an adhesive?

The answer depends on how critical is the use of the adhesive, its location in the building, the different climatic conditions to be met in service, and the character of loads imposed on it. Which adhesives are good enough for each specific application--and how do we tell? Further, the proper design may permit adequate performance with an adhesive while another design would prevent it from performing as required.

More efficient use of conventional and new building materials involves increased use of the systems approach where adhesives play an increasing role. New and different adhesives are continually being developed and proposed for use in these systems. An orderly and adequate method of evaluation and appraisal of their properties is necessary if houses and other structures are to be constructed safely, economically, and efficiently.

This paper considers the relevant properties of an adhesive so that we can rationally design in the same way as with any structural connection. The discussion is generally in terms of bonding wood, although the principles will apply to other adherends as well.

1 Presented in part at the ASTM D-14 committee meeting on adhesives, October 7, 1971, in Williamsburg, Va.

2 Maintained at Madison, Wis., in cooperation with the University of Wisconsin.
Conventional Adhesive Practice

Conventional adhesives for bonding wood structurally have always produced the strongest joints when applied to freshly machined, well-fitted surfaces with bonding under pressures of 150 to 200 pounds per square inch. This required such careful attention to details that proper bonding was possible only with suitable quality control, such as could be obtained in factories. Field gluing for structural purposes was not recommended nor generally practiced. Conventional adhesives gave a rigid, thin glueline that was, for structural design purposes, stronger than the wood itself; therefore, the designer ignored the glueline and concerned himself only with the design stresses for the adherends.

The only exception to this practice was related to selection of the adhesive used. Beyond such factors as pot life, temperature of set, and rate of cure, the important factors from the engineering standpoint were durability (resistance to exposures possible or probable in service) and possible creep under long-continued service loadings. Once the selection was made, it had no further influence on design.

These restraints limited adhesive applications for building construction to a few specialized structural elements—glued-laminated beams and arches, trusses, wood-plywood box beams, and some stressed-cover wall, floor, and roof panels.

Adhesive Bonding in Building Construction

The assembly of components for buildings, as now being practiced, does not allow close control over bonding conditions. For this purpose, adhesives must be capable of bonding a surface as is without machining, be competent to fill gaps between poorly fitting surfaces, and be able to form adequate bonds under relatively low pressures. They should provide sufficient time after adhesive spreading for the components to be assembled, but should set soon after at a rapid rate so the assembly can be moved without damage to the bond. Many of the new and essentially unproved adhesives hold promise of fulfilling these requirements. Assemblies will include both those made in the factory and those made in the field.

The question is: “How can we evaluate adhesives so we can be sure they meet construction needs?”

No simple set of tests answers all the questions posed by raw material manufacturers, adhesive formulators, design engineers, code agencies, lending institutions, contractors and builders, and others involved in providing better housing at reasonable costs. Some users select adhesives on the basis of durability, mechanical properties, and behavior in fire situations. Others are interested in characteristics associated with their use—working properties, bonding requirements, and cost. (Too often adhesives are sold mainly on the basis of cost and how simple they are to use.)

Broader interest among all groups is on durability, the mechanical properties, and performance in fire. But this is where we find the greatest gap in our storehouse of information on adhesives. This is where the major research effort should be placed to assure the proper selection and use of adhesives in building construction.

The Forest Products Laboratory has had a long-standing interest in seeing that our Nation’s timber resources are used wisely and efficiently. While dealing primarily with wood, the Laboratory’s scientists appreciate other materials useful in building construction. Consequently, they recognize the need to use the most appropriate material; in some instances this may mean combining wood with another material to take maximum advantage of the unique properties each has to offer. The role adhesives can play in this combining process has been of concern throughout the years, becoming increasingly important as adhesive technology brings forth new materials. Out of these concerns has evolved a plan of attack on the problem of evaluating adhesives for use in buildings.

Systematic Adhesive Evaluation for Strength

The evaluation system described here is a step-by-step process of accumulating fundamental information on the durability and mechanical properties of adhesives and how these properties vary with time and changes in temperature and moisture conditions. The evaluation system makes use of test methods already accepted as stan-
standard, modifies standard methods where needed, and may encourage development of new methods.

