ADHESIVES IN BUILDING CONSTRUCTION

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ADHESIVES IN BUILDING CONSTRUCTION

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– Robert H. Gillespie
– David Countryman
– Richard F. Blomquist

PREFACE

Housing is the greatest single demand for wood in the United States. Projected trends show an increasing demand for wood in the years ahead to add new dwellings, replace old ones, and repair and improve existing dwellings. It is important to develop more efficient building practices, such as those provided by adhesive technology. Ideally, user needs will be supplied at a high level while at the same time our timber resources are conserved.

This handbook is designed to serve as a guide to efficient use of adhesives for building construction. It is intended for architects, engineers, contractors, builders, building supply dealers, code officials, and others who may have limited experience with wood and adhesive technology. While the primary emphasis is on adhesive bonding of wood and wood-based materials to each other in light-frame construction, the handbook also includes the bonding of wood to other construction materials.

Each chapter was authored by an individual or group very familiar with that particular phase of adhesive bonding. A quick overview of each chapter is given in chapter 1 under "Surveying This Handbook," page 4. This is a "state-of-the-art" report, and new technology is being developed continuously. The compilers hope this publication can stimulate orderly and progressive changes in technology with the improved resources being included in subsequent revisions. Background information is referenced at the end of most chapters.

Mention of a chemical in this handbook does not constitute a recommendation; only those chemicals registered by the U.S. Environmental Protection Agency may be recommended, and then only for uses as prescribed in the registration-and in the manner and at the concentration prescribed. The list of registered chemicals varies from time to time; prospective users, therefore, should get current information on registration status from Pesticides Regulation Division, Environmental Protection Agency, Washington, D.C. 20460.

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CHAPTER 1:

ADHESIVES IN CONSTRUCTION[1]

Many people consider themselves experts in the use of adhesives after having licked postage stamps and bonded them to envelopes with great success. This familiarity with unexacting applications of adhesives may lead to an unjustified self-assurance when considering bonds for critical applications (fig. 1) where failure may cause property damage or even loss of life. But even those who have spent a career in some one aspect of adhesive technology may be inadequately informed about other aspects.

This handbook is a broadly based survey of assembly adhesive bonding. It includes information on the adhesives and techniques appropriate to that field. Assembly bonding is sometimes called secondary bonding in contrast to that practiced in the manufacture of primary building materials such as plywood, particleboard, and laminated beams.

TYPES OF ADHESIVE APPLICATIONS

Selecting an adhesive for assembling building components depends to a great extent upon the nature of the application. Roughly five categories of use may be identified:

(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 and stiffness for a period shorter than the life of the structure (such as resisting racking stresses while being transported).

(4) Secondary structural, where failure due to service loading would not involve life, safety, or structural integrity, and where failures would be readily recognized and easily repaired.

(5) Nonstructural, such as accessory and trim attachment.

For the most exacting applications, such as prime structural, close attention to all steps in the bonding process is necessary. These steps include choice of proper joint design, judicious selection of substrates and adhesives, adequate preparation of substrates for bonding, proper mixing of adhesive components, selection of bonding equipment, proper control over variables in bonding, inspecting and testing the bonds, and careful handling of the assembly after bonding. Ignoring any one or more of these important steps may lead to m&manufacture of the bonds and possible failure in service.

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[1]Written by Robert H. Gillespie of the U.S. Forest Products Laboratory.

SERVICE ENVIRONMENTS

When selecting an adhesive for use in building construction, consideration must be given to the environmental conditions that are anticipated in service. Particularly important are the maximum temperatures and moisture situations that may be encountered. In roof sections, maximum temperatures as high as 71° C (160° F) are not uncommon, while outside walls may reach 49° C (120" F), and floors usually range from 16° to 32° C (60° to 90° F). Moisture conditions may vary over a broad range of relative humidity but can also include soaking in water. Unplanned wetting conditions, such as leaks in roofs, moisture condensation in sidewalls and roofs, or flooding of floors by plumbing leaks, must be taken into account when selecting adhesives, as well as any other adverse conditions that may arise during the service life. Conditions during construction must also be anticipated, such as prolonged soaking, wetting and drying cycles, and extremely low or high temperatures.

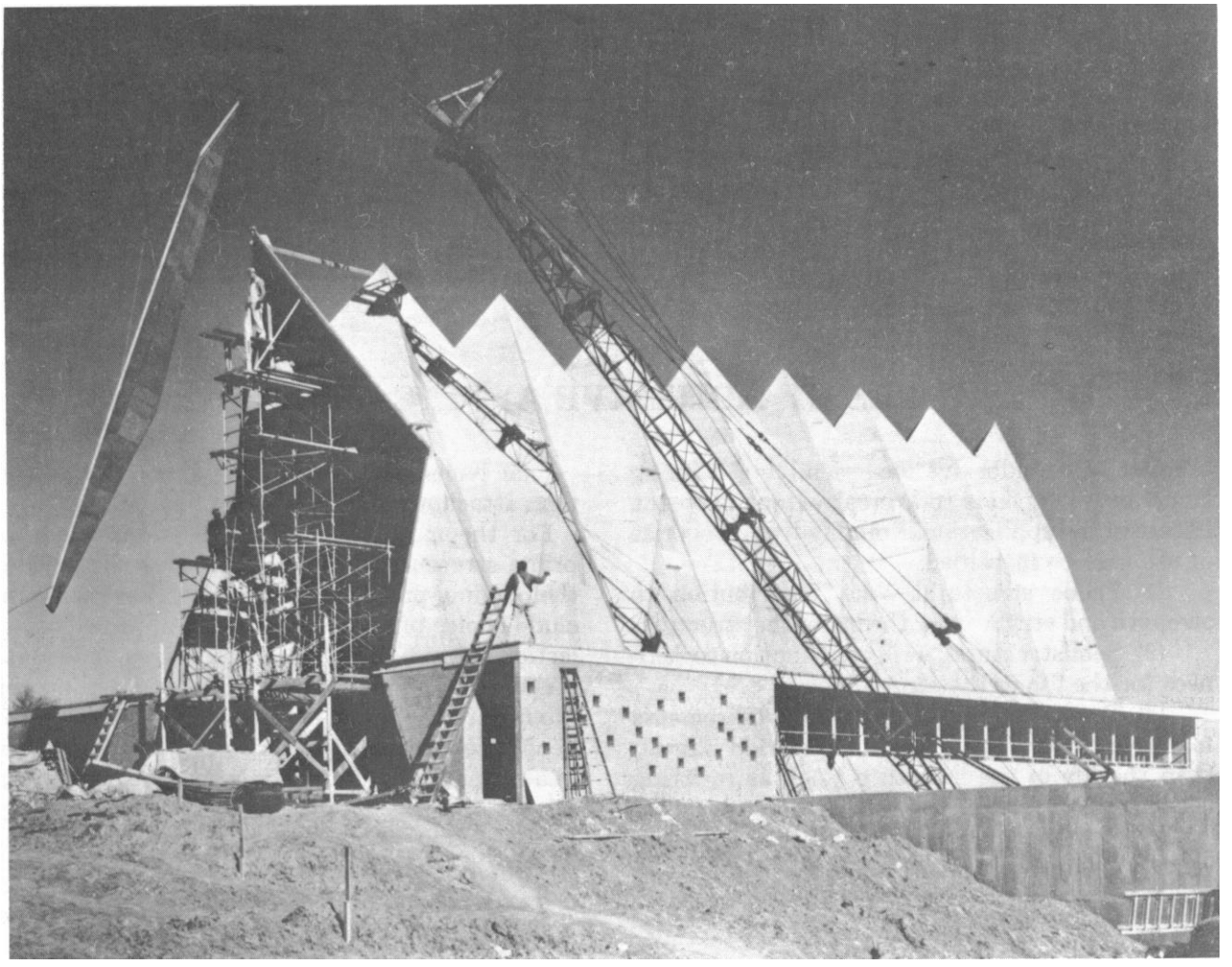

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Figure 1.–Futuristic "space planes " roof design is made possible by adhesive technology.

WHY BOND WITH ADHESIVES?

Three advantages are offered by bonded assemblies over conventional construction: (1) More efficient use of material to save cost, weight, and volume; (2) opportunity to preassemble building components to save time and onsite labor; and (3) improved performance by achievement of more rigid joints to develop the full strength of materials.

Adhesive bonding provides flexibility in design and in the use of different materials. Some combinations can be fastened only with adhesives: For example, a hardboard facing to a paper honeycomb core. Adhesive bonding also makes it possible to remove defects from lumber and bond smaller pieces together again. Lower grades of lumber can be bonded into composites with the defects placed to minimize their effect on strength and stiffness. In other cases, the defects in low-grade lumber can be randomly located and reinforced by clear wood in adjacent members to provide the desired strength and stiffness in the composite.

Adhesives used in bonding assemblies offer the distinct advantage of transferring stresses efficiently from one member of a composite to another. With rigid adhesives, the composite has a strength and stiffness far greater than the sum of the individual members, and greater than when assembled with mechanical fasteners. Structural components bonded with adhesives can be designed with smaller members than when mechanical fasteners are used. This advantage is best demonstrated in sandwich panels, where thin, strong faces are bonded to thick, lightweight core material, or in stressed-skin panels, where the faces are bonded to lumber framing. These systems represent highly efficient construction through adhesive bonding.

However, the advantages of adhesive bonding can only be attained through an exacting attention to each stage of the bonding process. If adhesives are not used knowledgeably, or are applied without sufficient care, the advantages of bonding may be supplanted by such disadvantages as erratic or unsatisfactory performance.

SELECTING FROM THE ADHESIVES AVAILABLE

Adhesives are available to meet a broad range of performance requirements in service. Adhesives for different uses possess varying degrees of durability, a performance category which includes resistance to heat, moisture, swelling and shrinking stresses, micro-organisms, chemicals, and fire. The adhesive must also be chemically and physically compatible with the various types of substrates with which it will be used and must resist creep under sustained loads.

Adhesives also very widely in the working properties that dictate how they can be applied and how the bond is formed. Working properties desirable during fabrication include (1) ease of mixing and applying, with minimum care and equipment needs; (2) tolerance to a broad range of temperatures during application; (3) adequate working time to permit assembly, but rapid setting thereafter; (4) tolerance of surface misfit, with ability to fill gaps; and (5) minimal requirements for exacting or sustained application of pressure after assembly. No single adhesive is ideal for all applications. Selection must be made for each application on the basis of performance requirements, type of substrates, working properties needed, desired production rates, and cost.

IN-PLANT BONDING AND ONSITE BONDING

In-plant bonding may be defined as the fabrication of bonded assemblies indoors at some central location, from which they are transported to the location of service. Onsite bonding is the fabrication of bonded assemblies at the location of service, and usually under conditions where variables affecting bond strength are difficult to control.

Satisfactory bonding is most certain under plant conditions. To achieve satisfactory bonds, controls are required on moisture content of materials, surface preparation, adhesive mixing and spreading, pressure application, and time and temperature for bond development. Plant bonding most readily provides the necessary conditions, equipment, and personnel for adequate bonding of building composites. Components most often plant bonded include items such as beams, trusses, and panels, flat or curved, framed or of the sandwich type.

The precautions required for effective plant bonding are even more exacting for onsite bonding because control is more difficult to maintain, especially over temperature, pressure, and material moisture content. Onsite bonding, when properly controlled, offers some advantages over plant bonding; larger pieces can be made without the concern for transportation size-limits or the uncertainties of delivery schedules. Most assemblies bonded in the field are those most conveniently built in place, such as T-beam floor systems, thin-shell structures, and rigid frames. In these cases, good bonding technique is essential to assure bonds which are uniform, strong, and durable.

SURVEYING THIS HANDBOOK

Typical Applications. -Adhesive applications in building construction are too numerous to consider each in detail. Examples include in-plant practice and site-bonding techniques; small- and large-scale production; simple, composite, and more complex assemblies; and the fabrication of some selected types of joints. The content of chapter 2 is limited to a few typical applications illustrative of the variety of techniques commonly recommended.

Structural Design Considerations.–The proper design of joints to yield satisfactory performance is covered in chapter 3. The greatest contribution to stiffness and strength in a composite is provided by rigid adhesives. Design calculations are simplified when rigid adhesives are used. Less rigid adhesives can also make a contribution to strength and stiffness depending upon the mechanical properties of the adhesive and the bondline thickness. Methods for calculating the contribution of the less rigid adhesives to shear slip and deflection under load are discussed. Proper design must also consider adhesive performance at high humidity, low or high temperatures, or under various other environmental conditions, because the service environment is often more critical than the loading.

Substrates.–A study of substrates can make it possible to take fullest advantage of their individual properties through adhesive bonding. Many different substrates are obtainable for today's building needs. The materials commonly used in sandwich construction exemplify the broad range of substrates that are suited to adhesive bonding. These include such facings as plywood, particleboard, fiberboard, resin-treated paper, plastic laminates, asbestos-cement board,

metal sheets or foils, and porcelain-enameled metal. The core can be continuous as with lumber, insulating fiberboard, or foamed resins, or discontinuous as with expanded honeycombs of paper, fiber, or metals. The properties, performance behavior, and requirements for surface preparation of substrates commonly used in composites are presented in chapter 4.

Adhesives. –The adhesive types most commonly used in assembly bonding include casein, urea resin, resorcinol and phenol-resorcinol resin, polyvinyl resin, rubber- and other elastomer-based adhesives, polyurethane, and epoxy systems. A more cursory treatment will be accorded adhesives such as animal, starch, soybean and blood, phenol-resin, and melamine-resin types because of their limited applicability to assembly bonding. The bonding of multimembered composites often requires the use of room-temperature-setting adhesives because of the time required to raise bondline temperatures for heat curing in large assemblies of thick wood members. Means for accelerating the rate of cure of the adhesive after assembly will be covered and will include the use of hot presses, portable high-frequency units, preheated material, separate application of catalysts, and resistance-wire heating. The properties of adhesives, and the criteria for selection for particular applications are covered in chapter 5.

Equipment for Fabrication.–The fabricator of adhesive-bonded assemblies can choose from a number of fabrication techniques and from a variety of equipment for adhesive spreading, assembly, and pressing. The choice depends in large part on the working properties of the selected adhesive, on the production rates desired, and on whether plant or onsite bonding is involved.

One of the most pronounced differences between plant and onsite bonding is in the equipment available. Plant bonding may involve highly automated lines for high-speed production of many units. Plant bonding may also use sophisticated techniques such as hot platen pressing of assemblies or radiofrequency curing of bondlines. Onsite bonding involves much simpler equipment, such as trowels, spatulas, or calking guns for applying the adhesive and mechanical fasteners for pressing the bonded joints. The equipment and techniques available to the fabricator are discussed in chapter 6.

General Bonding Techniques.–Understanding the techniques for good bonding (chapter 7) is essential to develop satisfactory bond quality. Optimum bond performance demands proper control of the bonding process. The selection of the right adhesive, of the proper joint design, and of certified quality in the adhesive must be followed by satisfactory bond formation before the desired performance can be assured.

Test Methods and Specifications.–The chapter on test methods and specifications (chapter 8) reviews those most applicable to adhesives and their use in building construction. Tests and specifications are developed for specific purposes. Some apply only to adhesives to certify their capability to meet certain performance requirements. Others apply to the bonded joints and serve as quality-control tests to monitor the bonding process. Because the bonded structural elements in buildings must maintain serviceability without failure for many years, tests and specifications to define and evaluate permanence of joints are essential.

Inspection and Control.–Adhesive bonds of uniform quality cannot be achieved without the assurance that all phases of the manufacturing process have been under proper control during fabrication. A good inspection and control program is vital to production. Regulatory bodies, independent testing agencies, plant management, and plant operators all play a role in the development and application of a suitable quality assurance program. Chapter 9 supplies guidelines for developing satisfactory programs to reduce the likelihood of mismanufacturing bonded joints during production.

Glossary. –Definitions of terms describing adhesives, substrates, and bonding processes are included in an appended glossary. These are essentially the standard definitions given in ASTM D 907, Standard Definition of Terms Relating to Adhesives, supplemented by other definitions as needed.

FUTURE DEVELOPMENTS

New adhesives continue to be developed as adhesive technology expands. This leads to new opportunities for fabricating improved composites for building construction. Certain practices recommended in this handbook may soon be outdated, to be supplanted by new and better ones. The development of our next generation of adhesives may be stimulated by the thoughts expressed herein-either through pointing out performance requirements and the direction future research might take, or by describing a system that elicits demand for "a better way." In either event, this handbook will have served its purpose. It is hoped that it will contribute to better housing through more efficient and less costly adhesive bonding.

CHAPTER 2:
TYPICAL APPLICATIONS[2]

Both rigid and nonrigid adhesives are widely used today in the wood construction industry for conventional and "factory built" structures. When the bonded members of a structural component are designed to act as a composite element, rigid-type structural adhesives-such as casein, phenol, resorcinol, or melamine-are required. Nonstructural adhesives such as elastomerics[3] can improve the performance and efficiency of floor and wall systems formerly constructed with nails only. This chapter will discuss the applications of rigid and nonrigid adhesives for plant-bonded and onsite-bonded applications. Plant bonding takes place indoors at a central location, from which bonded assemblies are transported to the location of service. Onsite bonding takes place at the location of building construction, and usually outdoors.

PLANT-BONDING APPLICATIONS

The procedures for a plant-bonding operation may differ considerably from plant to plant. Assemblies may be completed on jigs, one at a time, by workmen at individual shops within a plant. Specialized crews may complete the fabrication of assemblies in stages as work moves on a production line. Or, the crews themselves may move, succeeding each other throughout the several stages of bonding. The procedures will differ depending on the unique problems in bonding each type of assembly and on the size and resources of the plant.

But whatever the organization of work in any plant, the essential advantages of plant bonding remain the same. In several ways, plant bonding offers a higher degree of control over adhesive applications than does onsite bonding. Plant bonding is characterized by freedom from the uncertainties of weather, availability of factory equipment, a higher potential for crew supervision, and the possibility of an exacting quality control.

Components

Prefabricated structural components are used to speed up the construction process. Also, structural bonding often permits more effective use of materials than is possible with mechanical fasteners only. Because rigid adhesives require controlled conditions to fully develop their structural properties, components requiring these adhesives should be plant-fabricated to assure reliable structural performance. Structural components using plywood and lumber rigidly bonded, such as stressed-skin and sandwich panels, trusses, plywood beams, and folded plates, generally require plant fabrication. Design procedures and fabrication specifications for such components are available. Generally, code acceptance of typical components is readily available when fabrication can be certified by an independent agency as conforming to these specifications.

For plant bonding of components, the fabrication and storage area should be such that minimum temperatures never fall below the 10° to 21° C (50° to 70° F) range. This area should be

[2]Written by J. M. Carney, David Countryman, Bruce E. Lyons, Jack Minneci, and John D. Rose of the American Plywood Association, Tacoma, Wash.

[3]The term "elastometric" adhesive as used here is intended to signify a "gap-filling construction adhesive" formulated with an elastomer base.

dry with sufficient space to allow bonded components to cure undisturbed.

Lumber used in the manufacture of structural components is usually stress graded, and has restrictions on dimensional variations, cross grain, knots and knotholes, twist, cup, and moisture content. The surfaces to be bonded are often resurfaced to minimize dimensional variations in the lumber and to insure contact over the entire surface area. Dimensional uniformity in individual components is essential for proper installation and performance. Design stresses have been accepted by major building codes for softwood plywood conforming with recognized product standards. Other materials may be used also, provided their engineering properties are acceptable to the governing building codes.