There are essentially three stages of evaluating an adhesive: (1) Qualifying an adhesive for a particular use; (2) evaluating bonded joints for the intended use; and (3) determining the quality control needs for manufacturing the joint.

In qualifying an adhesive for an end use, the adherends should be selected for high strength and stiffness so the physical properties of the adhesive have maximum opportunity to control the strength level. Only high-quality, well-bonded specimens should be tested to determine the maximum capability of the adhesive.

In evaluating joints for an intended use, well-bonded joints should be prepared with different adherends—those that will be used in construction. Here, the interaction between adherend properties and adhesive properties is evaluated.

In determining quality control needs, tests should be designed to evaluate bonding condition variables that may affect bond quality. These establish the limits under which satisfactory bonds can be formed and underlay a quality-control program to insure that the adhesive is properly used.

Nature of Uses

It is important to analyze the different places where adhesives could be used to assemble materials into an element or join modules to form a building. The nature of the use dictates the different facets of design as well as the adhesive requirements.

The ‘nature of the use,’ can be classified roughly into five categories:

1. Prime structural, with contribution to strength and stiffness for the life of the structure.
2. Semistructural, with contribution to stiffness for the life of the structure.
3. Temporary structural, with requirements for strength or stiffness for a period shorter than the life of the structure.
4. Secondary structural, where failure due to service loading would not involve life safety or major structural damage, and the failure would be readily recognized and easily repaired.
5. Accessory and trim attachment.

Most critical category is prime structural where strength and stiffness are required throughout the service life. Next most critical is semistructural use, where failure would not result in loss of structural integrity. Field-glued floor systems can be in this category.

An example of temporary structural is the critical need, but for only short periods, to improve over-the-road resistance during the transportation of panels, modular structures, or factory-built homes. Both stiffness and strength are important during transportation because loadings are dynamic and energy absorption is critical.

Secondary structural classification is more difficult to define and describe. The criteria of what constitutes “nonmajor structural damage, readily recognizable, and easily repaired” are relative. In a recent design problem where two modules were joined, a field connection met these criteria. At the upper junction of the two modules, a connection transferred lateral wind forces from one module to the other. When both modules were connected there was an adequate resistance to the racking forces. However, if the connection failed, the unit on the windward side would deform until it contacted the leeward unit, then both units would combine to resist the total force. The first one would not be damaged by the displacement required to bring it into contact, so this was considered a ‘secondary structural application.’ A failure would be readily recognized and easily repaired. While annoying, there was no danger from the life-safety standpoint.

Least critical is use for accessory and trim attachment, sometimes termed cosmetic applications. Here, replacement through redecoration is expected and can be performed without detriment to the structure.

In all instances, the objective must be that the adhesive will function as an engineering material.

Estimating Long-Term Durability From Short-Time Studies

For all adhesives, it is essential that we know something of their long-term performance. It is most important for prime structural applications and has some bearing on all classifications of use except those adhesives for short-lived structures. For new adhesives the most urgent need is to
predict accurately how long and well they will serve. One way is to study how fast a bonded specimen will lose its strength in a controlled environment. This approach is currently being pursued at the Forest Products Laboratory. It is an attempt to isolate the causes of adhesive-bond degradation and study each as a separate influence as much as possible.

The causes of adhesive-bond degradation are heat energy, chemical energy, and mechanical energy. Basic measurements to allow the calculation of this energy or its effect are those of temperature, chemical concentration (which can be moisture or some other chemical), and force (which in wood joints includes the swelling and shrinking stress as well as those imposed by service loadings).

In actual practice, measurements are made of how fast strength changes in a controlled environment. Thus this system of durability evaluation is called the rate process method. The rates of degradation are accelerated by exposing specimens to elevated temperatures, with the measured results then being extrapolated to service temperatures for forecasting the adhesive’s service life.

The effects of the degrading factors are evaluated in the order of: (1) Dry heat, (2) moisture, (3) chemicals, (4) swelling and shrinking stresses, and (5) micro-organisms.