Adhesives to be selected must possess adequate structural characteristics for the particular application, and must possess good working and curing properties. Several categories of adhesives are currently available to meet varied needs in the building construction field; they include the synthetic resins, the elastomerics, and casein (chapter 5).

Stressed-Skin Panels

Stressed-skin panels are fabricated flat or curved. The flat panels are composites of stringers (usually 2-in. lumber) with plywood skins bonded to either one side or both sides. In two-sided panels, the stringers are placed on edge, evenly spaced between the skins. In one-sided panels, stringers may be used singly, or may be reinforced on the bottom side with a flat lumber piece to form inverted "T" flanges. In cases where special depths are needed, plywood may be ripped to form the stringers. The plywood skin is oriented with its face grain parallel to the stringers in most cases, and it may be scarf-jointed to carry bending stresses (fig. 2).

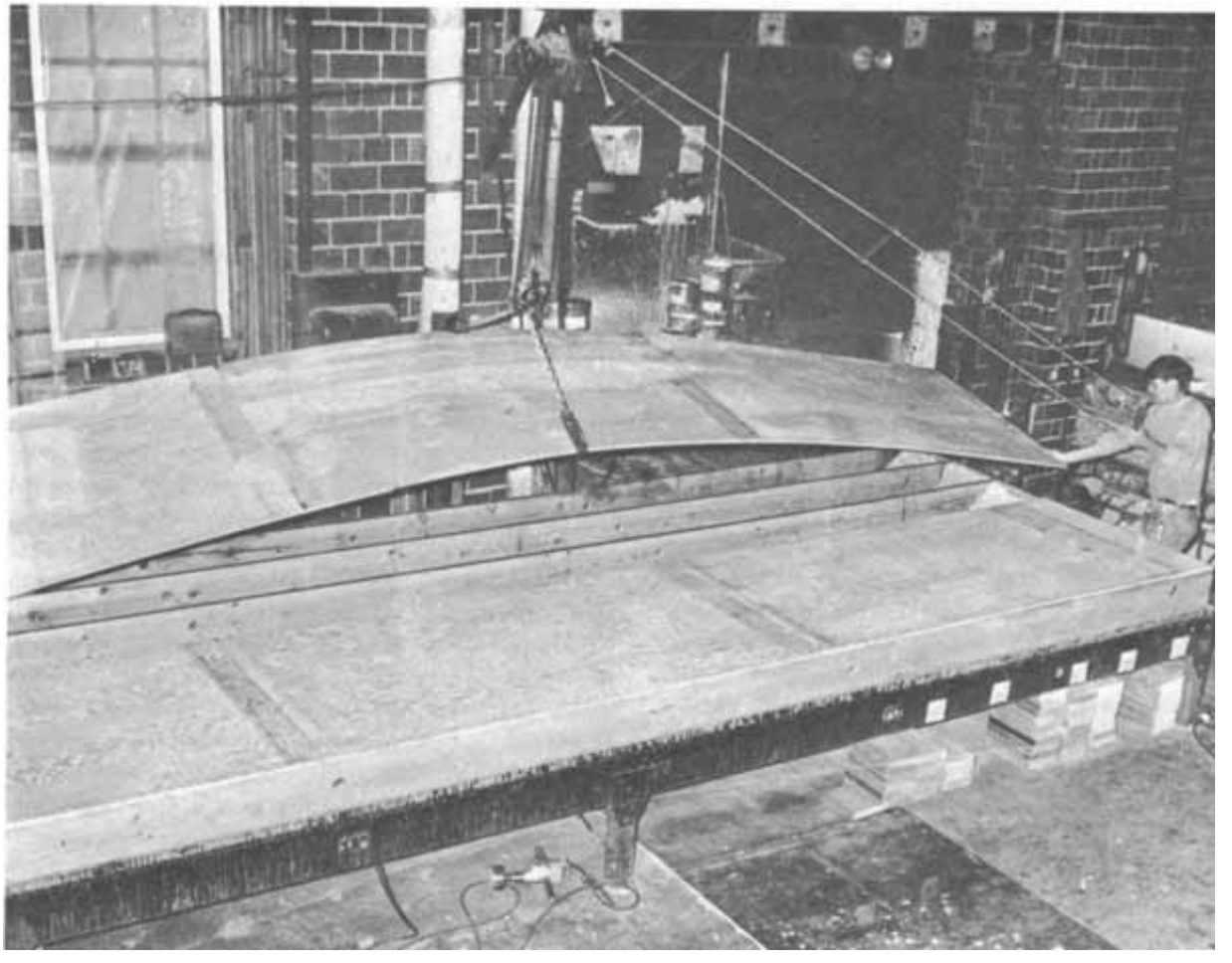

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Figure 2.– Factory application of a scarf-jointed plywood skin in production of stressed-skin panel.

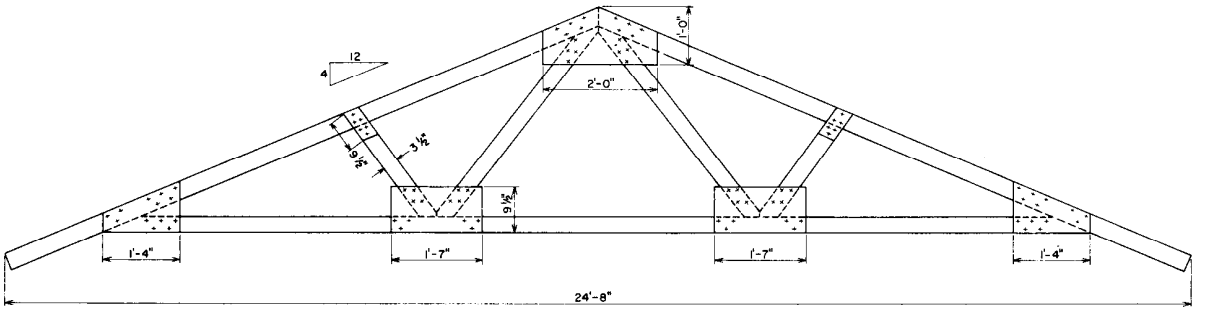

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Figure 3.– Residential truss with plywood gusset plates bonded to framing members. The gussets are 3/8-in. C-D interior-type plywood; framing members 1-1/2 x 3-1/2 inch in cross section; and 4d nails (indicated by cross on sketch) are used to apply bonding pressure.

Flat stressed-skin panels are designed to act like a series of built-up I-beams, with the skins taking most of the moment stresses as well as performing a sheathing function, while the stringers take shear stresses. They may be designed for different combinations of axial and transverse loading. Various insulation materials may be included in the fabrication of stressed-skin panels, but they are not considered as contributing structurally to the panel design. Provision may be made for ventilation of the interior of closed panels used for roofs.

Curved stressed-skin panels can be fabricated with curved plywood or lumber ribs (evenly spaced), or with a solid plywood core. They can be designed as flexure panels that do not develop horizontal thrust, or as arch panels with the horizontal thrust carried by tie rods or abutments. The structural requirements of curved panels are determined by the overall design of the structure, so the feasibility of incorporating them should be ascertained early in the planning for any given project.

Stressed-skin panels may also be used in abstract architectural roof designs called "space planes." For these designs, triangular panels are arranged to form skewed intersecting planes.

Sandwich Panels

A structural sandwich panel is an assembly consisting of a lightweight core laminated between two relatively thin, strong faces. Sandwich panels are usually flat, but may be curved. Faces of the panels may be materials such as plywood, gypsum, metal, or hardboard. The core material may consist of resin-impregnated paper honeycomb, a rigid plastic foam, or a combination of the two. In some panels a polyurethane core may be foamed in place while bonding to the faces.

Sandwich panels are used for both load-bearing and nonload-bearing applications. Structural sandwich panels can be designed for axial and transverse loading, in which case the shear properties of the core material used become important.

Trusses

A common bonded component is the roof truss or trussed rafter. Each is used primarily for roof framing, generally spaced 16 to 48 inches on center, with 24 inches predominating. In this way, roof sheathing is applied directly to the rafters without any intermediate purlins.

In constructing trusses, structural-quality adhesives are used to combine lumber elements (usually 2-inch dimension) with plywood gussets to form rigid joints for trusses (figs. 3,4). Typical light-frame truss designs include W-type, kingpost, parallel chord, and occasionally a scissors type with sloped bottom chords to provide sloped ceilings. Rigidly bonded joints produce a stiffer truss than a pinned joint, but also introduce secondary bending stresses into the truss members.

Long spans are practical-up to 60 feet or more. In shorter spans-generally up to 32 feet–a kingpost configuration may be used. This type of truss has a single vertical web member attached to the upper and lower chords at the centerline by plywood gusset plates. Single W-trusses are also common. They have four web members in the shape of a W intersecting the upper chords, generally at their midpoints, and the lower chord at its third points. The advantage of the W-truss

is that the chord member sizes may be kept small because the web members support them. In longer spans the support points may be increased by using a double-W configuration in the webs.

For flat roofs a parallel chord truss may be used. This is one in which top and bottom chord are essentially parallel (the top chord may be pitched slightly for roof drainage); lumber members are attached with bonded gusset plates to form the webs. Some use has been made of parallel chord trusses to provide clear span floor construction with subflooring attached directly to them.

A feature of trusses with bonded plywood gusset plates is their exceptionally good stiffness and strength as compared with trusses using mechanical fasteners only. The bonded plywood gusset stiffens the joint against rotation and changes the entire stress distribution within the truss, as compared with a smaller mechanically fastened gusset plate or bolted connection. Stock plans for plywood-gusseted trusses in residential spans are available from several sources.

Box Beams

Box beams are composites of lumber flanges and plywood webs. The top and bottom flanges are preferably continuous members consisting of full-length, scarfed- or finger-jointed adhesive-laminated lumber, but they may also consist of several layers of lumber having staggered end butt joints. Plywood webs are bonded to the flanges. Webs may be sandwiched between multiple flange members, or two webs may be attached to single flanges to form a "box" or rectangular section. The webs are designed to transfer shear stresses, while the flanges carry most of the compressive and tensile stresses. Box beams have been used on spans up to 120 feet.

An adaptation of the conventional plywood beam is a light I-beam joist that is automatically produced in high-speed equipment in continuous lengths and in depths ranging from 10 to 24 inches. This joist uses nominal 2- by 3-inch flange members which may be made of parallel-laminated veneer, with a single 3/8-inch plywood web having its face grain perpendicular to the flanges. Alternatively, the flange may be composed of thin veneer parallel laminated so as to disperse any defects. The web is forced into a tapered groove in one face of the flange members, and bonded with a rigid adhesive. No intermediate stiffeners are used, although end stiffeners are installed over bearings on the job. These beams have been designed to permit holes for utilities to be cut in the web, as needed, when holes are located in designated areas of the web. Beams are shipped in lengths up to 80 feet, and used in floor and roof construction for spans from 18 to 35 feet.

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Figure 4.– Application of pressure to bond gusset plates on plant-bonded king-post trusses.

Folded Plates

The folded plate roof system is composed of multiple units of wood plates acting like I-beams, inclined against each other, and connected along parallel ridges and valleys (fig. 5). The plates are fabricated with plywood skins over lumber chords, and framed with rafters perpendicular to the chords. Folded plates are supported at the valley ends, and span in a direction parallel with the ridge. Tie rods are required perpendicular to the span.

Skins may be structurally bonded to framing to form individual plates, or laminated chords and stressed-skin panels may be shipped separately and assembled on the job with mechanical fasten-

ers. Spans are typically 40 to 60 feet, but have been much longer.

Radial folded plates utilize the same design principles as parallel chord folded plates. Radial folded plate chords radiate from a common point or compression ring, forming alternate ridges and valleys. Roof systems of this design range up to 200 feet in diameter.

Scarf-Jointed Lumber and Plywood

Sections of lumber or plywood may be end-joined with structural adhesives to form continuous pieces capable of transmitting full allowable stresses. These jointed members may in turn be used to construct the various structural components. Either flat-sloped scarf joints or finger joints may be used (fig. 6) (see chapter 3). The angle at which joint surfaces are cut is critical with both types of joint, and so these joints are most successfully made in plant-bonding situations.

Component Systems

Prefabricated wood components can be adapted and engineered to almost any residential, commercial, industrial, or institutional building design. Choice of individual components for floor, wall, and roof systems becomes simply a matter of determining what combination of standard elements will provide the most economical and efficient approach to the desired building design. The key to economy with prefabricated components is to incorporate repetitive components wherever possible.

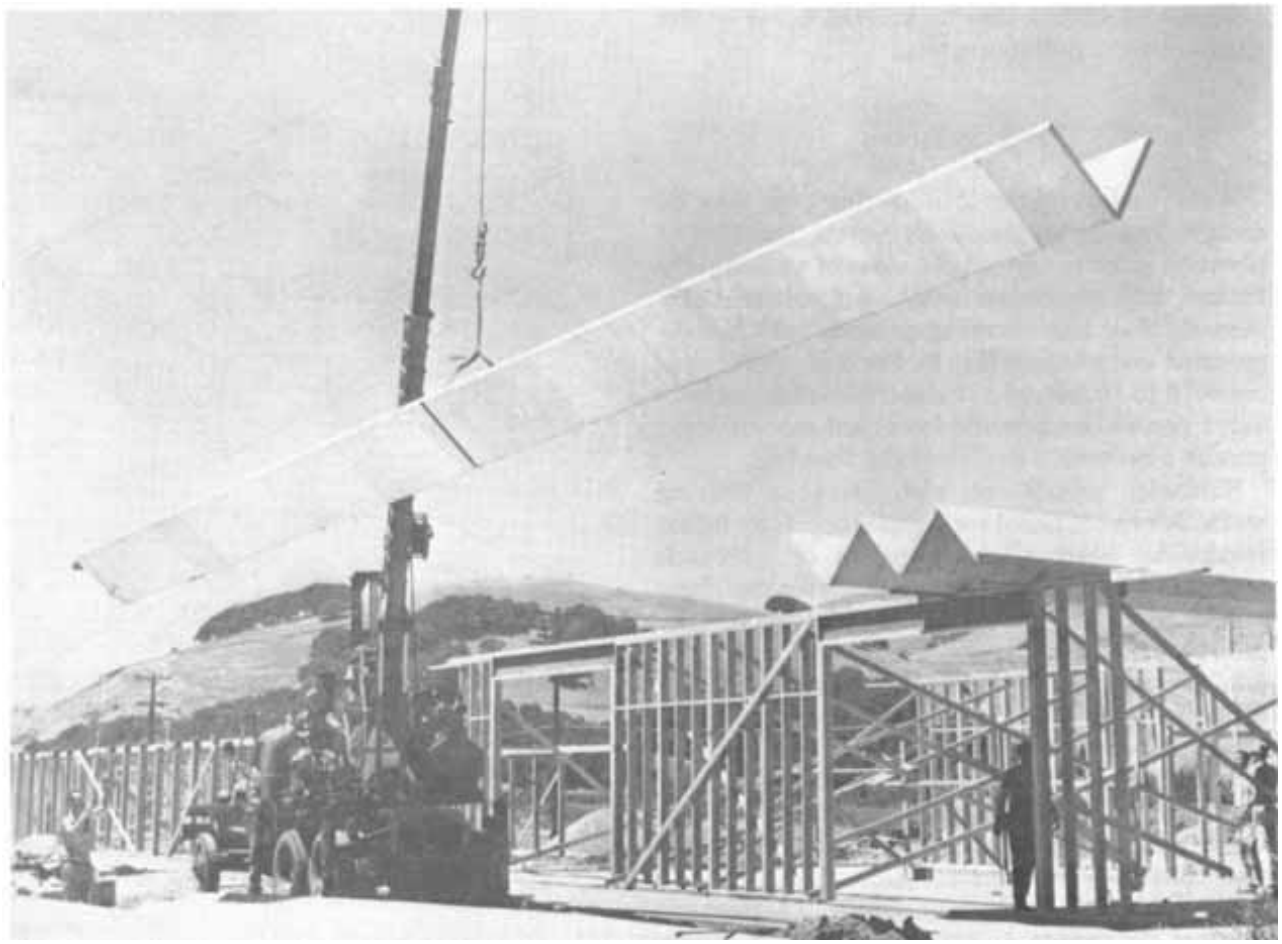

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Figure 5.– Installation of a factory-assembled plywood folded plate roof section.

Floor Systems

Floor systems can incorporate bonded box beams as framing in multilevel floor construction. Spacings may be up to 20 or 30 feet with intermediate floor joists and conventional sheathing, or in combination with stressed-skin or sandwich panels. Clear spans made possible with long beams eliminate the need for interior supports, columns, and footings. Bonded plywood I-beams have good dimensional stability, are long and lightweight, and can be used effectively at spacings up to 48 inches in a manner similar to lumber floor joists.

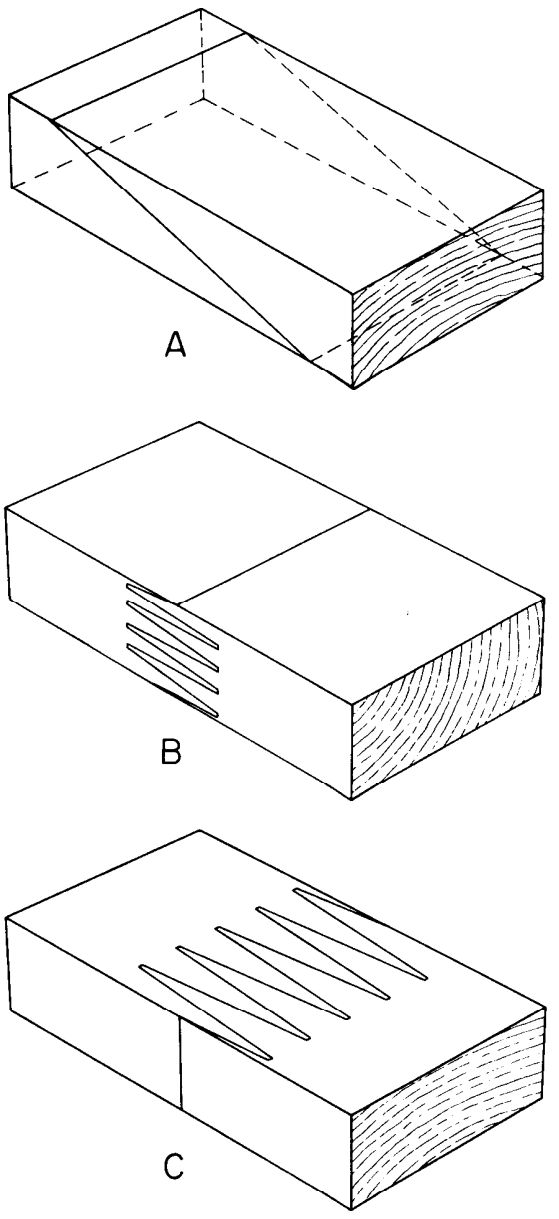
Typically, stressed-skin floor panels can be used with conventional 50-pound-per-square-foot loading for spans up to 30 feet, or with 100-pound-per-square-foot loading for spans up to 20 feet. Such panels facilitate rapid erection of floor systems in multilevel buildings (fig. 7). They are often supplied as a one-sided panel, in either 4- or 8-foot widths and in lengths equal to the span or to the building width.