An adhesive for building construction should resist thermal degradation at service temperatures. Hopefully, it should resist dry heat as wood does, for wood will last up to thousands of years in desert climates. After demonstrating that an adhesive has high resistance to dry heat, then elevated temperatures can be used to study the effects of moisture or other chemicals with the assurance that thermal degradation will be minimal.

The effects of moisture often govern whether or not an adhesive can be used in exterior environments or whether its use should be restricted only to interior application. For this reason, forecasts of life expectancy should be made for joints at different levels of moisture content.

The effects of chemicals that may be present in the adhesives, in the substrates, or in the surroundings can be evaluated by the rate process techniques as interactions in the dry heat or moisture evaluations. Chemicals that may affect adhesive durability include catalysts and other ingredients in adhesives, extractives, fire-retardant and preservative treatments in wood, metallic ions from metal adherends, oxygen from the air, and air pollutants. Each may require special evaluation.

An example of how the rate process techniques are used for adhesive durability forecasting is shown in figures 1 and 2 for evaluating dry heat effects on mastic-type construction adhesives. Many specimens, lap shear specimens in this case, are exposed under no load at a controlled temperature and sets are removed periodically for strength tests.

The logarithm of shear strength is plotted against time in figure 1 to give least squares regression lines for each exposure temperature. From this, the time for half the shear strength to be lost is calculated in each case. The log of these half-life values is then plotted against the reciprocal of the absolute temperature to yield the straight-line relationship shown in figure 2. This temperature-dependence relationship, first proposed by Arrhenius many years ago and further defined by Eyring and coworkers more recently, adequately describes the strength-loss data. It is the key to forecasting service lives by extrapolation (dashed lines in fig. 2).

Adhesive A would lose half its shear strength by thermal degradation in 1,600 years at 27°C (80°F.), while adhesive K would take only 350 years.

The same techniques can be used to evaluate the effects of moisture. Lower temperature levels are generally used and the amount of moisture present is carefully controlled. The easiest control is by “swamping” the bondline with water as in the water-soaked condition. The shear strength half-life values so obtained are plotted in the same manner as in figure 2, resulting in another line lower and to the right, which extrapolates to shorter half-life times under service conditions.

Similarly, the effect of oxygen can be determined in an oxygen bomb test by measuring strength loss rates as expressed by half-life times. With adhesive formulations that contained effective antioxidants, this increase in oxygen
Figure 1.--Effect of heating upon strength of mastic-type adhesive bonds.

concentration did not accelerate strength loss above that caused by thermal effects. With formulations containing ineffective antioxidants, half-life times fell well below that occasioned by thermal degradation. In this manner, cause and effect relationships in the degradation process can be established.

This rate process technique uses extensive extrapolation outside the range of experimental conditions used---something all of us were taught not to do. However, the challenge is to come up with a system that has any better scientific validity to forecast durability to 50 years and beyond.

The effect of swelling and shrinking stresses on adhesive durability has been difficult to evaluate, particularly by rate process techniques. But research is continuing. It is quite likely that bonds fracture because of a combination of circumstances depending upon the mechanical properties of the adhesive, the properties of the adherends, and the size and geometry of the joints. Mechanical property measurements might shed some light on the swelling and shrinking factor as a cause of degradation. This factor has traditionally been evaluated by two types of standard cyclic exposure tests. In one, a physical property test is applied to specimens before and after a particular cyclic exposure sequence, such as described in ASTM C-481 and D-1183. In the second type, the extent of bondline delamination is measured after a cyclic exposure, as exemplified by ASTM D-1101 and D-2559. Similar useful tests appear in industry and product standards.

The effect of micro-organisms is a special case that can be evaluated by standard procedures. Usually all that is needed is the answer to the question: “Do micro-organisms attack the adhesive or not?” The standard ASTM tests D 1174, D 1286, and D 1877 can provide the answers.

4 Titles of these and other ASTM Standards mentioned in this paper are given at the end of the report.
Mechanical property measurements need to reflect the ability of a bonded joint to sustain loads in the expected range of service conditions. The effect of maximum temperatures must be assessed. In roof sections, maximum temperatures as high as 160° F. are not uncommon, while outside walls may reach 120°F., and floors usually range from 60° to 90° F. The temperatures used in accelerated aging range from 140° to over 290° F., so it is necessary to extrapolate the results back to the service temperature range. However, with mechanical properties the measurements can be made in the actual temperature range of interest.

Data should be collected on each adhesive so the engineer can select the most appropriate one for a specific design requirement. Because of the different temperatures and moistures possible in service, adhesives are evaluated at 80°, 120°, and 160° F., both wet and dry. The dry tests would simulate normal conditions in floors, side walls, or roofs. The wet test would reflect adverse conditions such as leaks in roofs, moisture condensation in side walls and roofs, or flooding of floors by plumbing leaks.

Evolution of Design Stresses

To design rationally with any adhesive, an engineer must know its long-term durability, and what adjustments he must make for loading, variability, service conditions, and margin of safety.

One approach to solving this problem is suggested by the way design stresses are assigned for wood. Values for the mechanical properties of clear wood specimens (ASTM D 2555) are converted into design values by a series of factors that adjust the ideal situation to that of a real-life situation (ASTM D 245). If this analogy is applied to an adhesive joint, using shear stress as an example, an equation like the following would develop the design stress:

Design = Mean Stress x Variability x Exposure x Quality x Safety x Duration x Load Factor
increased one-third because of the shorter duration.

The challenge is to design test procedures that will yield accurate estimates for each factor with as much efficiency as possible.

In developing design criteria and uses for engineering materials, all stress conditions usually must be considered--tension, compression, and shear in all planes. In gluelines, however, two applications are important--tension perpendicular to the glueline and shear along it. With the conventional thin rigid glues in wood, design stresses for the gluelines themselves were not considered because it was assumed that gluelines were stronger than adherends. With the, wide variety of adhesives available today, and many used in thick gluelines as with construction adhesives, this assumption can no longer be made.

Two types of testing units are required, a universal testing machine and a dead load apparatus. The load–deformation curve from the universal testing machine will provide the short–term rupture stress, shear modulus, shear slip stress, and stress and slip at the proportional limit. The time–deformation record from the dead load apparatus will yield information on creep properties and time to rupture.

One series of measurements, run on a universal testing machine (UTM), uses parallel-plate shear specimens under the following conditions:

- Highest quality bond
- Shear loading: Cyclic at low strains to measure shear modulus; followed by loading to rupture in 1–3 min.²
- Measurement: Load–deformation record
- Temperature: 80°, 120°, 160° F.
- Moisture: Dry and soaked
- Glueline thickness: 10, 30, 60 mils

Ten or more replications yield mean values for each property and a measure of the variability factor. When measurements are made at three different temperatures and two moisture conditions, estimates of the factor for exposure result. If different glueline thickness levels are evaluated, part of the quality control factor may be estimated. These tests are for short-term or live-load situations.

For long-term dead loads another set of measurements needs to be made with a continuous-load apparatus. The same kinds of specimens can be used in compression shear under the following conditions:

- Highest quality bond
- Load levels: 90, 80, 70 . . . ? pct. UTM value
- Measurement: Time–deformation record
- Temperature: 80°, 120°, 160° F.
- Moisture: Dry and soaked

The applied loads should be selected fractions of the values obtained on the universal testing machine for the adhesive in question. The time to rupture provides the information for the factor accounting for duration of load. When the measurements are made under different temperature and moisture conditions or with a different glueline thickness, more data for the exposure and quality-control factors are obtained.

The continuous dead load tests are the most time-consuming and difficult to carry out. There is a real need for test development here. There are standard tests for measuring creep in metal-to-metal lap shear specimens, ASTM D 1780, D 2293, and D 2294; and for plastics, D–674. There are also numerous proposals described in the literature. Each has its advantages and disadvantages, but better experimental systems are needed.

One example of the kind of useful data that can be obtained with a dead load apparatus is shown in figure 3. In this case, it is a composite for three species of softwoods. Similar behavior curves should be obtained for adhesives being evaluated or for other building materials. The figure 3 plot of bending strength (from ASTM D 2555 and D 245) shows that continuous application of 60 percent of the load required to break the specimens on a universal testing machine in 3 to 5 minutes would result in rupture in 50 years. Theory as well as experiment says that the load required for rupture for viscoelastic materials is a linear function of the log of time. The curve can be determined in about 1 to 2 months' time.