Wall Systems

Wall systems of the load-bearing type may be designed using stressed-skin panels. Bonding of plywood skins to one or both sides of walls lightly framed with dimension lumber will substantially increase their load-carrying capacity both in compression and bending (fig. 8). For high walls in excess of 8 to 10 feet, as in industrial buildings, two-sided panels can provide increased capacity and permit a reduction in size of the framing.

Sandwich panels can also serve as bearing walls. A typical panel for a one-story 4- by 8-foot residential bearing wall consists of 1-1/2-inch foam core with 2- by 4-inch perimeter members placed flat and set so as to form a tongue-and-groove joint. The bonded skins may consist of 3/8-inch or thicker plywood, gypsum board, or other materials. Such panels can also serve as interior nonload-bearing partitions and exterior curtain walls. For cold storage buildings, thicker foam-core panels are used either to line existing floor, wall, and roof areas, or for the insulated wall construction.

Bonded beams can be built into wall sections as headers for garage doors and window openings. These beams can be designed to support roof framing loads on spans up to 20 feet, depending on available depth. For these applications, a symmetrical beam section is preferred, since unbalanced sections may twist laterally under long-time loads. They are usually designed to have the same thickness as the wall itself.

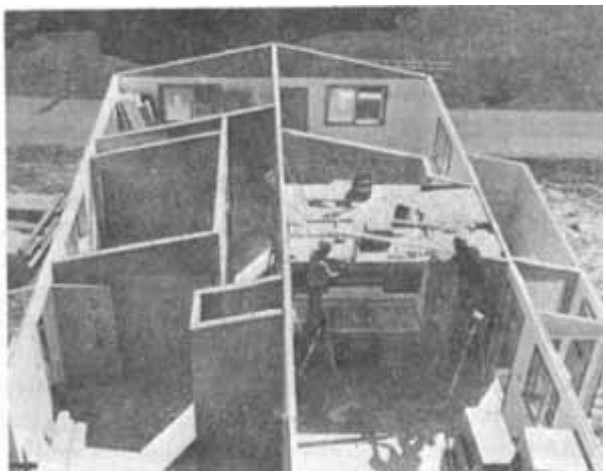


M 138 527

Figure 6.– End joints for splicing lumber and panel products: ***A,*** scarf joint; ***B,*** horizontal finger joint; ***C,*** vertical finger joint.

M 141 907

Figure 7.–A factory-built stressed-skin floor panel being moved onto supporting structure.



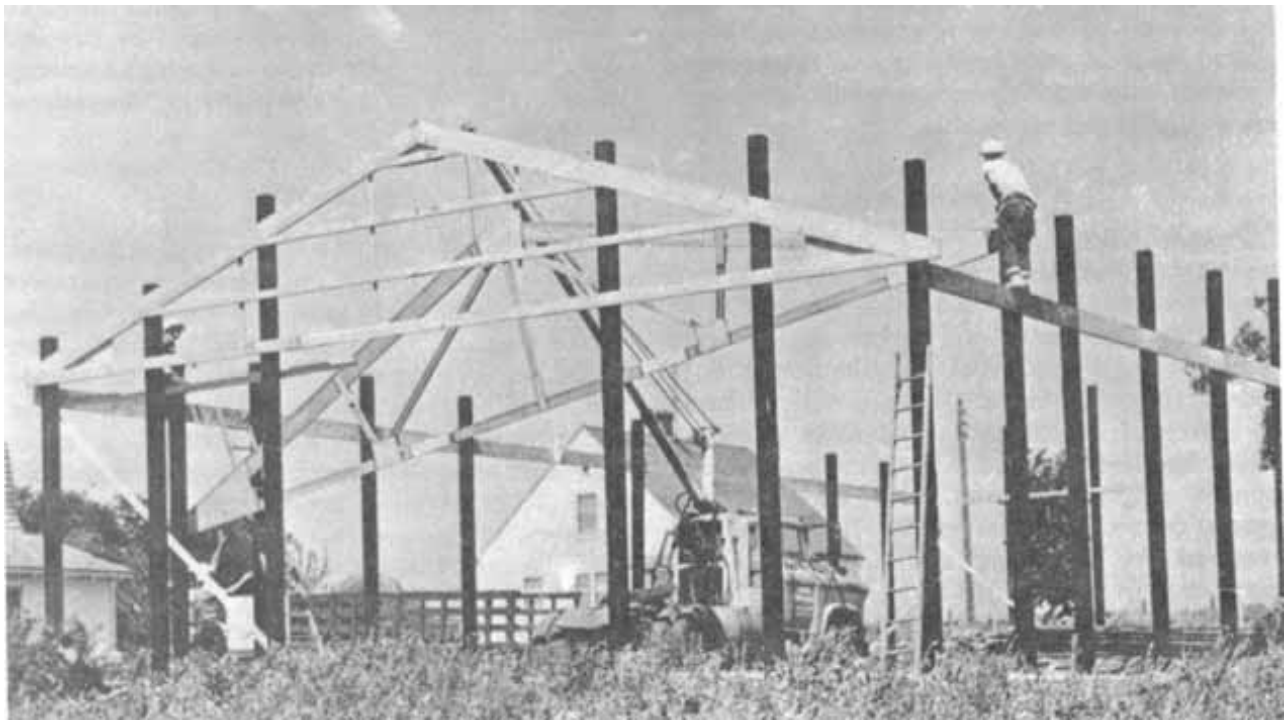
M 141 917

Figure 8.–Partially erected panelized factory-built home.

Roof Systems

In roof systems, bonded trusses in residential, commercial, and industrial buildings can eliminate the need for interior supports. The trusses are spaced 16 to 48 inches so that roof sheathing is applied directly without purlins. In residential construction, trusses with bonded plywood gussets are used with various roof slopes in both W-type and king-post designs.

Where longer spans are required for industrial, agricultural, and commercial buildings, W-type members are common for spans up to 60 feet or more (fig. 9). These trusses can be designed to support overhead light industrial equipment and



M 141 923

Figure 9.–Erection of prefabricated roof trusses on pole frame construction.

machinery. They are sometimes shipped in two sections and mechanically spliced at the job site.

A stressed-skin panel and beam system may have panels spanning up to 40 feet between supports, but 20-foot spans are more common. Supporting members are typically laminated or plywood box beams. When box beams are used, they are most efficient in the 40-foot span range.

Curved stressed-skin panels over simple post-and-beam supports provide an interesting roof line. Curved panels have also been successfully combined with flat stressed-skin panels. They can be used for spans in the 20-foot range, and are commonly used in school construction, as well as for canopies.

Folded-plate roof systems provide an attractive sawtooth effect. They are economical in clear spans of 40 feet or more. Radial folded-plate roofs have been used with a circular or a multisided symmetrical floor plan to provide an unusual architectural appearance.

Assembling Plant-Bonded Component Systems

Recognized design and fabrication specifications are available for most structurally bonded components and should be followed. Design calculations by an engineer or architect may be required by local code authorities to substantiate their use, although in some cases tabular designs are available and acceptable.

Procurement

Precise fabrication of the individual components as designed is essential, especially with respect to dimensions and tolerances, so as to assure easy assembly and proper fit. Accurate dimensioning is also required in the field prior to placing the components. All design details should be conveyed to the fabricator when soliciting bids. Shop drawings should indicate precise component dimensions, and both standard and special connection requirements. If the hardware required for mounting and connecting components is to be provided by the fabricator, this responsibility should be specifically established. Any hardware to be attached by the fabricator prior to delivery should be clearly indicated on the shop drawings.

Certification of component quality should be coordinated with both the fabricator and appropriate building code authorities prior to delivery. Certification is often accomplished through the use of a stamp identifying the components as having been inspected by a qualified independent. testing agency recognized by the building official.

Installation

The ease and speed at which panelized systems can be installed are among their main virtues. Use of precisely fabricated panels, delivered at the right time, and properly cared for prior to installation, can save erection time. Adhesive squeezeout in panel joints, dimensional variations between panels, or dimensional changes caused by improper storage can make tongue-and-groove connections, splices, and other joints difficult to fit.

Storage at the construction site can be minimized by proper scheduling. The fabricator should be notified in advance of any unusual site conditions which might affect the unloading or storage of components. Some builders specify precise locations at the site for storage of specific components. When prolonged site storage is unavoidable, components should be placed under cover, or stacked on evenly spaced supports and covered with plastic. The covered ends should be left open for ventilation. If components are tightly wrapped when stored outdoors, the sun and moisture can combine to produce a high humidity that may result in degradation or dimensional changes.

Erection

Prior to erection of components, all supports, connecting hardware, and erection equipment should be accurately located. Normally, bolts, lag screws, spikes, and common nails are used in conjunction with framing anchors, special connectors, custom-fabricated plates, and metal shapes. Erection equipment often includes a crane, spreader bars, slings, grapple hooks, and scaffolding. Tools required for fitting, such as drills, routers, planes, crowbars, and hammers, should also be conveniently available to facilitate rapid erection.

Components should be delivered and stacked in an order convenient for erection. Any special items should be conspicuously marked by the fabricator. Floor and roof panel systems require starter panels, standard panels, and end or "filler" panels. The end panels should be designed

so variations in width can be accommodated easily. During the installation procedure, panels should be spaced slightly at all edges to avoid buckling from any subsequent expansion. Therefore, care should be taken in dimensioning the panels so that the spacing can be accommodated. Panel-to-framing connections are usually made with common nails or lag screws.

Because the structural performance of panelized systems may depend on specified connection and anchor details, alterations should not be made without consulting the designer. Where lag screws or spikes are used to connect panel ends to bearing walls or support framing, pilot holes may be needed to prevent splitting the members. Common panel-to-panel connection details include tongue-and-groove, splined, and shiplap joints.

With curved flexure panels, space for slight movement–generally 3/8 inch or less-must be provided at one end. The other end is firmly fastened to end walls or support framing with no movement allowed. Arch panels require a tension member connection (usually a tie rod) to carry thrust loads at end supports.

Box beams are normally butt-connected through the use of steel angle ledgers. Where they butt into other beams, the interior framing of the main support beams must be designed to carry the fastener loads. Any connections that are nonstandard should be carefully detailed by the designer.

Lateral support of deep beams is often necessary for the top and sometimes the bottom flanges, particularly during erection. Panels or joists and sheathing support the top flange, but diagonal bridging of the bottom flange is sometimes required before full design loading can be imposed.

Erection of folded-plate roof systems requires special attention to details for ridge and valley chord connections. Forces developed in structures of this type are transferred through these connections-usually through bolts with oversized washers, lag screws, spikes, and nails. Metal plates and angles are used to transfer loads to tie rods, beams, or the tension plate of supporting end walls.

The plates are usually assembled on the ground into V or inverted-V shapes, then hoisted into place. Field connections are made at the valleys or the ridges, which are usually accessible without extensive scaffolding. Special metal connector plates are often used for erection and bearing. When tie rods are used instead of other tension members, connections are made through the ends of column supports.

Ridge chord connections for all but very large folded plates are made by cross nailing. Valley chords, on the other hand, are bolted on all but the smaller plate designs because the close nailing required might split the chord members. The forces in valley chord members prohibit the use of tight nailing schedules. Where bolts are spaced far apart, cross nailing between the bolts may be used as reinforcement.

Camber should be used to facilitate drainage for single-span components. Drainage for buildings fabricated with single-span components must be carefully designed, because inadequate cambering may cause drainage problems such as ponding if not compensated for during construction.

Utilities

Installation of mechanical utilities requires special consideration with prefabricated sections unless only one of the skins is attached.

Wiring is most often accommodated in the joints between sections of panelized systems. With two-sided panels this is usually accomplished by providing extra space between floor-ceiling panels over wall supports. Similarly, a wiring chase is provided between wall panels by holding back the framing member at the side, with access being from a hole drilled through the top plate.

A modified two-sided stressed-skin panel can be used in 24-inch widths with stringers spaced 12 inches on center. The bottom skin is designed to be placed over half of the bottom width, providing a 12-inch chase equal in depth to the stringers, suitable for air ducts and plumbing drains. Finish material is then applied over the bottom skin and open chase.

One-sided floor, wall, and roof panels offer the greatest freedom for installation of utilities and of effective membrane vapor barriers on the warm side. This ease of installation is often a determining factor in overall design considerations. Where two-sided panel strength is required in floor and roof systems, the inverted-T flange design can often provide the necessary strength and stiffness, along with the access advantages of a standard one-sided panel. Utility paths that run perpendicular to the panel stringers may be carried between panel ends at the supports, in a fur-

red space under the panels, or if required holes are small, as for wiring, drilled through the stringers.

Spaces between the valley and ridge chords of folded plates will serve as utility paths, but they must be carefully designed since transfer of forces between chord members on folded plates is critical. Some designs permit the use of flashing that bridges the valley, forming a triangular space that is used for utilities. The flashing may be tapered at the ends if appearance is a factor.

Where plywood beams are part of the floor or roof support system, utility paths running perpendicular to the beam spans are often required. Holes may be cut through beam webs if they are placed near the center of the beam depth. Round holes are less damaging structurally than square ones and, for simply supported beams, the holes should be kept away from the beam ends where possible. In any case, utility paths should be considered along with the overall beam design.

Pros and Cons of Bonded Component Systems

Generally, component users can expect a shorter construction period, which often permits a reduction in overall construction-financing costs. Also lower losses due to materials waste and lower labor costs can be realized both in the shop and at the job site. Material and weight savings are often substantial. It is sometimes possible to use components with prefinished skins, with resulting additional savings in onsite labor.

The obvious advantage of a componetized panel construction system comes from the speed with which large areas can be covered or enclosed (and insulated) in one step (fig. 10). This factor is especially advantageous in areas where the construction season is short, or where weather is erratic. Once a building is enclosed, the interior finishing can be scheduled during the bad weather.

As another advantage, many architectural effects achieved through the use of wood folded plates are often not economically possible with other materials and construction procedures. Alternate methods often involve relatively expensive concrete or metal designs.

Most of the disadvantages of componetized panel systems derive from the limited degree of modification that the systems will allow. As systems deviate from the use of standardized panels for floor, wall, and roof areas with few openings, their advantages diminish. The value of a component system for floor, wall, or roof systems with large numbers of openings in arbitrary locations is questionable. Also, the cost and delay necessitated by design may reduce savings. Standard panels should be employed whenever possible.

Another disadvantage of panel systems is that they are not readily adaptable to varied utility layouts, although methods exist to mitigate this problem. Likewise, box beams may not be suited to situations where depth is a limiting condition. Although holes can be drilled in box beams in certain locations within the webs, this separate operation can be eliminated by recourse to open web systems.

Horizontal stressed-skin and sandwich panels that are relatively long compared to their depth may bow up or down with seasonally changing humidity, particularly if they have an unsymmetrical cross section. This effect can be alleviated by providing adequate anchorage to supports and by leaving room for expansion at panel end joints. Bowing can also occur with wall panels when a moisture content imbalance prevails between the two faces, particularly if the panel is thin.

Modular Homes

For the purpose of this discussion, modular housing is defined as prefabricated volumetric units which, when transported to the site and attached to one another, form one living unit set on

M 141 919

Figure 10.–Installation of stressed-skin panel roof system in panelized factory-built home.

M 141 914

Figure 11.–Rapid erection of factory-built modules on wood foundation.

a permanent foundation. The two most popular uses today are sectionalized, single-family houses, generally comprising two modules, and stacked multifamily housing where two, three, or four modules make up one living unit. At present, most modular units are wood framed with wood exteriors and gypsum- or wood-paneled interiors. In some ***cases,*** steel framing has been substituted for wood framing, with particular emphasis on wall studs, floor joists, and girders. Precast concrete units are also used.

Modular units are presently viewed as a method to solve three fundamental problems with respect to construction of housing units: A growing shortage of skilled site labor, rapid escalation in cost of housing, and cyclic construction restrictions due to weather constraints. Many proponents indicate that improved quality control is especially important, and is achievable only in plant-produced housing.

The growing shortage of skilled tradesmen has been well documented by recent Federal studies which point out that, as the current demand for housing units increases, replacements for the current group of skilled workers decreases- Coupled with this, there is a surplus of unskilled and semi-skilled workers seeking employment. Yet they are equipped only to handle limited segments of construction, where productivity can be high through repetition of the same task.

Increased cost of construction in the housing industry is said to result from inefficiencies in materials handling and job continuity at the building site. As yet, there is no clear indication that use of modular housing reduces overall costs below those of conventional construction methods. However, construction financing costs can be reduced by speeding the building process.

Many of the problems resulting from inclement weather (rain, snow, and freezing) can be over-

come by utilizing modular units which are completely enclosed and protected from the adverse environment. Scheduling problems can be considerably improved, provided that the rate of preparing sites and foundations does not outstrip the capacity of the plant to provide modular units.

Historically, sectionalized, single-family detached houses have been the main goal of modular construction. Federal Housing Administration acceptance of this type of single-family housing goes back to the 1930's. Most sectionalized modular units are made up of two sections, 12 or 14 feet wide, which, when fastened together, form a rectangular single-family detached house (fig. 11). Because of current road restrictions, most units are 12 feet wide and are built with a relatively low sloping or flat roof. Recently the architectural community, as well as marketing proponents in the manufacturing companies, have begun joining more than two modular units, or coupling two modular units with manufactured panels, to provide other esthetically pleasing housing configurations. Specialized applications such as portable classrooms and various small commercial structures also lend themselves well to modular construction. Almost always, one of the modular units contains all of the plumbing and primary electrical service and is generally termed the wet unit.

Recently, modular housing proponents have turned their production more towards multifamily dwellings, rental apartments, townhouses, and condominiums. These proponents have felt a need to optimize land utilization in the face of rising land costs and to encourage the construction of duplicate units in the production line. Most companies at present stack units only two stories high, although a few three- and four-story modular buildings have been constructed. As in single-family detached houses, all of the mechanical and primary electrical needs of a living unit are usually contained in one of the modules. In some cases, however, a second bath is included in the upper unit and connected to the lower basic wet module through a flexible coupling.

The modular core unit illustrates a third modular concept. This core unit can be combined with onsite conventional building or plant manufactured panels. The core unit permits a reduction in cost and erection time by minimizing onsite plumbing and electrical construction. Modular core units are generally back-to-back kitchen and bathroom designs where all fixtures and cabinets are inplace and either enclosed or semienclosed for protection against inclement weather (fig. 12). This concept generally restricts onsite labor to the carpentry trade, except for the minor amount of site hookup by an electrician and a plumber. In some areas this concept is sufficiently popular so that firms specialize in core construction, with sale of the core unit to contractors. The modular core unit is now being used in multistory as well as single family and garden apartment construction.

Manufacturing Procedures

With proper control, plant-manufactured modular units can be built with adhesives with good assurance of an adequate adhesive bond. The temperature and moisture content of both the plant environment and the materials of construction can be controlled when applying and curing selected adhesives. In addition, the cleanliness of a plant helps to exclude dirt or construction debris from adhesive bondlines. However, because the primary labor source will be unskilled or semiskilled help, good supervision is a primary requirement. A confined, logical layout of manufacturing facilities permits good supervision and enhances quality control.

The modular units generally begin at one end of the plant and move down the production line through various stations until the completed unit

M 141 920

Figure 12.–Bathroom-kitchen core module being moved into place in factory-built panelized construction.

is ready to move out to a holding area or the construction site. Subassembly areas parallel to the flow of the unit permit the construction of panels, components, or mechanical-electrical subassemblies so that when a modular unit reaches a given station, a minimum amount of time is required to attach the subassembly to the unit. These subassembly areas include exterior and interior wall jig tables, truss or beam assembly positions, and cabinet areas.

The floor of the unit, including the surfacing, is generally assembled on the main construction line. However, where steel framing is a part of the system, the framing is usually welded at a subassembly area in a separate building.

In a few plants, modular units do not flow down a production line. In these plants, subassemblies are brought to assigned assembly areas and crews move up and down the production line to units which require their specialty. This procedure represents construction of modular housing exactly as if built onsite, but with improved control of the environment and supervision of workers. Productivity may be lower with this procedure, but good cost data are not presently available.

Adhesive Applications

Adhesives are desirable in the construction of modular housing to achieve material economy and to insure that the unit can be transported and erected without structural or finish damage.

Floors

In almost all modular housing production facilities, floors are assembled on the main production line. Floors are, for the most part, lumber framed and surfaced with a single layer of plywood or particleboard. Plywood has been the predominant floor paneling material because, unlike mobile homes, modular housing units must conform with building codes. These have long recognized plywood single floor construction.

Floor framing is generally identical to that of onsite construction utilizing 2 by 6's, 2 by 8's, and 2 by 10's spaced 16 or 24 inches. Usually the band joist around the perimeter of a modular unit is the same depth as used for the joists. Joists are generally end nailed through the perimeter framing, or supported by joist hangers or ledgers. Laminated beams are occasionally used in place of the perimeter framing members unless the walls are constructed as girder walls.

Floors may be designed as stressed-skin panels to reduce weight, amount of material, and overall floor system thickness. The bonded panel floors, utilizing plywood skins, act as T-beams, often permitting a reduction in joist depth of 2 or more inches for a given span. This reduction is important because bridge height restrictions limit total unit height, and therefore a reduction in floor depth can provide additional roof design options.

Bonding of floors eliminates floor squeaks and increases floor stiffness compared to conventional nailed-only floor construction using equivalent materials. However, the assembly should not be made so light as to permit undue vibration under foot traffic even though the calculated stiffness falls within acceptable limits.

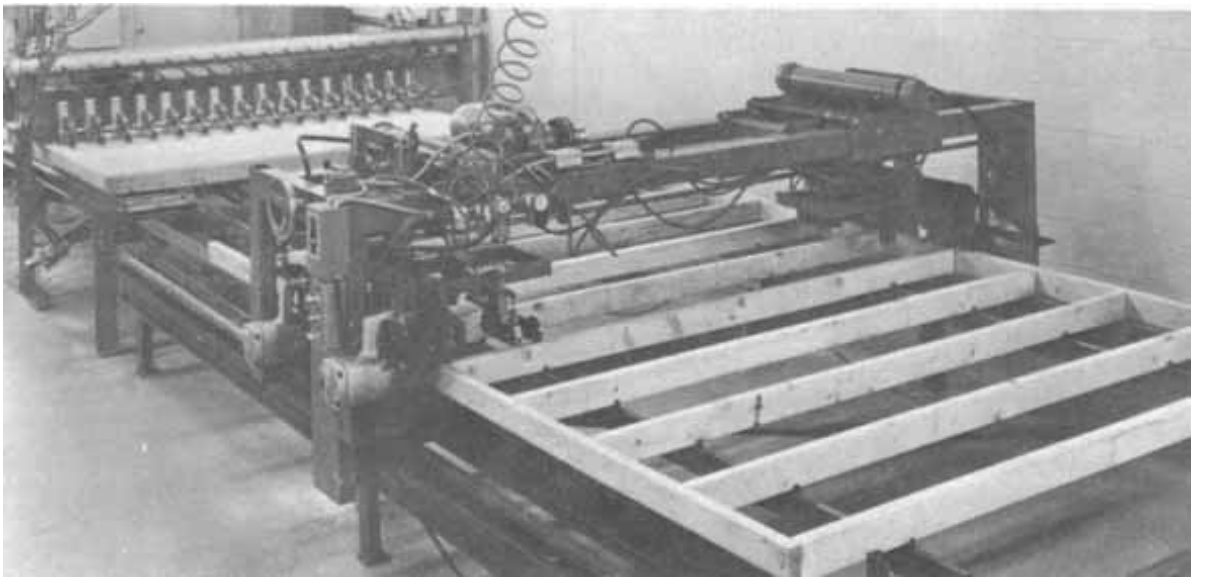
The floor sheathing material is almost always nail-bonded to the framing system either with rigid or elastomeric adhesives. The rigid structural adhesives are usually applied with a hand roller, and elastomeric adhesives are usually applied with a gun (chapter 6). If all adhesive is applied before panels of a floor system are placed in position, a reasonable amount of open assembly time is required of the adhesive (chapter 7). Where engineering or code requirements do not require a structural- or elastomeric-type adhesive to accommodate longer spans or reduced deflection, builders occasionally use other adhesives, usually polyvinyl acetate (chapter 5).

When steel framing is used instead of lumber framing for floor systems, adhesives are also used between the plywood single floor and the framing members to improve floor performance and to take dynamic stresses. The only adhesives being used for this at present are certain elastomerics which are compatible with both wood and steel substrates.

Walls

Bonded wall construction in modular homes can supply the rigidity to permit cantilevering of units, use of intermittent foundation supports, and the space savings of load-bearing flat stud walls.

Walls are almost always fabricated on wall jig tables in a flat position. There are, however, some manufacturers who have vertical or near vertical jigs to accommodate attachment of wall sheathing and paneling to wall framing. Standard



M 139 453

Figure 13.–Equipment for nailing wall framing and stapling sheathing to frame.

wood stud wall systems are almost universally used and are generally built in a subassembly area using special semiautomatic or automatic wall-framing assembly machines (fig. 13). Mechanical fasteners only are used during the assembly of the wall framing.

Interior paneling or exterior panel siding is applied to one side only of the wall assembly at the subassembly jig area. Where structural interior paneling is used, it is generally nail-bonded to the framing members so as to provide a rack-resistant wall. Gypsum board is then applied over the structural paneling. Structural interior paneling permits the use of lapped or beveled siding on the exterior surface. (Because such sidings provide little rigidity, they must be backed with structural sheathing if rigidity has not been supplied to the interior wall surface.)

When unbacked nonstructural paneling such as gypsum board is to be used for the interior surface, structural panel sheathing must be applied to the frame exterior for rigidity.

Whether interior or exterior paneling is applied at the jig table, the opposite surface is not applied until after the assemblies have been attached to the floor unit of the module. Thus, the wall cavities are open so that the electrical and mechanical utilities and insulation can be installed.

The other finish surface is thus applied in a vertical position. The application of this second panel facing substantially increases the bending and shear strength of the wall assembly.

To further increase the rigidity of the wall, many manufacturers nail-bond the siding or sheathing to the studs using elastomeric construction adhesives that do not sag or run down vertical surfaces. However, the adhesive tends to restrain expansion of wood or wood-faced siding panels, and buckling between studs is occasionally reported under high moisture conditions. (This can be minimized or prevented by spacing edges of siding panels to allow for expansion, using thicker siding panels, or bonding only the sheathing-not siding-panels to studs when "double-wall" construction is used.)

Where the interior bearing wall of one modular unit abuts another, the studs are often placed flatwise with panel facings glued to them. Such a bonded structural assembly requires a properly engineered design to establish that it will support the required roof loads. Several manufacturers use this type of interior wall to maintain the advantages of standard stud wall thickness, and to gain additional living space. Walls with studs flatwise are fabricated in the same general way as exterior walls described above. When two flat stud walls are joined at the building site, they are generally fastened together with mechanical fasteners.

When noncontinuous supports are utilized, or where cantilevering takes place, the bonded wall assembly acts as a girder wall or thin box beam. Such walls must carry not only static floor loads, but static roof loads as well, which dictates use of a rigid, yet high-performance adhesive.

When units are transported from the manufacturing facility to the building site, the walls often must carry large dynamic forces if the unit is to arrive without damage to the exterior or interior finishes. These walls should be able to absorb energy with minimum deflections. For this-reason also, elastomeric-type adhesives to increase rigidity are widely used in modular housing. If distress does take place, it is generally at the taped gypsum joints, particularly near wall openings, which then require onsite patch-up labor, tending to offset the cost advantages associated with plant manufacturing.

Roofs

In roof construction almost all trusses or special ridge and framing beams are bonded. I- or box-beams are often used because road clearance heights restrict the maximum height of the roof line. These components are manufactured at subassembly areas on special jig tables, permitting simple yet rapid fabrication. Rigid adhesives are a requirement because they do not creep at the elevated temperatures, 60° to 77° C (140° to 170° F), that may occur in the roof space.

Roof sheathing is not generally nail-bonded to roof framing in modular housing. However, some manufacturers do so to add torsional strength to the unit and thus to minimize damage to interior surfaces resulting from transportation and assembly stresses. Since the manufacturers are using the adhesives for a temporary structural

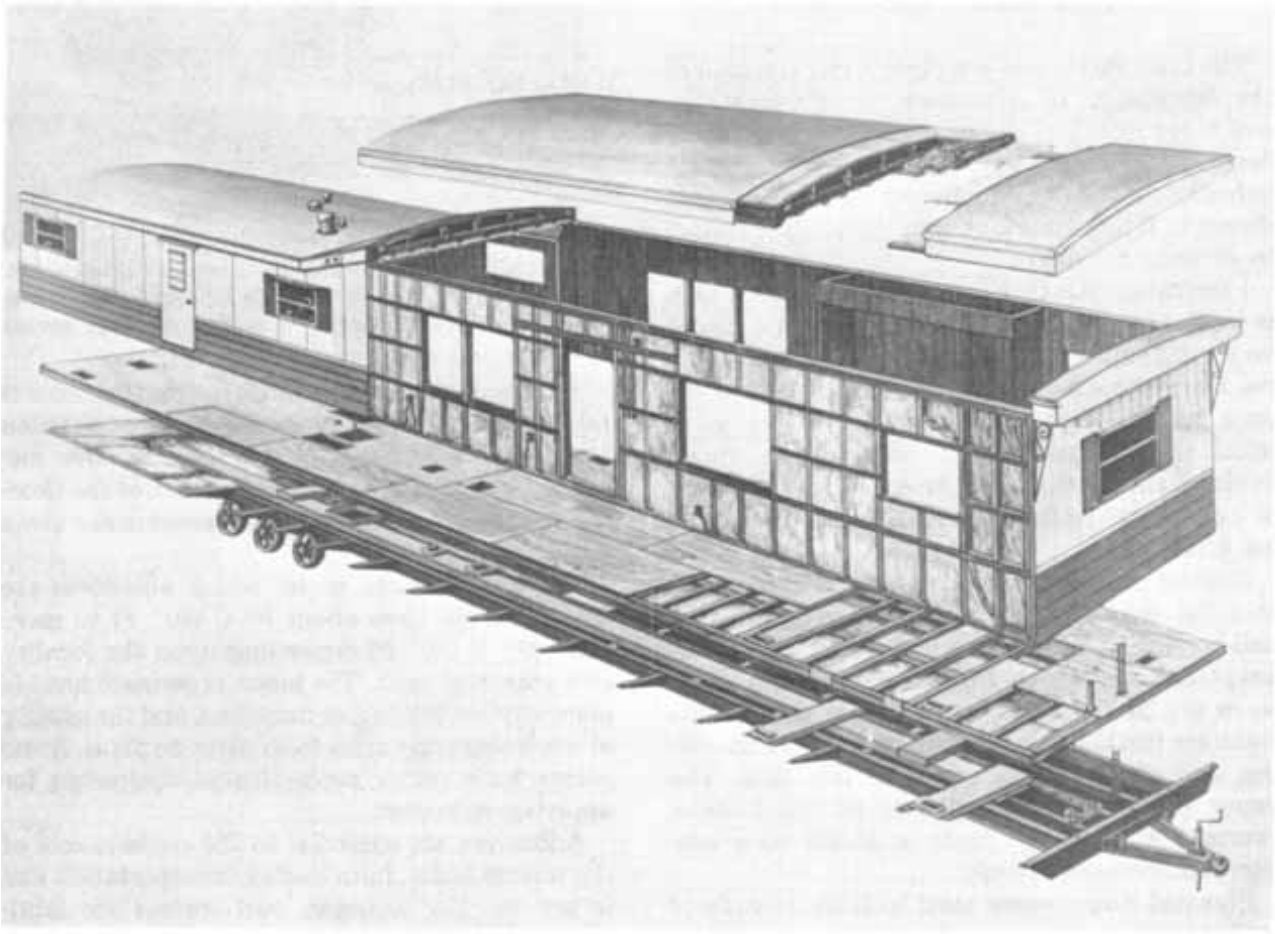


Figure 14.–Exploded view of mobile home construction. M 141 906

application only, the use of easy-to-apply nonrigid adhesives is justified.

Mobile Homes

Mobile homes are single-family transportable structures built in a factory, using assembly-line production techniques. The structure is fastened to a steel chassis with wheels for towing to the purchaser's site, where it is usually used without a permanent foundation. Mobile home sizes exceed 8 feet in width and 32 feet in length, with a majority of the units produced in 12- and 14-foot widths and 40- to 60-foot lengths, depending on over-the-road dimension limits in various states. They are also manufactured in the form of two adjoining units (double-wide mobile homes), or with a folding or telescoping room section which can be positioned at the site to provide additional living area (expandable mobile home).

Manufacturing Procedures

The manufacture of a mobile home consists of the fabrication of a number of subassemblies which are installed on the chassis as it proceeds down the assembly line. A composite of general industry practice for mobile home construction is shown in figure 14. Plant capacities range from 2 to 40 units per day.

Fabrication starts with the steel chassis, which is welded in a separate operation and then placed on the assembly line. The floor framing of nominal 2-inch dimension lumber is usually assembled on a jig and then placed on the chassis, after which the floor paneling is nail-or staple-bonded in place. The finished floor coverings (usually vinyl or carpeting) are then installed before any walls are attached.

Interior partitions and outside walls are made in a jig, with the prefinished interior paneling nail-bonded to wood studs before the assemblies are placed on the unit. Interior partitions and fixtures are placed on the unit before the outside walls are installed. Insulation, vapor barrier, wiring, and plumbing are added at this time. The vapor barrier must be placed on the interior (warm) surface of the studs or severe condensation problems may result.

Plywood ridge-beams used to support ends of roof trusses in clear-span living areas consist of two or more layers of plywood staple-bonded together with a polyvinyl acetate adhesive, and are prefabricated in two half-sections (fig. 15). Roof trusses are manufactured in a jig and then placed in another jig to attach ceiling panels to the lower chords of the trusses, and to install insulation and vapor barriers. This subassembly is then lifted by crane and placed on top of the unit. Roofing and siding, usually metal, are then installed directly over framing, and interior furnishings are completed before the finished unit leaves the plant. Occasionally plywood or other strong panel materials are used as sheathing or substrates between acoustical ceilings and supporting members. These serve to stiffen the roof-ceiling assembly and distribute loads to adjacent trusses.

M 144 550

Figure 15.–Ridge beam in double-wide mobile home will be mechanically fastened to a similar beam in adjoining unit. The beam is made with 5/8-by 4-inch plywood flanges staple-bonded to 5/8-inch plywood web using polyvinyl acetate adhesive.

The conditions under which the mobile home is fabricated are generally conducive to production of bond joints of satisfactory quality. Dry materials are generally used, since much of the flooring and prefinished paneling is stored in dry areas within buildings.

The temperatures under which adhesives are applied range from about 5° C (40° F) to more than 27° C (80° F) depending upon the locality and season of year. The labor experience level is generally semiskilled or unskilled, and the quality of workmanship varies from plant to plant. Some plants have rather sophisticated equipment for applying adhesives.

Adhesives are essential to the performance of the mobile home, both during transportation and in service. For example, roof trusses are fabricated with lumber smaller than that in conventional house construction and are highly stressed under design load conditions. Bonded plywood

gussets are often used in these trusses to provide enough stiffness and strength so they will perform as required. Likewise, the light 2-inch floor framing requires the additional rigidity supplied by adhesives. Each structural assembly must be designed or tested in accordance with specified procedures to meet structural requirements (HUD Mobile Home Construction and Safety Standards). For adhesives used in structural applications, special performance requirements have been imposed in some cases.

The metal mobile home chassis is flexible until the bonded sidewalls are attached. The walls act as deep beams, or girder walls. They stiffen the unit for road transporation and for subsequent in-service installation when supporting piers are placed under the chassis.

Legislation to control the design and construction of mobile homes has been enacted. The HUD Mobile Home Construction and Safety Standards have been adopted as a basis for design and installation of structural, plumbing, heating, and electrical systems. This standard includes structural design and test requirements for roof, wall, and floor assemblies.

Adhesive Requirements

In selecting adhesives for use in mobile homes, properties to be considered include durability (moisture resistance), aging characteristics, and gap-filling characteristics. The adhesive's working life, open assembly time, and curing time must also be considered. Adhesives must have a high rate of strength development at plant temperatures. Also important to adhesive selection are the different materials to be used as substrates and the surface condition of these materials. Adhesive cost is also of importance to the mobile home manufacturer. Adhesives preferably should be ready-mixed and easily applied.

Durability

Resistance of the adhesive to extremes of moisture and temperature should be appropriate to the location of its use. The adhesive should protect the unit not only until placed on building site but also during the full life expectancy of the structure. The fact that fabrication of the mobile home is completed under cover does not preclude the possibility that moisture may become a problem in actual use. For example, condensation or high humidity may occur in the closed cavities of roofs or walls, and roofs or plumbing fixtures may leak.

In roof cavities the temperature may reach 71° C (160° F) during summer months, often accompanied by relatively high moisture conditions. Under these conditions, the shear strength and creep resistance of the adhesive must be sufficient to prevent failure of the assembly.

The adhesive should not become embrittled or deteriorate during the service life of the structure. If it should do so, the ability of the structure to withstand inservice loading conditions, such as snow loads or foot traffic, could be seriously impaired.

Gap-Filling Characteristics

The adhesive must be capable of providing a bond between framing and paneling with bondline pressure provided only by mechanical fasteners. Because the small nails and staples normally used have limited holding power, the adhesive must contribute significantly to the strength and stiffness of the structure.

Also, the adhesive must bond satisfactorily at bondline thicknesses equal to the ordinary tolerances of fit between bonding surfaces of the substrates. In instances where the mismatch between surfaces exceeds 1/16 inch, mastic adhesives are advisable. Closer fits than this must be attained if other kinds of adhesive, such as polyvinyl acetate, are to be used. Excessive gaps must not be permitted, for if they occur in critical locations and are beyond the capacity of the adhesive, the performance of the assembly may be unpredictable.

Assembly Characteristics

The assembly time of the adhesive should be long enough to permit joining and fastening of components before the adhesive sets. In many plants, an open assembly time of 10 to 15 minutes is required to complete assembly and fastening of the wall, roof, or floor section.

The adhesive's rate of strength development must be rapid enough so that the assembly can be handled shortly after bonding. Roof truss-ceiling assemblies and wall assemblies must endure being lifted by crane within 30 to 60 minutes after the nail- or staple-bonding operation has been completed. Likewise, floors are subjected to continuous foot traffic and some relatively high dead loads for as much as 8 hours after the panels have

been bonded to the framing. The adhesive must complete its cure under these conditions, withstanding flexing of the underlayment relative to the joists.