²Rates of loading in making standard tests of wood are traditionally adjusted so that loading to ultimate is accomplished in 3 to 5 minutes, but in adhesive evaluations the rates of loading have been increased so ultimate load is achieved in 1 to 3 minutes. This results in greater efficiency in testing and is possible because of improvements in testing machines and data–taking equipment that have come into use since the standards were developed for testing wood.
to give reasonably safe extrapolation to 50 to 100 years.

The quality control factor must be evaluated in a separate set of tests. These tests would involve the actual adherends proposed for the end use—softwood lumber, plywood, hardboard, particleboard, or some other adherend. Only stress at rupture need be measured at one temperature and moisture condition, as in the following suggestion:

Variable quality bond
Shear loading: 1-3 minutes to rupture
Measurement: Stress at rupture
Temperature: 80°F (27°C)
Moisture: 42 percent relative humidity

The information generated will help define the requirements of the manufacturing process and the quality control program to assure the desired bond quality. How fast bond strength develops governs when the assembly can be moved and stressed without damage to the structure.

**Deflection Criteria Versus Strength Criteria**

When deformation is an important factor in a specific application, adhesive selection becomes more difficult. Past experience with thin rigid gluelines provides little basis for the decision. Thin, rigid gluelines contributed little to cumulative deformation compared with the other parts of the structure. "Yielding" adhesives were used only where service loads were low in relation to design loads, and then frequently a prototype test under simulated service conditions was used to demonstrate probable behavior.

Actually, such adhesives may be used advantageously many places in a structure. But again specific information is necessary on characteristics. Information on creep-slip characteristics should be obtained from the tests during stress-rupture evaluations. Shearing modulus values should be obtained both under standard exposure conditions and those simulating conditions that can occur in service.

If one were to take the same formula approach as for design stress, the result for estimating deformation under design conditions might be:

\[
\text{Deflection} = \frac{6Pd^2}{4\pi E}\]

The formula is simpler, but one has less precedent on which to decide what should be included. For wood, the species average modulus is used, with the only adjustment being moisture content of use, generally either green or dry.

The slip or other deformation properties of materials depend on temperature and possibly moisture, more so for adhesives than for wood. Calculation of a design modulus thus should reflect the expected conditions. Conceivably, with a temperature-sensitive adhesive, the exposure factor could be greater than 1.0 under snow loading conditions on a roof.

The quality control factor is significant also.
because a 60-mil glueline in a critical joint would have six times the slip of one 10 mils thick because slip is inversely proportional to glueline thickness.

The factor of safety is largely a “judgment call;” some have suggested the use of about 80 percent because life safety is not involved.
Summary

This paper outlines a proposed testing program to insure proper selection and use of adhesives in building construction. It requires a lot of testing, but only if an adhesive has unlimited potential for the most critical uses. In actual practice, it would be advisable to make the first measurements at the extremes of temperature and moisture conditions suggested. This would determine whether the adhesive should even be considered in applications for critical use.

The conclusion is erroneous that only rigid adhesives with high strength will prove adequate for critical uses. The actual stresses at design loading in many structures are quite low because the total bonded areas are large. So there is a place for adhesives with lower unit strengths than conventional adhesives. There are also applications where stresses are low or short-term such as where adhesives are used for surface fastening, to provide additional stiffness or bracing functions, to develop diaphragms as shear walls for improved wind and earthquake resistance.

For the most critical uses, the successful application of adhesives in building construction will depend upon gathering the facts about durability and mechanical properties. With such information, engineers will be able to use adhesives wisely in rational design; code agencies, authorizing agencies, and lending institutions will have the supporting evidence necessary to approve their use; and consumers will benefit from the long-term performance of the structures they buy,
### Selected ASTM Standards Dealing With Adhesives

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* Conducting forest and range research at over 75 locations ranging from Puerto Rico to Alaska to Hawaii.

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