Generally, the adhesives are not the only source of stiffness and strength for the subassembly, because mechanical fasteners are almost always used in conjunction with the adhesives. Fasteners usually consist of staples spaced about 4 to 6 inches on center for trusses, and about 12 to 16 inches on center for prefinished interior paneling used for walls. For floors, spacing of nails, screws, or staples is about 6 to 8 inches on center. Staples and nails are almost always pneumatically driven, so that the pressure applied to the bondline is generally less than if nails were hand driven.

Matching Adhesive To Substrate

A variety of materials are used as substrates in fabricating bonded components and subassemblies. Substrates include plywood and particleboard underlayment for floors, prefinished hardboard or plywood paneling for walls, and plywood for truss gussets. In practically all cases, these panels are bonded to wood framing. While the panel materials are almost always stored under cover and bonded in dry condition, lumber may have wet surfaces if stored outside prior to use. The problems in selecting an adhesive which will perform satisfactorily in roof, wall, or floor applications are simplified if similar types of materials are bonded in each application; for example, wood framing to wood paneling products.

Adhesive Cost

Because of the large quantity of adhesives used in the production of a mobile home unit, their cost becomes important. Their ease of application effects cost, for if the method of application is time consuming, or if complicated mixing procedures must be followed, the labor to apply the adhesive may be excessive. In addition, production delays cannot be tolerated on the assembly line.

ONSITE BONDING APPLICATIONS

Onsite bonding offers a number of practical advantages over plant bonding. For example, a bonded element may be so large that it can only be built in the field (fig. 16). Onsite bonding eliminates problems with scheduling delivery of bulky factory-bonded components. Also, costs can be reduced by eliminating the plant overhead, the expense of shipment, and the need for special equipment to handle large components onsite.

Onsite bonding applications can be divided into prime structural, which require rigid adhesives, and semistructural, which permit the use of nonrigid adhesives. (Rigid adhesives do not creep in joints under sustained stress, but nonrigid adhesives may-chapter 5.) Thus, such nonrigid adhesives as contact cements should not be used in trusses or beams unless the design allows for the nonrigid action of the bond. They can be used to stiffen an assembly where it will not endure sustained loading, and where the bondline strength is not critical to the building's structural integrity.

Some elastomeric adhesives can be readily used in onsite bonding, but considerable caution should be exerted in using rigid adhesives such as casein or resorcinol. These are sensitive to factors such as moisture content of the wood, smoothness of the surface, pressure requirements, and temperature, all of which are difficult to control in onsite bonding.

M 138 198

Figure 16.–A bonded hyperbolic paraboloid roof on a service-type building.

For such reasons, the regulatory agencies generally require special inspection of major structures which are to be bonded onsite. However, smaller assemblies such as trussed rafters or garage beam headers are frequently acceptable to building officials, particularly when adequate nailing is used in conjunction with the adhesive. Also, in many cases, construction occurs outside the jurisdiction of any building code.

Rigid Adhesives

The choice of a rigid adhesive for onsite use is generally narrowed to either casein or resorcinol. Casein is an extremely reliable adhesive for interior applications and may be used in typical protected conditions such as the gusset plates of roof trusses or other covered applications where high moisture conditions in service are not likely. Resorcinol adhesive should be used wherever the bondlines are exposed to the weather. Also, it should be used where high humidities are typically encountered, as in most agricultural buildings.

Structural elements which have been onsite bonded successfully include trussed rafters, rigid frames, and plywood box beams. Typically, these consist of 2-inch lumber framing joined with plywood gussets or web members. Stress grade lumber is used and it should be dry, surfaced, and free of cup or warp. Plywood may be either sanded or unsanded and should be of an identified standard grade having recognized working stresses. Acceptance of the assembly by regulatory agencies, where needed, is facilitated if lumber and plywood are grademarked by a recognized agency as conforming with the applicable product standards.

Fabrication may be accomplished at the building site using the building floor as a working surface. Where possible, it is preferable to provide some form of shelter against the weather. A simple jig is helpful, with sufficient room around it for handling the assemblies after they have been fabricated. The jig may consist of blocks nailed to the floor or to a table, with provision for any necessary camber included.

Adhesive, after proper mixing, is usually spread on both contacting surfaces using a brush or roller. Nails or staples are used to obtain the necessary contact pressure. Fastener schedules as shown in table 1 have been used satisfactorily for nail-bonding plywood to lumber. Plywood surfaces are flexible and can conform to irregularities in the lumber surface with the use of fastener pressure only. However, with lumber-to-lumber joints heavier nailing schedules are required and, even so, auxiliary pressure, as from clamps, may be required.

Table I.–*Nail and staple schedule for nail-bonding plywood to lumber*

Plywood thickness	Nails[1]		Staples[2]	
	Sue	Spacing[3]	Size	Spacing[3]
3/8 inch	4d	3 inches on center	1-1/8 inches	3 inches on center
1/2 to 3/4 inch	6d	4 inches on center	Not recommended	

[1]Nails–Box, common, cement coated, or T-nails.
[2]Staples–16 gage with 7/16 inch crown width.
[3]Use 2 rows of nails or staples for 4-inch-wide lumber, 3 rows for 6-inch-wide lumber, and set in 3/4 inch from lumber edge. Stagger nails from opposite sides.

After fabrication, the element should be put aside and not disturbed until the adhesive has set. Curing can take place after the element has been put in place if it is not loaded heavily while the curing proceeds. Data on cure time as affected by temperature are available from the adhesive manufacturers.

The nails or staples are used only to maintain contact while the adhesive is setting. They are not considered to add to the strength of the bonded joint or the member because the adhesive itself is so rigid that it carries virtually all the stress on the joint. However, should there be a partial failure of the adhesive bond, the mechanical fasteners are available to help carry the stress.

Rigid Frames

Plywood gusset plates may be bonded to lumber members whenever an exceptionally rigid joint is desired. For example, rigid frames can be made by connecting straight posts to rafters with plywood gusset plates to form moment-resisting joints. Although usually nailed only, such frames can be stiffened substantially by the addition of adhesive at the gusset plate joint.

In-Line Joists

Lumber members may be spliced into a single, continuous length, as for large floor joists, using plywood gussets, The gussets should be of the same depth as the lumber pieces or of greater depth, and a gusset should be bonded to each side of the lumber pieces. The size of the plywood gusset will depend on the strength required at the joint. For example, if a joist is spliced a short distance away from the support, the bending stress on the gusset plate is less than if it were spliced at its midspan or over the center support of a two-span system. The continuity over the support made possible by using a bonded gusset plate substantially improves the resistance of the joist against deflection. It also facilitates floor panel layout and speeds construction when joists are pretrimmed to exact length.

Beams

Beams can be made onsite having lumber top and bottom flanges with bonded plywood webs attached to either or both sides. These beams may be used as headers over window or garage door openings, and as ridge or other beams where solid sawn lumber members may not be suitable or available. In the case of window headers, a depth of about 14 inches is usually available with ordinary framed residential construction. For shorter spans, a single layer of 1/2-inch plywood sheathing may be bonded to the outside of a 2 by 4 top and bottom flange. The interior surface will generally be finished off with the interior drywall. For longer spans, a pair of 2 by 4's may be used on both top and bottom edges, with 1/2-inch plywood forming the inside surface, set flush with and taped to the drywall. The strength of the header can be increased still more by using 3/4-inch plywood on both sides.

Obviously, larger sizes can also be built to accommodate greater spans or loads, but usually building dimensions prescribe a limitation on depth and width. Lumber members should be full length where possible, but if butt joints are required, they should be staggered and considered in the structural design of the member. Plywood joints may be butted and bonded over a vertical lumber stiffening member, and similar stiffeners may be placed at the ends of the beam where it bears on the supports, in order to prevent buckling of the web.

Occasionally a large sized major element is built on the site for one reason or another. For example, bonded box beam sections have been made in lengths of 60 feet or more with up to 8-foot depth. Hyperbolic paraboloids, consisting of a number of layers of plywood staple-bonded to each other and to the framing system, have been designed as shell structures to be built on the job. In all such cases, extreme care is required, both in the design and fabrication, to assure a good bonding job, particularly with respect to items such as the fit of the bonded surfaces.

Nonrigid Adhesives

Nonrigid adhesives, generally of the elastomeric type, are used in construction in a semistructural capacity to impart additional stiffness, as in composite flexural action, or to provide a bracing function, or as a means of surface fastening in lieu of mechanical fasteners. Such bonds are not presently recognized in the codes as increasing structural strength although they actually do transmit high levels of shear stress, usually in excess of the strength of the substrate.

M 141 909

Figure 17.–Applying an elastomeric construction adhesive for an onsite-bonded floor system.

For short-term loads, their performance may be relied on, and methods of determining their structural contribution are presently being developed. However, for loads applied over a long period of time, the possibility that the joint will deform, particularly at elevated temperatures, has so far prevented their being considered as transmitting stress.

The elastomeric adhesives, especially, may be used advantageously for onsite bonding because of their excellent handling characteristics, gap-filling properties, and accommodation to a wide range of temperature and moisture conditions during the bonding process.

Floors

A typical application of nonrigid adhesives for onsite bonding is the fastening of plywood floors to lumber joists using elastomeric adhesives (fig. 17). This assembly increases the stiffness of the joist substantially. The bonding develops T-beam action which also increases floor stiffness between joists. Thus, a particular joist can often be used on a longer span than if the adhesive were not used.

At the same time, bonding the plywood reduces the stress on the nails so that there is less likelihood of squeaks in the floor or of nails backing out (nail popping), which may show through a resilient floor. As a result, the system reduces costs by permitting the use of a single layer of floor, with less nailing than is otherwise required. Frequently, the added strength is adequate to allow a longer span, a reduction in the lumber size, or a wider spacing of joists.

The increased spans for joists having a bonded plywood floor are recognized by the major regulatory agencies, which also require adhesives to conform with specification AFG-01 or ASTM D 3498.[4] These specifications describe the performance requirements for adhesives to be used for this application. The specification covers performance requirements under conditions likely to be encountered in onsite construction, including wet or frozen lumber, high and low temperatures, and thick bondlines resulting from less than a perfect fit between members.

In constructing the floor, elastomeric adhesives are applied in a bead to the surface of each joist just prior to application of the plywood panels. In addition, a bead of adhesive is put in the groove of the tongue-and-groove joint to join plywood edges, and the panel is then positioned on the joist and attached with nails spaced 12 inches. Joints are left open 1/16 inch to allow for the possibility of swelling of the panels. It has been determined that adhesive in the tongue-and-groove joint increases the strength of the assembly very substantially.

The beneficial effects of bonding on a typical residential wood joist floor are shown in the case of a 26-foot-wide house having a center bearing partition. Without bonding, 2 by 8 joists spaced 16 inches are required; whereas, if a 3/4-inch plywood subfloor is bonded to the 2 by 8 joists, they may be spaced 24 inches. In a 28-foot-wide house with a center bearing, conventional construction requires 2 by 10 joists spaced 16 inches on center. If 5/8-inch plywood is bonded to the joists, they may be reduced to 2 by 8's spaced 16 inches.

Plywood is also bonded to steel and aluminum joists with elastomeric adhesives together with mechanical fasteners such as self-tapping screws or hardened steel nails. This construction also stiffens the joist substantially.

Underlayment

Many wood residential floors are of double layer construction. The subfloor serves as a structural working platform to which an additional layer of underlayment is applied. The added layer provides a smooth surface for finish flooring, such as thin resilient tile. The underlayment also shims the level of a tiled floor up to that of the hardwood strip flooring or carpeting which may be used adjacent to it. The underlayment permits use of a lower grade of material for subfloor and conceals any incidental construction damage. It also permits the offsetting of joints between panels in the subfloor and the underlayment.

Typical panel materials used for underlayment include plywood, particleboard, and hardboard. The primary requirements are good dimensional stability in all directions and uniform thickness to prevent the panel joints from showing through the finish floor. Also, the underlayment must be strong and stiff enough to bridge any roughness or openings in the subfloor, such as from cupped boards.

[4]Complete references to published standards appear under "Background Information" at end of chapter.

Underlayment panels are usually nailed or stapled in place, but more satisfactory results can be obtained if they are also bonded. Bonding will tend to stabilize the floor by reducing dimensional changes due to moisture pickup or changes in humidity. Also, it will substantially increase the stiffness by developing composite action between the two layers of floor, particularly when joints are offset between layers. This will permit the floor to carry heavy concentrated loads between joists with less deflection. Bonding will also reduce the number of mechanical fasteners required.

M 138 198

Figure 18.–Application of mastic adhesive to studs for bonding wall panels.

Requirements of the adhesive are less stringent for installation of underlayment to subfloor than for bonding a subfloor to joists. This is because the underlayment is installed as one of the final construction operations, when the room is dry and heat is generally available. Adhesive should have the ability to fill gaps reasonably well, particularly if the subfloor is quite rough. Also, some resistance to moisture is desirable to guard against delamination in case of plumbing leaks.

Adhesives which have been used for bonding underlayment include casein, polyvinyl acetate, and elastomers. The subfloor should be dry and broom clean. Adhesive may be applied either to the underlayment panels or to the subfloor, generally with a calking gun, a notched spreader, or brush or roller; Adhesive is often applied in patterns, frequently in 3- or 4-inch-wide strips spaced about 12 inches on center across the panel, with an additional strip along each edge. Other patterns used include a diagonal X across each panel-again with all four edges spread. Underlayment is applied with its joints offset with respect to any joints in the subfloor, and with end joints staggered with respect to the other underlayment panels. A stiffer floor will result if the face grain of underlayment is perpendicular to the supporting framing. Nails or staples are used to maintain contact between the underlayment and the subfloor while the adhesive is setting. Deformed shank nails are desirable to minimize nail popping problems later.

Roof and Wall Diaphragms

Sheathed roofs, floors, and walls which brace a building against lateral forces are called diaphragms or shear walls. They are sometimes stiffened with nonrigid adhesives. Lateral forces involved are from wind or earthquakes. All buildings should be designed to resist wind, while those in areas of seismic activity should also be designed to resist earthquakes.

A horizontal roof or floor diaphragm distributes the lateral loads to the vertical diaphragms such as walls and partitions which, in turn, carry the loads to the foundation. Engineering design methods exist for calculating the stresses in the diaphragm members. Stiffness of the diaphragm is essential because it reduces deflection under lateral loads and thus reduces the possibility of damage to members such as windows and other fragile parts of the building.

Most wood diaphragms consist of plywood or other panel materials attached to lumber framing with nails, applied according to a schedule determined by the engineering design. However, adhesives have been proposed as a possible means of increasing the stiffness and strength of these diaphragms. Field-applied elastomeric adhesives, which are relatively flexible, may have particular advantages in absorbing the energy of the back-and-forth shaking developed by seismic action. One bonded horizontal diaphragm design has ob-

tained a code recognition. Although there are no code requirements at present for bonded shear walls, tests at the Forest Products Laboratory and the American Plywood Association have shown increases in strength and stiffness over assemblies using only nails.

Bonding of panels, both interior finish and exterior sheathing or siding, also substantially increases stiffness of the wall under wind loads applied normal to the surface. Tests have also shown a significant reduction in stress in the framing member under such conditions, suggesting some potential economies in wall construction. It should be noted, however, that bonding the thinner siding direct to studs has been questioned as potentially increasing their tendency to buckle under moisture content increases. This application is, therefore, still under investigation.

Although there are no code requirements at present for bonded diaphragms, tests at the Forest Products Laboratory and the American Plywood Association have shown substantial increase in strength and stiffness over assemblies using only nails. Tests have also shown a significant reduction in stress in the framing member under such conditions, suggesting some potential economies in wall construction. However, at present, this application is still under investigation.

Interior finish wall paneling is frequently applied directly to framing with nonrigid adhesives (fig. 18). Framing may be lumber or metal studs, while the wall paneling itself may be gypsum board, hardwood plywood, hardboard, or other panels. For certain wall constructions, it is desirable to install a backing panel directly to the studs. The backing panel may consist of gypsum, insulation board, or plywood with the finish panel or lumber applied to it.

Adhesive is used instead of mechanical fasteners primarily to reduce potential damage to prefinished surfaces of paneling materials which may arise from the nailing process. The appearance of a prefinished surface is preserved by eliminating most of the nails as well as the labor of nailing, setting, and filling.

Application of a panel backing material to the studs permits the use of a thinner, less expensive finish panel, and can reduce cutting and waste by permitting panel joints to occur without being limited by the location of the framing members. Several acoustically rated wall constructions incorporate the use of panels bonded to backing. Typical are gypsum finish panels bonded to sound-deadening board or to plywood, with the latter frequently nailed to the framing members.

Adhesives may not be as effective as mechanical fasteners in maintaining integrity of a fire-rated assembly. Where fire resistance is required, any substitution of adhesives for the specified nailing schedule should be checked.

Mastic adhesives generally are applied from a gun: a bead is applied to the stud, or if solid backing is used, in a pattern so as to bond the edge and intermediate areas of each panel. Adhesives conforming to ASTM Standard C 557[4] were developed for joining gypsum wallboard to wood framing. These adhesives are commonly used for other interior wall paneling materials also. The adhesive panels are usually nail-bonded at top and bottom where the nail heads will be subsequently covered by trim.

Wood To Concrete Or Masonry

Nonrigid adhesives are convenient for attaching wood strips to concrete or masonry, such as in bonding furring strips to basement walls to attach a finish surface. Also, the warmth and resiliency of a wood floor can be achieved over a concrete slab by bonding wood furring strips to the concrete, to be followed by either hardwood strip flooring or panel underlayment with resilient flooring.

In many of these applications, the nonrigid adhesive is required to resist moisture that may penetrate through the slab or walls or that may condense on it if an adequate vapor barrier is not present. In addition, the adhesive should have sufficient bond strength to resist any tendency of the furring strips to warp.

Elastomeric adhesive is applied in a bead directly to the masonry. Contact must be maintained with masonry walls. Where the surface is quite irregular, it may be necessary to shim the furring strips with wood shingle wedges. In this case, the shims may be bonded to the masonry and the furring strips to the shims, leaving an air space behind the strip.

Use of adhesives is usually faster than drilling or use of masonry nails. For applying wall sills to a concrete slab or foundation wall, adhesive bonding is substantially more flexible than the use of preset anchor bolts. However, building code requirements should be investigated to determine if it is a permissible substitute.

BACKGROUND MATERIAL

American Plywood Association

Supplements to Plywood Design Specifications (PDS)

Design of Plywood Curved Panels–PDS Supplement No. 1
Design of Plywood Beams–PDS Supplement No. 2
Design of Plywood Stressed-Skin Panels–PDS Supplement No. 3
Design of Plywood Sandwich Panels–PDS Supplement No. 4

Fabrication Specifications

Fabrication of Plywood Curved Panels–CP-8
Fabrication of Plywood Beams–BB-8
Fabrication of Plywood Stressed-Skin Panels–SS-8
Fabrication of Plywood Sandwich Panels–SP-61
Fabrication of Plywood Folded Plates–FP-62
Fabrication of Trussed Rafters with Plywood Gussets–FT-8

Laboratory Reports (LR)

Plywood Girder Walls for Transportable Buildings–LR 116
Plywood Roof Framing for Transportable Buildings–LR 117
Field-Glued Plywood Floor Tests–LR 118
Plywood Folded Plates-Design and Details–LR 121
Plywood Ridge Beams for Mobile Homes–LR 124

Other

Adhesives for Field Gluing Plywood to Wood Framing–Performance Specification AFG-01
Structural Adhesives for Plywood-Lumber Assemblies–Technical Note Y391
Plywood Diaphragm Construction-Pub. No. U310
APA Glued Floor System–Pub. No. U405

American Society for Testing and Materials

Adhesives for Fastening Gypsum Wallboard to Wood Framing–ASTM C 557
Adhesives for Structural Laminated Wood Products for Use Under Exterior (Wet Use) Exposure Conditions–ASTM D 2559
Protein-Base Adhesives for Structural Laminated Wood Products for Use Under Interior (Dry Use) Exposure Conditions–ASTM D 3024
Adhesives for Field Gluing Plywood to Lumber Framing for Floor Systems–ASTM D 3498

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U.S. General Services Administration:
Federal Specifications
Adhesive, casein-type, water- and mold-resistant, MMM-A-125, 1955, 4 p.
Adhesive, polyvinyl acetate, resin emulsion (alkali dispersible), MMM-A-180, 1972, 6 p.
Adhesive, urea-resin-type (liquid and powder), MMM-A-188, 1960, 7 p.

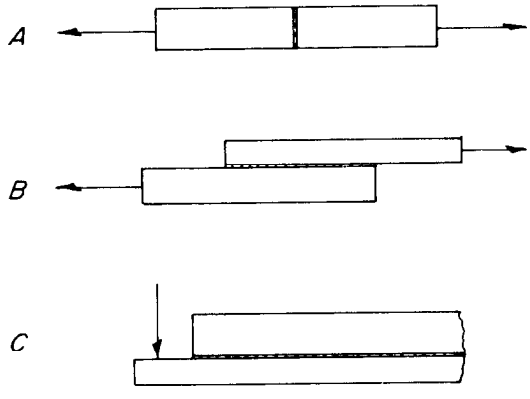
CHAPTER 3:

STRUCTURAL DESIGN CONSIDERATIONS[5]

Joining small pieces to produce large members, and component parts to create structural sections, can be done efficiently and effectively with adhesives. The many parts of buildings can be joined by mechanical fasteners such as nails, screws, and bolts. But these fastenings can be located only at discrete points, while adhesive bonding can be continuous. Adhesives thus can produce joints of much larger area than mechanical fasteners. Adhesives unite large areas at low stress and thereby achieve structural performance similar to rather high loads per mechanical fastener. The large area of adhesive bonds prevents structural failure and allows use of relatively weak material. It also results in good rigidity because of low deformation at low stress.

This chapter relates the qualities of bonded joints to the performance of structural assemblies. Maximum strength is developed in structural assemblies only when the components are held together rigidly. The diminution of strength caused by nonrigid joints can be compensated for by proper design and by an increase in the size of component parts.

Basic joints and the stresses induced in them are shown in figure 19. The shear joint is preferred because a large shearing area can be incor-



M 141 762

Figure 19.–Basic joints and stresses normally imposed: *A*, tension: *B*, shear: and *C*, cleavage.

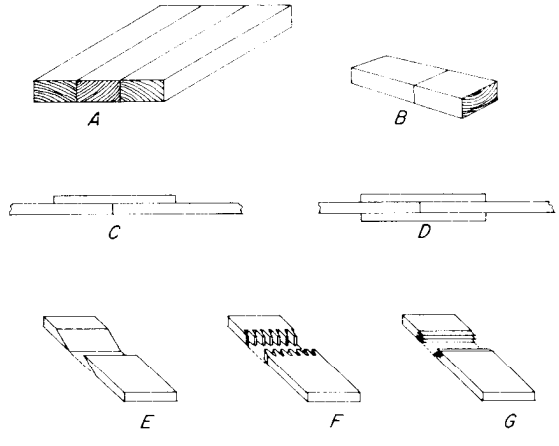


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Figure 20.–Methods of bonding small pieces in the production of larger components: *A*, side-grain joint; *B*, end-grain butt joint; *C*, butt or side joint with single splice plate; *D*, butt or side joint with double splice plate, *E*, scarf joint; *F* and *G*, finger joints.

[5]Written by Edward Kuenzi of the U.S. Forest Products Laboratory.

porated. Then shear stress is low so that adhesives of exceptionally high shear strength are not needed, The tension joint is to be avoided because the smaller joint area causes high tensile stresses. The cleavage joint should also be avoided because it causes high tensile stresses at the joint end.

ADHESIVE-BONDED JOINTS IN COMPONENT PARTS

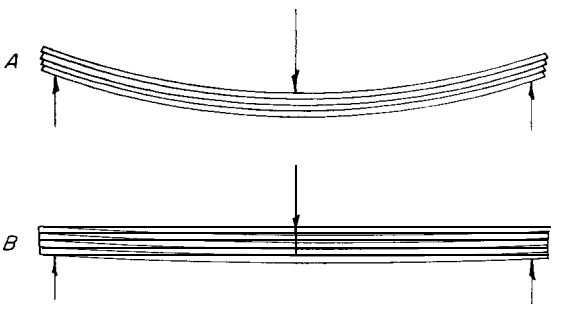
The production of large component parts from smaller pieces can be accomplished efficiently by adhesive bonding. Side-grain joints shown in sketch ***A*** of figure 20 are very effective in producing wide boards from narrow stock. These joints are not used in usual building construction. The end-grain butt joint as shown in sketch ***B*** of figure 20 is not effective in producing long boards from short ones. This joint tends to be weak because of the small effective bond area in proportion to member size and because of the difficulty in bonding end-grain surfaces of wood. Sheet components, such as plywood, can be joined using splice plates as shown in sketches C and ***D*** of figure 20, if the splice plates can be accommodated in the design of the structural component. The amount of lap area in the splice must be sufficient to reduce shear stresses, caused by forces in the plane of the sheet, to allowable levels. The forces in the plane of the sheet tend to cause bending at the joint with a single splice plate, but not in joints with double splice plates.

The most effective way to joint sheet materials and end-joint laminations is to use the scarf joint shown in sketch *E* of figure 20. The strength of this joint is dependent on the slope of the scarf (tangent of the angle between the scarf surface and the board surface). The tensile strength of clear, straight-grained boards or plywood end-joined with scarfs of various slopes is given as percentage strength of the wood or plywood in the following tabulation:

Scarf slope	*Percentage strength*	
	Lumber	*Plywood*
1/12 or less	90	100
1/10	85	100
1/8	80	100
1/5	65	75

Specimens with scarf joints having slopes 1/8 or less and bonded with resorcinol adhesive were found to withstand repetitions of stress (fatigue loading) as well as the wood itself.

Finger joints such as the ones shown in sketches ***F*** and G of figure 20 can be used to join edges of sheet materials or ends of lumber. The strength of the joint is greatly dependent upon joint fit and sharpness of fingers. Poorly fitting joints are weak, as are joints with wide fingertips. Well-made finger joints with sharp tips are from 75 to 90 percent as strong as scarf joints with the same slope as the slope of the finger edges. Repetition of stress has a more deleterious effect on finger joints than scarf joints, the strength being only about 80 percent of scarf joint strength after 30 million load repetitions.



M 141 761

Figure 21.–Deflection causes slip between layers. ***A,*** but is resisted by the beam laminated with rigid adhesives, ***B.***

The basic joints for component parts shown in figure 20 have variations, such as tongue-and-groove side joints, serrated, hooked, and double-slope scarf joints. These variations may assist in positioning the parts, but they do not impart additional strength. Their use requires extremely careful workmanship to insure proper fitting of the joints; otherwise, their adoption will result in poor joints. In all these machined joint configurations, damage to machined finger joints and other pieces must be avoided in handling, before and during bonding.

ADHESIVE-BONDED ASSEMBLIES

Assembly of component, parts into structural members or assemblies can be extremely effective if done by bonding rather than with mechanical fasteners. A familiar analogy is the welding of structural steel components rather than bolting or riveting. As noted previously, the relatively large area of bond reduces stress and can assist in maintaining stiffness. The prime reason for assembling with rigid adhesives is to prevent slip between layers and thus prevent excessive deflection of the assembly. The sketches of figure 21 show effects of slip in the layers of a laminated beam on its deflection. It can be shown that the bending stiffness of a rigidly bonded beam of *n* layers is (n^2) times the bending stiffness of a beam with no adhesive between the layers. Thus, for the beams in figure 21 the bending stiffness of beam ***B*** would be 4^2, or 16 times that of beam *A*. Hence beam ***B*** would deflect only 1/16 as much as beam ***A.***

Construction assemblies that can be used as floors, walls, roofs, ceilings, and partitions are shown in the sketches of figure 22. The bending stiffness of these assemblies can be greatly increased by bonding the parts together with a rigid adhesive. Construction ***A*** (conventional construction) is usually assembled by nailing; construction ***B*** is usually bonded; and construction C cannot be utilized unless it is bonded. The relative effectiveness of the bond can be assessed by applying the following formulas for the bending stiffness of the assemblies. Formulas are given for the parts unbonded and also for the assemblies bonded with a rigid adhesive. A comparison of the values for the assemblies can aid in deciding whether a rigid adhesive is of prime importance toward maintaining proper structural stiffness without excessive use of materials. (Details concerning the use of a nonrigid adhesive will be discussed later.)

Bending Stiffness Formulas

For the following formulas,

a is joist or stud spacing or panel width (fig. 22),
b is joist, stud, or stringer width (fig. 22),
d is joist, stud, or stringer depth (fig. 22),
E is modulus of elasticity; subscript s denotes joist, stud, or stringer, subscripts *1* and *2* denote skin or facing,
F is subscript denoting flexure as applied to facing modulus of elasticity,
h is distance between centroids of principal moment-carrying components (fig. 22),
I is moment of inertia in the quantity (EI) for bending stiffness,
n is number of stringers in stressed-skin panel,
t is thickness of skins or facings (fig. 22), and
U is subscript denoting unbonded,
B is subscript denoting bonded.

Construction A (Conventional) Joists or Studs with Sheathing)

The bending stiffness per width "a" is given by the formulas:

Unbonded

$$(EI)_U = \frac{1}{12}(E_{1F}at^3 + E_s bd^3) \qquad (1)$$

Rigidly bonded

$$(EI)_B = \frac{E_1 at_1 E_s bdh^2}{E_1 at_1 + E_s bd} + (EI)_U \qquad (2)$$

Construction B (Stressed-Skin Panel)

The bending stiffness per panel width "a" is given by the formulas:

Unbonded

$$(EI)_U = \frac{1}{12}(E_{1F}at_1^3 + E_{2F}at_2^3 + nE_s bd^3) \qquad (3)$$

Rigidly bonded

$$(EI)_B = \frac{[4E_1at_1E_2at_2 + nE_sbd(E_1at_1 + E_2at_2)]\,h^2}{4(E_1at_1 + E_2at_2 + nE_sbd)} + (EI)_U \qquad (4)$$

Construction C (Sandwich Panel)

The bending stiffness per panel width "a" is given by the formulas:

Unbonded

$$(EI)_U = \frac{1}{12}(E_{1F}at_1^3 + E_{2F}at_2^3) \qquad (5)$$

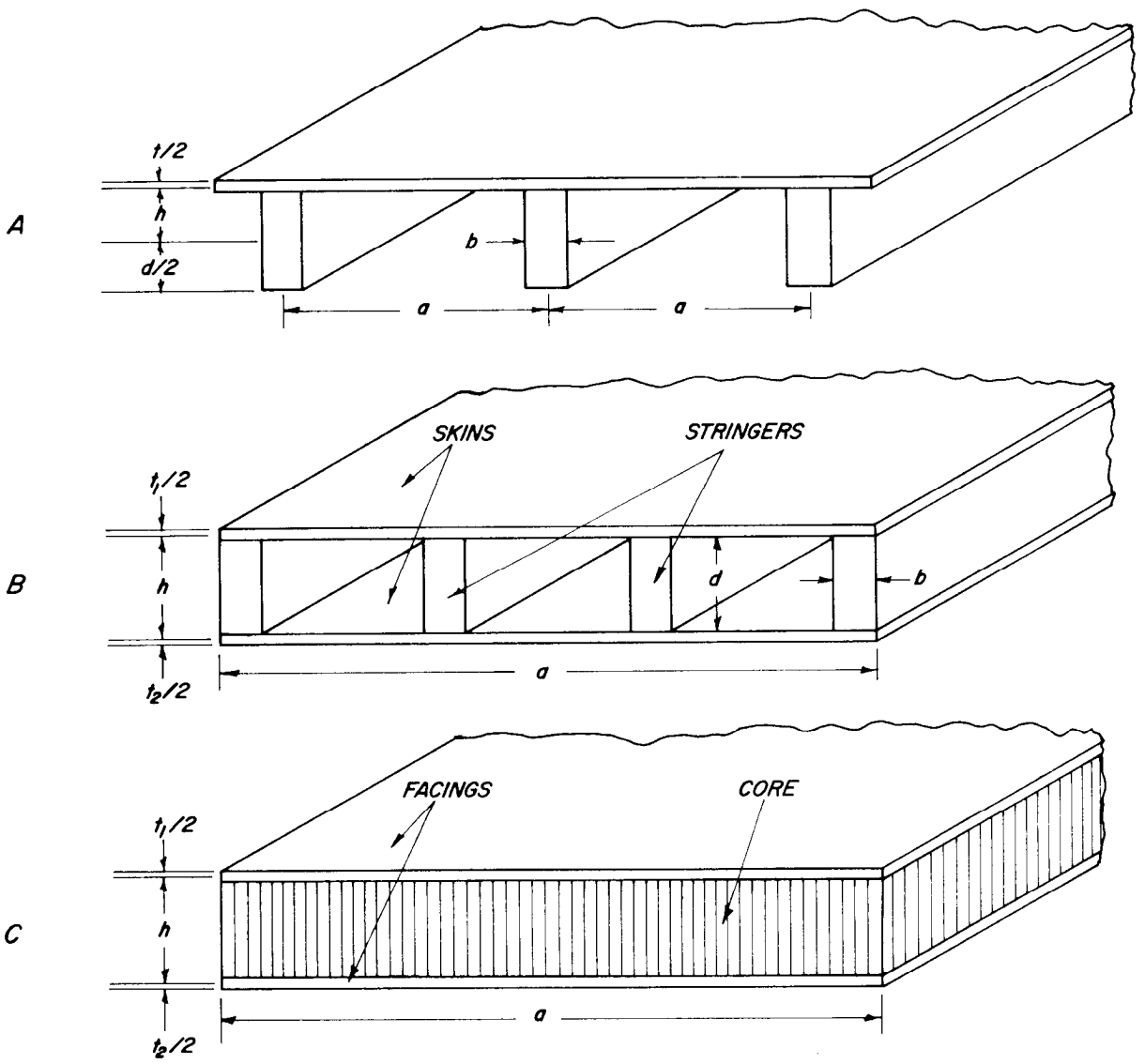


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Figure 22.–Adhesive-bonded assemblies: *A*, conventional construction; *B*, stressed-skin construction; and *C*, sandwich panel.

Rigidly bonded

$$(EI)_B = \frac{E_1 a t_1 E_2 a t_2 h^2}{E_1 a t_1 + E_2 a t_2} + (EI)_U \qquad (6)$$

Examples: Bending Stiffness

Determine the effect on bending stiffness of a rigid bond for a conventional floor and wall construction.

Floor

Two- by 8-inch Douglas-fir joists spaced 16 inches on centers; 5/8-inch sanded Douglas-fir plywood with face grain direction placed perpendicular to joist length (plywood edges are assumed to be bonded together so that the sheathing is completely effective). Data for use in formulas (1) and (2) are as follows:

E_{-1F} is $0.311E_L$ effective plywood flexural stiffness perpendicular to face grain direction.
E_1 is $0.389E_L$ effective plywood compressive stiffness perpendicular to face grain direction.
E_L is modulus of elasticity of Douglas-fir parallel to the grain. a is 16 inches, *t* is 0.625 inch, *b* is 1.5 inches, *d* is 7.25 inches, and *h* is 3.94 inches.

Substitution of these values into formulas (1) and (2), after assuming $E_s = E_L$, results in:

$$(EI)_U = 47.74E_L$$

$$(EI)_B = 92.21E_L$$

Therefore, if a rigid bond could be utilized, the floor would be about twice as stiff as if unbonded. (Any gaps between plywood edges will cause additional floor deflection.)

Wall

Two- by 4-inch Douglas-fir studs spaced 16 inches on centers, 3/8-inch Douglas-fir plywood sheathing with face grain direction placed parallel to stud length. Data for use in formulas (1) and (2) are as follows:

E_{1F} is $0.910\ E_L$ effective plywood flexural stiffness parallel to face grain direction.
E_1 is $0.534E_L$ effective plywood compressive stiffness parallel to face grain direction.
E_L is the modulus of elasticity of Douglas-fir parallel to the face grain direction.
a is 16 inches, *t* is 0.375 inch, *b* is 1.5 inches, *d* is 3.5 inches, and *h* is 1.94 inches.

Substitution of these values into formulas (1) and (2) results in:

$$(EI)_U = 5.42E_L$$

$$(EI)_B = 12.91E_L$$

Therefore, if a rigid bond was used, the wall would be more than double the stiffness than if unbonded.

Shear Stress Formulas

The bondline shear stress in the constructions ***A, B,*** and C assembled with rigid adhesive bonds can be calculated with the following formulas. An approximate formula that is ultraconservative (gives stress values that are too high) and applies to all of the constructions is:

$$F_s = \frac{V}{hx} \qquad (7)$$

where

F_s is bondline shear stress;
V is shear load; and
x is total width of bondline in cross section supporting shear load V.

More accurate formulas for the shear stress at the bondlines of the constructions shown in the sketches of figure 22 are given in the following:

Construction A

$$F_s = \frac{V}{bh}\left[1 - \frac{(EI)_U}{(EI)_B}\right] \qquad (8)$$

where

V is shear load per width "a" of the construction; $(EI)_U$ is given by formula (1); and $(EI)_B$ is given by formula (2).

Construction B

$$F_s = \frac{V(EQ)}{nb(EI)_B} \qquad (9)$$

where

$$(EQ) = \frac{E_1 at_1 (2E_2 at_2 + E_s nbd)h}{2(E_1 at_1 + E_2 at_2 + E_s nbd)} \qquad (10)$$

where

V is shear load per panel of width "a"; and $(EI)_B$ is given by formula (4).

Construction C

$$F_s = \frac{V}{ah}\left[1 - \frac{(EI)_U}{(EI)_B}\right] \qquad (11)$$

where

V is shear load per panel of width "a"; $(EI)_U$ is given by formula (5); and $(EI)_B$ is given by formula (6).

The shear stress calculated by these formulas should not exceed the shear strength of the adhesive bond or preferably some lower allowable design stress value, or the allowable shear stress of the materials being bonded. The formulas apply to constructions bonded with "rigid" adhesives. The degree of rigidity of a "rigid" adhesive must be similar to or greater than the least rigid material being bonded.

Examples: Shear Stress

The same bonded conventional constructions considered previously will be checked for shear stress.

Floor

Two- by 8-inch Douglas-fir joists spaced 16 inches on centers; 5/8-inch Douglas-fir plywood sheathing. Shear load *V* is 640 pounds (this shear would be produced by a uniformly distributed load of 80 pounds per square foot on a 12-foot span).

From formula (7)

F_s = 108 pounds per square inch;

from formula (8)

F_s = 52 pounds per square inch.

Wall

Two- by 4-inch Douglas-fir studs spaced 16 inches on centers, 3/8-inch Douglas-fir plywood sheathing. Shear load *V* is 107 pounds (this shear would be produced by a uniformly distributed load of 20 pounds per square foot on an 8-foot span).

From formula (7)

F_s = 37 pounds per square inch;

from formula (8)

F_s = 21 pounds per square inch.

Thus the adhesive shear strength needed for these constructions to have maximum structural effectiveness is not remarkably high, even under adverse exposure to heat and moisture.

Beams

Wood-plywood box beams and I-beams of cross sections shown in figure 23 can be designed to utilize materials efficiently and provide adequate stiffness and strength. The use of a rigid adhesive is essential although estimates can be made of beam performance for adhesives with finite rigidity. Properly designed webs need not be of plywood, as here indicated, but can also be of hardboard, particleboard, and any suitable material of known or predictable strength.

The bond shear stress, using notation shown in figure 23 is given by the formula:

$$F_s = \frac{V}{2dh}\left[1 - \frac{(EI)_U}{(EI)_B}\right] \qquad (12)$$

where V is shear load on beam,

$$(EI)_U = \frac{1}{6}[Ebd^3 + E_w W(h + d)^3] \qquad (13)$$

$$(EI)_B = \frac{1}{2}Ebdh^2 + (EI)_U \qquad (14)$$

E is elastic modulus of the lumber flanges and E_W compression modulus of elasticity of the plywood webs.

Nonrigid Adhesives

The effects of nonrigid adhesives (adhesives with low-finite shear stiffness) on performance of constructions shown in figure 22 and beams shown in figure 23 can be estimated by applying the following formulas.

The midspan deflection of simply supported constructions under uniformly distributed load is given by the formula:

$$\Delta = K_\Delta \frac{5WL^3}{384(EI)_B} \qquad (15)$$

where

? ?is midspan deflection;

$K_?$?is coefficient given by chart ***A*** of figure 24:

W is total load carried by construction (width same as that used to calculate *(EI)*);

L is span length: and

$(EI)_B$ is bending stiffness of construction as if bonded with a rigid adhesive (see formulas (2), (4), (6), and (14)).

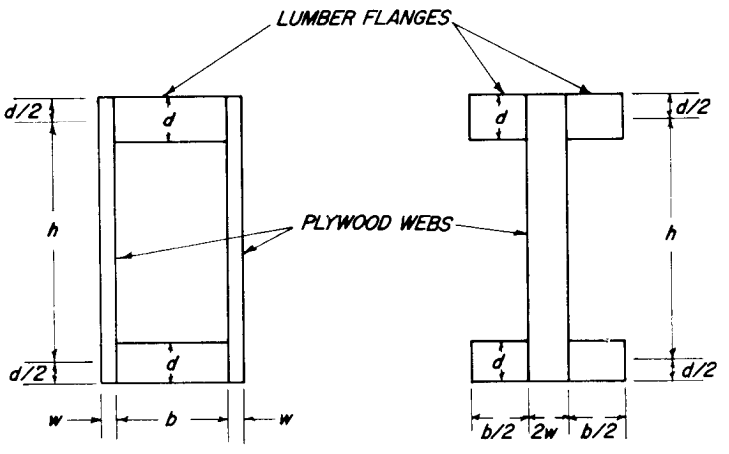

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Figure 23.–Cross sections of wood-plywood box beam (left) and I-beam (right).

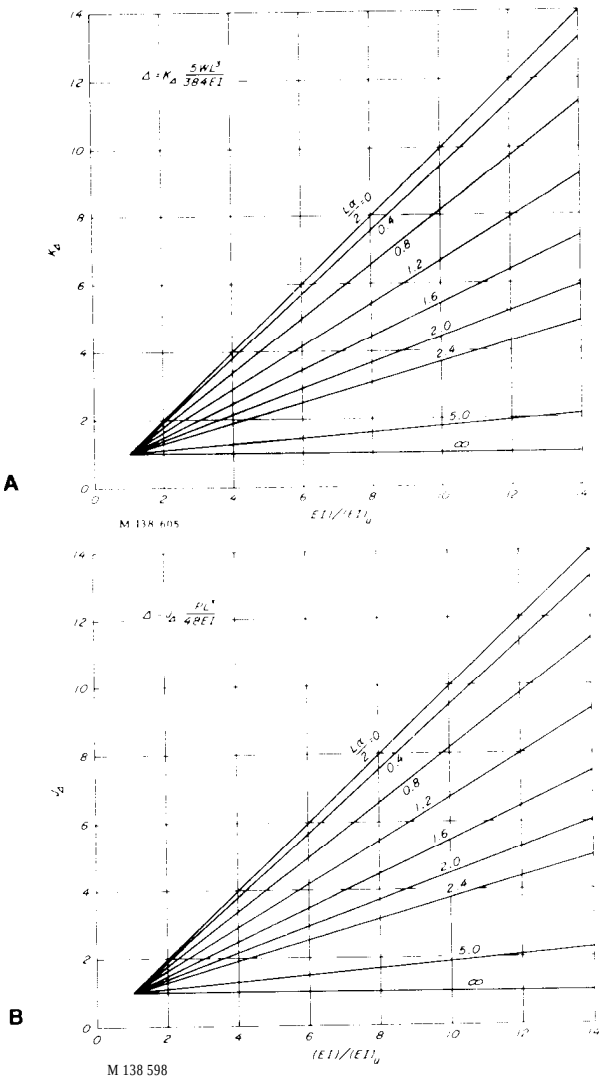

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Figure 24.–Deflection coefficients for constructions under *A*, uniformly distributed load; and *B*, concentrated midspan load.

The midspan deflection of simply supported constructions under concentrated midspan load is given by the formula

$$\Delta = J_{\Delta} \frac{PL^3}{48(EI)_B} \qquad (16)$$

where

P is midspan load; and

J_{Δ} is coefficient given by chart *B* of figure 24.

Other symbols as defined for formula (15).

The shear slip between principal moment-carrying members of the construction is given by the formulas:

For uniformly distributed load

$$\delta = K_{\delta} \frac{W}{Sh} \qquad (17)$$

where

δ is shear slip;

K_{δ} is shear slip coefficient from chart ***A*** of figure 25;

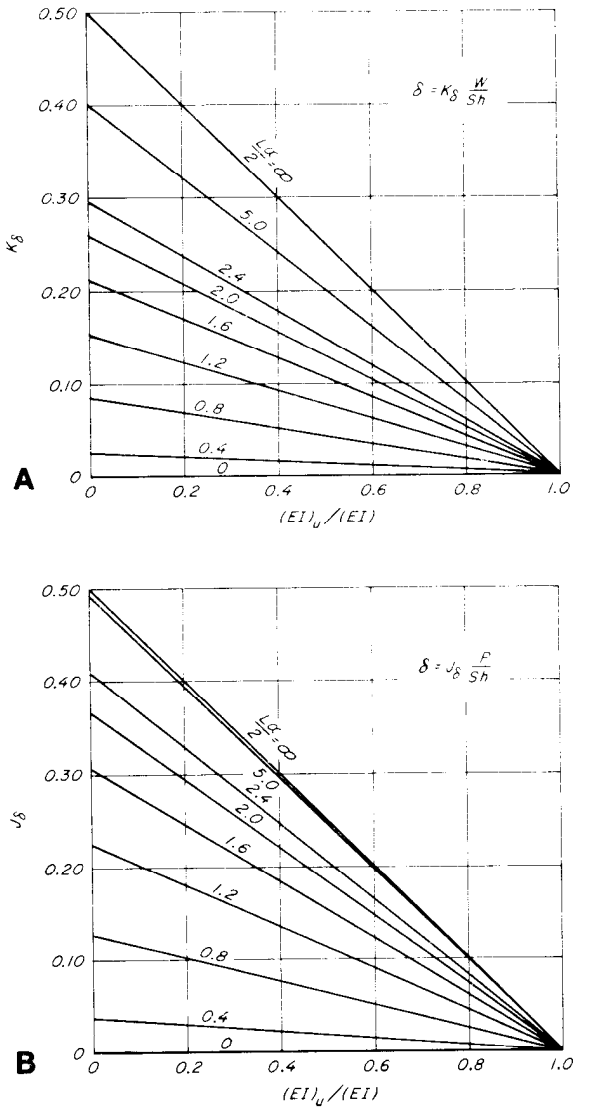

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Figure 25.– Shear slip coefficients for constructions under ***A,*** uniformly distributed load; and ***B,*** concentrated midspan load.

W is total uniformly distributed load;

h is distance between centroids of principal moment-carrying members of the construction; and

S is shear load per unit span length to cause unit slip between principal moment-carrying members.[6]

For concentrated midspan load

$$\delta = J_\delta \frac{P}{Sh} \tag{18}$$

where

P is midspan load; and

J?is shear slip coefficient from chart ***B*** of figure 25.

Other symbols as defined for formula (17).

In order to use the charts of figures 24 and 25 the parameter ??must be computed. The formula for ?*2* is given by

$$\alpha^2 = \frac{h^2 S}{(EI)_B - (EI)_U} \left[\frac{(EI)_B}{(EI)_U}\right] \tag{19}$$

where formulas for $(EI)_B$ and $(EI)_U$ should be used for the appropriate construction.

[6]Values of *S* can be determined from the slope of a shear-slip curve for the adhesive employed to bond the construction. The shear-slip curve can be obtained from a small shear specimen joined with the same adhesive as the construction. The width of the specimen should be equal to that of the construction shear joint (if smaller, the value shall be proportioned to that of the construction to compute *S* for the construction). An effective joint shear rigidity, ?, with units such as pounds per inch of length per inch of slip, can be obtained by dividing the slope of the shear-slip curve by the length of the adhesive joint. *S* is given by $S = \frac{n}{m}$?, where *n* is the number of shear planes across the width of the construction and *m* is the number of shear planes through the depth of the construction.

Example:

Determine effects of nonrigid adhesive bond on deflection and shear-slip of previous floor example.

Two- by 8-inch Douglas-fir joists spaced 16 inches on centers; 5/8-inch Douglas-fir plywood sheathing, $E_L = 2 \times 10^6$ pounds per square inch, span of 12 feet. Adhesive bond of construction mastic with a linear initial shear stress-slip curve such that the slip is 0.01 inch at a stress of 20 pounds per square inch. For a 1-1/2-inch bond width and a single bond layer and a single joist, S = (1.5)??= (1.5)20/0.01 = 3,000 pounds per inch of length per unit slip.

From formula (19), ??= 0.0318; then ?L/2 = 2.29, and from figure 24A, K??= 1.30 and from figure 25A, K??= 0.14. Thus the mastic adhesive will allow the beam to deflect about 30 percent more than if bonded with a rigid adhesive and the shear slip would be

$$\delta = 0.14 \frac{1{,}280}{(3{,}000)(3.94)} = 0.0152 \text{ inch}$$

This would produce a shear stress of (20/0.01) (0.0152) = 30.4 pounds per square inch.

Gusset and Splice Plates

Design considerations for adhesives in construction assemblies have been concerned with lineal shear slip, i.e., shear slip along a line or in a given direction. The construction of frames, trusses, and girders utilizes gusset and splice plates to join members. These gusset and splice plate joints are subjected to rotary shear stress in the plane of the joint if the members joined are subjected to bending moments or are not joined axially (in-line) with each other. A sketch of the action of forces to produce rotary shear is shown in figure 26.

Rotary shear resistance must also be considered in the design of wall, floor, and roof frames to resist inplane shear distortion. Shear is caused by racking forces due to wind and earthquake, and the construction utilizes the sheathing to furnish nearly all of the racking resistance. The method of fastening the sheathing to the frame must transmit the forces through shearing, which also causes inplane rotary shear stresses.

Overall distortion of frames and trusses is minimized by employing a rigid adhesive in bonding gusset and splice plates to the members. Rigorous design criteria have not been devised to cover the joints discussed; however, it is known that racking rigidity of walls can be increased by factors of 2 to 5, and racking strength doubled by using a rigid adhesive to bond plywood sheathing to wall frames instead of simply nailing the sheathing to the frame.

Remodeling by Adhesive Bonding

The improvement in the stiffness and strength of existing construction assemblies by bonding on extra sheathing or members can be done very effectively by adhesive bonding. Pressure to guarantee good contact can be maintained for sufficient time to cure many adhesives by using nails or screws-perhaps special clamps-to hold the parts together.

A second facing or skin can be added to a conventional construction or additional depth added to joists as shown in the sketches of figure 27. Secondary gusset plates can be bonded to frames and trusses if stiffening is needed.

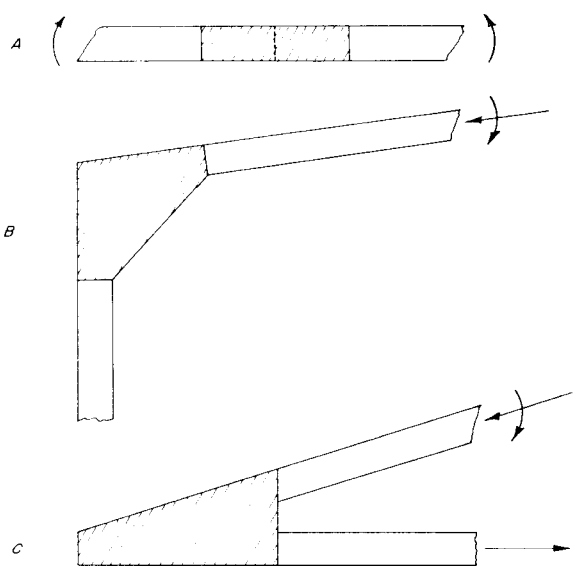

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Figure 26.– Action of forces that produce rotary shear in gusset and splice plates: ***A,*** splice plate; ***B,*** rigid-frame gusset: and C, truss gusset.

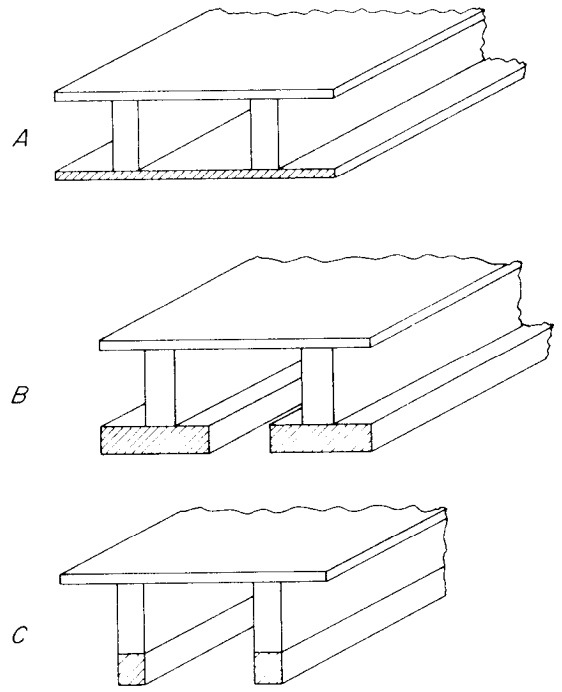

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Figure 27.– Improving stiffness and strength of existing construction by ***A,*** adding second face, or ***B*** and ***C,*** adding greater depth to joists.

Example:

Determine effects of adding a lower facing of 3/8-inch plywood to the joists of the previous floor example. A rigid adhesive will be employed.

Two- by 8-inch Douglas-fir joists are spaced 16 inches on centers; 5/8-inch sanded Douglas-fir plywood perpendicular to joists; 3/8-inch Douglas-fir plywood ceiling parallel to joists. Bonded with rigid adhesive. Data for use in formulas (3) and (4) are as follows:

E_{1F} is 0.311 E_L effective plywood flexural stiffness perpendicular to face grain direction.

E_1 is 0.389E_L effective plywood compressive stiffness perpendicular to face grain direction.

E_{2F} is 0.759E_L effective plywood flexural stiffness parallel to face grain direction.

E_2 is 0.374E_L effective plywood compressive stiffness parallel to face grain direction.

a is 16 inches, t_1 is 0.625 inch, t_2 is 0.375 inch, b is 1.5 inches, d is 7.25 inches, and h is 7.75 inches.

Substitution of these values into formulas (3) and (4), after assuming $E_s = E_L$, results in

$$(EI)_U = 47.79E_L$$

$$(EI)_B = 138.44E_L$$

Thus addition of the ceiling plywood increased the floor stiffness by a factor of 138.44/92.21 = 1.50 or an increase of about 50 percent over that of the bonded floor system (see p. 36).

ADHESIVE MECHANICAL PROPERTIES

Proper use of structural design considerations involves a knowledge of the mechanical properties of the adhesive. The properties must be at the expected condition of use-conditions that may involve moisture and temperature changes and combinations of these variables. Durability of the adhesive and its compatibility with the adherends for extended periods of time may be essential.

Evaluations of structural adhesives used in the past for various wood and wood-plywood components and construction assemblies have been limited to determining shear strength values at normal conditions and after various exposures and accelerated aging. The adhesives included casein, vegetable protein, phenolic resin, urea resin, phenol-resorcinol resin, and epoxy resin. These adhesives are normally considered to be rigid. Their strength can be sufficient to exceed wood strength even under adverse conditions. Their durability is discussed in chapter 5.

More recently a number of adhesives have been formulated for easy application and more universal use. These are sometimes called construction

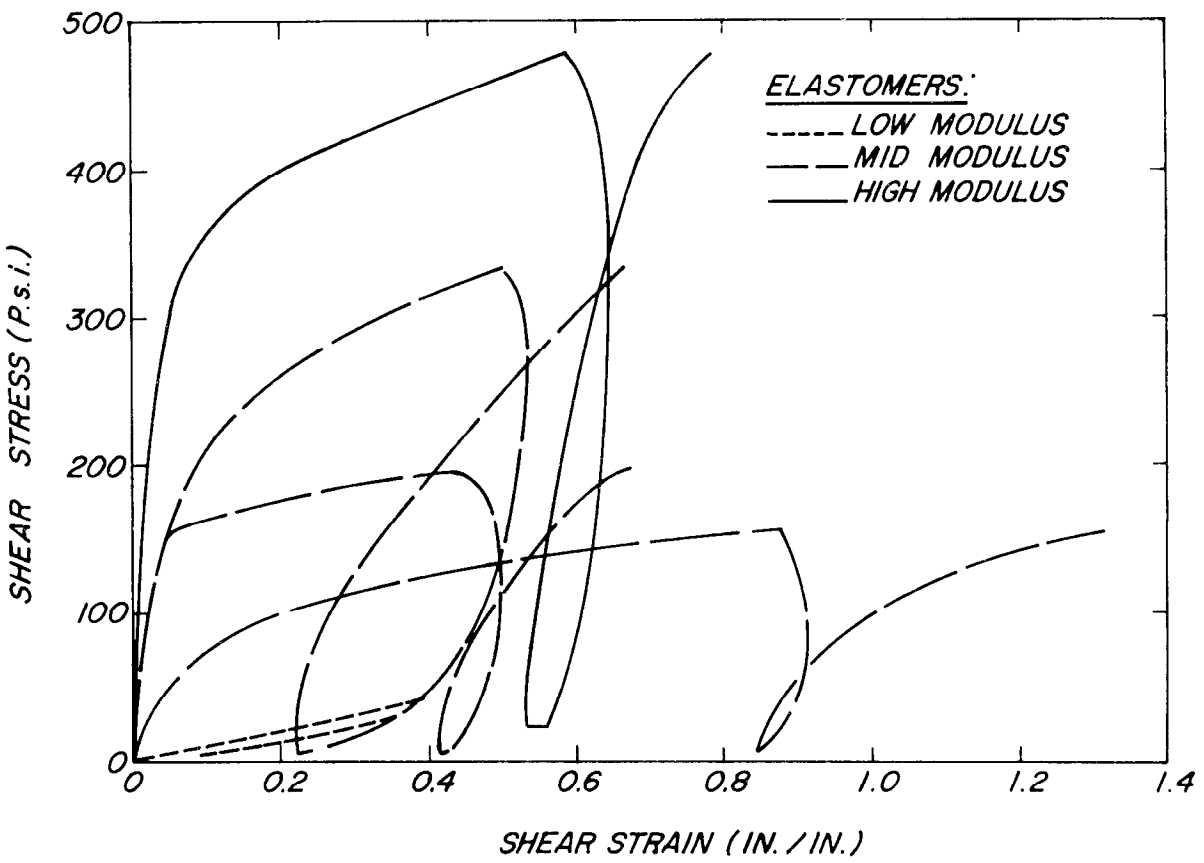

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Figure 28.— Typical shear stress-strain curves for elastomeric adhesives of varying moduli.

adhesives, and they are elastomers or mastics in handy applicator-containers. Their characteristics are described in chapter 5. Shear-slip data obtained for some of these adhesives show that they cannot be classed as rigid. Results of a few tests show shear stress-strain curves (fig. 28). The data for the curves were obtained from torsion tests of end-bonded aluminum tubes in which twist was measured for various amounts of torque applied to the specimen.

Two cycles of loading are shown, including an unloading curve between first and second loading. The second loading cycle for the low-modulus adhesive coincided so closely with the unloading cycle that a different line could not be shown on the graph. These data were obtained at normal laboratory conditions. Data at different temperatures, humidities, and after aging are not available at the present time.

Applicability of the nonlinear data toward predicting performance of components and construction assemblies joined with such adhesives is questionable and could only be approximate at best. The curve for the low modulus adhesive was nearly linear in appearance and the shear modulus from this curve was computed to be G = 10/0.1 = 100 pounds per square inch. For an adhesive bond with a thickness t_B = 0.05 inch, the shear-slip value ??= G/t = 100/0.05 = 2,000 pounds per square inch. This value was used in application example for nonrigid adhesives.

The behavior of various adhesives under continuous stress for long periods of time must be included as a design consideration; otherwise, excessive deflections can occur in bonded construction assemblies. Research in this area has not as yet yielded data or design information to include here.

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CHAPTER 4:

SUBSTRATES[7]

Substrates are those materials to which adhesives are applied. In bonded construction, they may serve as the principal load-bearing components in floors, roofs, or walls, as low-density cores in lightly stressed composite members, or in other ways.

Overlaps, a type of substrate, are thin layers of paper, plastic film, or other material bonded to panel products to provide a protective or decorative face, or a base for painting. Overlays provide surfaces having desirable qualities of hardness, smoothness, durability, or appearance in building construction. Effective bonding requires consideration of a number of properties of substrates and overlays.

SUBSTRATE PROPERTIES IMPORTANT TO BONDING

Density

Weight per unit volume is a simple definition of density commonly expressed in pounds per cubic foot or grams per cubic centimeter. Also, specific gravity is the ratio of a substance's density to that of water. Many physical and mechanical properties of a substrate depend to some degree upon its density. This is particularly true of wood or wood-based substrates. In general, as density for such materials increases, strength properties and modulus of elasticity increase while porosity and dimensional stability decrease.

Porosity

Good bonding does not always require that substrates be porous, as may be demonstrated by the bonding of metals and glass. Nevertheless, porous substrates are less difficult to bond than are the nonporous. Pores in the substrate that are penetrated by the adhesive increase the area of contact between adhesive and adherend. Furthermore, when the pores of an adherend speed the removal of adhesive solvent, such as water or alcohol, the pores increase the rate of strength development. However, porosity may allow excessive migration of the adhesive from the bondline prior to setting, resulting in a starved joint-one with an inadequate film of adhesive.

Surface Properties

Wettability by the adhesive solvent is essential to contact between adhesive and adherend. How well a liquid adhesive wets a solid substrate determines the compatibility between certain adhesives and substrates.

The smoothness of surfaces to be joined, or surface fit, affects good bonding. Cleanness of surfaces is important also. Surfaces compatible with a particular adhesive may be adversely altered by contamination, as with wood contaminated by oily preservatives. Likewise, well-prepared wood surfaces may lose their original flat and true fit for joints if exposed to an atmosphere of varying humidity too long before bonding. Aged wood surfaces may also exhibit deposits of airborne contaminants, or they may accrue wood extractives which have diffused to the surface. Substrates formed in molds or presses may possess a film of release agent. Metals may have an almost unnoticeable film of oil, added either as a protective agent or as a result of processing.

[7]Written by Frederick F. Wangaard, Colorado State University, Fort Collins, Colo.

Dimensional Stability

Most dimensional changes in wood or wood-based substrates result from changes in moisture content. Dimensional change in substrates may be predicted if their properties are known. It is essential that an adhesive be compatible with a substrate's dimensional change. In addition, temperature may directly effect dimensional change of any material through thermal expansion and contraction.

To bond materials having different dimensional-change characteristics, it is necessary to restrain warpage. Means of doing so include balanced construction, adhesive rigidity, and mechanically restraining the substrates or overlays and the bond between them. Alternate layers in plywood illustrate one successful way of restraining dimensional change in substrates.

Modulus of Elasticity

Modulus of elasticity, or Young's modulus, is an indication of the stiffness of a material. Modulus of elasticity = $\frac{\text{stress}}{\text{strain}}$ within the elastic range of a material. Consequently, for any imposed stress, the amount of the resulting strain is inversely proportional to the modulus of elasticity; conversely, for an imposed strain, the magnitude of stress developed is directly proportional.

When elastic substrate layers of differing dimensional stability are effectively bonded with a rigid adhesive, stresses are developed as a result of restraining their induced dimensional change. These stresses occur as shear in the bondline and as tension or compression in the substrate layers which are restrained. The internal loads in tension and compression resulting from these stresses are equal.

Thus the actual change in dimension will be the average of the unrestrained changes in the individual layers, weighted on the basis of their respective moduli of elasticity and their cross-sectional areas (or thicknesses in the case of equal widths, as in a rectangular panel). If these forces are symmetrically distributed according to principles of balanced construction, the bonded composite will remain warp-free so long as the adhesive bond is intact and no substrate failure occurs. If the adhesive permits slippage at the interface between substrates, stresses will be reduced, with obviously reduced gains in dimensional stability and possible loss of structural integrity.

Strength Properties

From the foregoing it should be evident that stresses arise in elastic substrates either as a result of loads imposed externally or as an internal response to the restraint of induced dimensional change. In either case, the substrate must possess sufficient strength in compression, tension, bending, and shear to resist the stresses that develop or the result will be failure. Differences between substrate materials in these properties and in modulus of elasticity are the basis for many efficiencies in bonded construction, permitting fabrication of materials into members of the minimum weight and size to support design loads. The substrate must be sufficiently strong in compression perpendicular to grain to resist the bonding pressure.

So long as the stresses developed are within the elastic range characterized by linearity between stress and strain, the modulus of elasticity serves well to relate stress to strain or vice versa. Beyond the elastic limit this relationship affords at best only an approximation. Consequently, strength values for most substrates discussed in this chapter must be considered at the elastic (proportional) limit as well as at the level of failure. For many materials, including wood, strength values as determined at the level of failure for short-term loading are inappropriate for predicting sustained load conditions because short-term loads do not involve creep. In a related manner, stresses developed through an imposed strain which is maintained over time are reduced as a result of relaxation.

Rheological Behavior

Rheology is the study of deformation and flow of a material; here it concerns the behavior of substrates over a period of time in creep (increasing strain under conditions of constant load) and relaxation (decreasing stress over time under conditions of constant strain).

These effects are relatively slight within the so-called "elastic range," but are of increasing importance at higher levels of stress or strain. As a

result of this behavior the long-term failure strength of wood in bending is only about 9/16 that measured in a static-bending test of 5-minute duration. Other materials exhibit greater or lesser amounts of creep depending upon the conditions of sustained loading.

Adhesives that tend to creep or relax more than the substrates contribute to premature joint failure and excessive deformation of load-bearing members. Bondline failure may result from excessive change in dimensions in environmentally stressed substrates.

TYPES OF SUBSTRATES AND THEIR CHARACTERISTICS

Most substrates employed in building construction are made either of wood or of wood-derived particles or fibers. Knowledge of their physical characteristics is essential to proper design of wood structures, particularly when estimating the suitability of substrates, their strength, and their tendency toward dimensional change. The discussion which follows will appraise physical properties of wood, wood-derived, and other substrates in terms of their selection and use for building construction.

One basic distinction between solid wood and such wood-derived substrates as random-oriented particleboard is wood's orthotropicity–the physical properties of solid wood differ greatly along its three axes (along the grain, radially across the grain, and tangent to the growth rings). The orthotropicity of wood presents some unique problems and possibilities when it is used as a substrate.

In such wood-derived products as plywood, hardboard, particleboard, and insulation board, the properties in the different directions are more nearly equal.

Lumber

Dimensions and Standards

Lumber may be surfaced in the green condition or in the dry condition following kiln drying or air seasoning. The latter practice of surfacing dry is preferable from the standpoint of subsequent bonding. American Softwood Lumber Standard, PS 20-70, recognizes different dressed dimensions for lumber at the time of manufacture, dependent upon whether planed dry or green. For example:

	Dressed size finches)	
Nominal size	***Surfaced dry***	***Surfaced green***
2 x 4	1-1/2 x 3-1/2	1-9/16 x 3-9/16
2 x 6	1-1/2 x 5-1/2	1-9/16 x 5-5/8
2 x 8	1-1/2 x 7-1/4	1-9/16 x 7-1/2
2 x 10	1-1/2 x 9-1/4	1-9/16 x 9-1/2
2 x 12	1-1/2 x 11-1/4	1-9/16 x 11-1/2

The National Design Specification for Stress-Grade Lumber and Its Fastenings provides detailed information on reliable working stresses for sawn structural lumber, both visually graded and machine stress rated, as well as for structural bonded-laminated timber. This publication also includes long-term horizontal shear stress values which must be developed in side-grain bonding, should the bondline be in a plane of critical shear stress, if full composite section properties are to be realized.

Smoothly planed clean surfaces, machined following seasoning, are well adapted to bonding. Critical bonding operations may require closer control in surface preparation. Rough-sawn surfaces are not adapted to good bonding. In such cases bonding to the surfaces may be adequate, but torn fibers are held only loosely to the sound wood below; such surfaces result in a low-strength joint often characterized by shallow, "fuzzy" wood failure.

Qualities Affecting Bonding

The surface characteristics of wood of greatest significance to bonding are its porosity and cleanliness. Any machined side-grained surface exposes thousands of excised cells per square inch of surface, in effect multiplying manyfold the surface area effective in bonding. Due to the longitudinal orientation of most of these minute

cells, the adhesive solids are retained close to the bondline whereas the more mobile solvent may diffuse more deeply into the wood through microcapillaries accessible to it within the cell walls.

The fluid properties of adhesives, together with such other qualities as their rate of cure, will affect the degree to which they are assimilated by porous substrates. Also, woods differ in their porosity. These qualities should be taken into account in selecting formulations of adhesive for wood bonding.

End-grain bonding is much more difficult to achieve partly because the cut cell cavities exposed on the surface extend deeply into the wood with consequent opportunity for loss of adhesive from the bondline. Another problem, of course, is that the directional properties of wood place exceptionally high demands on the strength of end-grain joints if the full strength of the substrate is to be developed. Scarf, finger, and other types of joints that increase the effective surface area while approaching side-grain bonding conditions have been developed for these reasons.

Wettability by the adhesive mix is a prerequisite to the establishment of contact between adhesive and substrate and subsequent development of bond strength. In some woods, the presence of natural extractive substances such as oils or resins may reduce wettability with consequent bonding difficulties.

As a general rule, hardwood is more difficult to bond than softwood, and heartwood is more difficult to bond than sapwood.

Wood that is expected to be exposed to damp conditions of service conducive to decay or insect attack is often treated with preservative. Other chemical treatments for wood involved in building construction have been developed to reduce the fire hazard. Preservative and fire retardant treatments present a number of problems where subsequent bonding is concerned (chapter 7).

Wood Moisture Content and Dimensional Change

Moisture is present in seasoned wood as hygroscopic moisture held in submicroscopic capillaries inside the cell walls. Hygroscopic moisture tends to attain an equilibrium with the surrounding atmosphere. The moisture contained in balance with a constant condition of temperature and relative humidity is the equilibrium moisture content (EMC).

The relationship of EMC of wood to relative humidity at temperatures from -18° to 40° C (0° to 110° F) is shown in figure 29. This figure clearly shows how EMC is related to a fixed condition of temperature and relative humidity.

If temperature is increased without changing the partial vapor pressure-as by placing wood in a heated compartment which is not vapor sealed from the surrounding air-the relative humidity in the heated compartment will drop and the EMC will decrease. This is comparable to the effect of winter heating of buildings in much of the United States.

Table 2.–***EMC-relative humidity relationships for several wood-base materials*** [1]

Condition	EMC of material						
Relative humidity at room temperature	Wood	Particleboard (five common brands)		Tempered hardboard		Decorative laminate (four common brands)	
		Range	Average	Range	Average	Range	Average
Pct	***Pct***	***Pct***	***Pct***	***Pct***	***Pct***	***Pct***	***Pct***
30	6.0	(6.2-7.0)	6.6	(2.7-5.3)	4.0	(2.4-3.6)	3.0
42	8.0	(6.5-8.5)	7.5	(3.2-6.0)	4.6	(2.8-3.8)	3.3
65	12.0	(8.4-9.7)	9.3	(5.7-8.1	6.9	(4.4-5.6)	5.1
80	15.8	(10.5-12.5)	11.6	(8.5-10.6)	9.5	(6.0-7.1)	6.6
90	20.0	(14.7-17.6)	16.6	(9.0-12.4)	10.8	(8.9-9.2)	9.1

[1]Solid wood data are based on desorption; all others are based on adsorption and are not directly comparable.

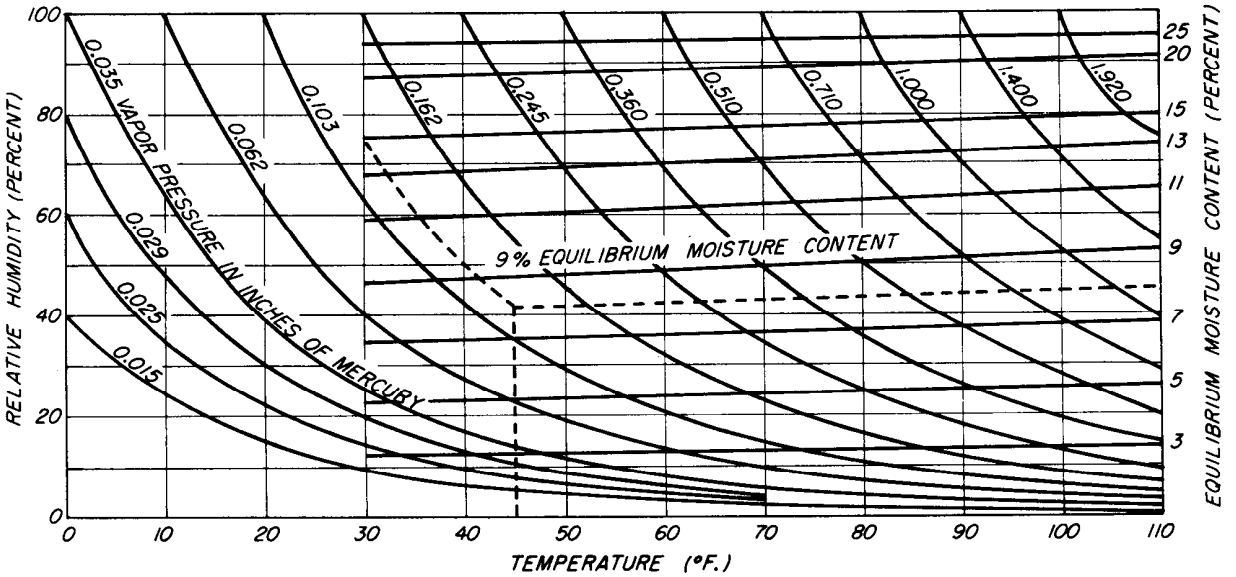

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Figure 29.–Relationship of EMC of wood to temperature and relative humidity.

The differential between outdoor and indoor temperatures accounts for much of the seasonal variation in moisture content of interior woodwork–from 5 to 13 percent. The relationships shown in figure 29 and table 2 explain why wood intended for interior use in most parts of the United States should be conditioned to about 6 to 8 percent moisture content.

Table 2 indicates not only the EMC obtained by wood over a range of relative humidities from 30 to 90 percent, but also by wood-based products such as particleboard, tempered hardboard, and decorative laminates. Those materials which contain substantial amounts of resins, or in which the wood fiber has been otherwise modified, show EMC values lower than for wood at the same humidity and temperature. Combinations of such substrates and overlays should be bonded at moisture contents corresponding to a specified temperature-humidity condition rather than at a constant moisture content. All adhesive-bonded products should be equilibrated prior to bonding and then bonded at a relative humidity and temperature similar to that expected in use. This will minimize problems associated with subsequent moisture change.

Wood is essentially stable in dimension along the grain but shrinks across the grain as moisture is lost below the fiber-saturation point. Shrinkage is usually 1-1/2 to 2 times as great in the tangential direction as in the radial direction. Shrinkage values for individual species to the ovendry condition are given in table 3. As with strength, shrinkage values increase with increasing density of wood.

As an approximate rule of thumb, volumetric shrinkage of wood in percent may be taken as 28 G, where G = green-volume-based specific gravity. For example, a wood having a specific gravity of 0.46, such as shortleaf pine or sweetgum, would be expected to have a volumetric shrinkage of 12.9 percent. Roughly 60 percent of this would be expected to be tangential shrinkage (7.7 percent) and 40 percent radial shrinkage (5.2 percent).

As shown in figure 30, shrinkage expressed as a percentage of green dimension is essentially linear with loss of moisture content below the fiber-saturation point. Consequently, the percentage change in dimension for a 1 percent moisture content change is approximately 1/30 that shown in table 3.

Dimensions are also influenced by changes in temperature. Such changes, however, are extremely small by comparison with swelling or shrinking due to temperature-induced changes in moisture content.

As may be noted in table 3, all properties are not equally affected by loss in moisture content in drying to the, air-dry condition-nor are all species equally affected in a given property. Wood gains in strength with loss in moisture, and'

Table 3.–*Strength values of clear wood in the green and air-dry condition;*[1] *shrinkage values given to ovendry*[2]

Species	Specific gravity ovendry weight; volume		Modulus of rupture		Young's modulus		Compression parallel to grain, maximum		Shear strength parallel to grain		Compression perpendicular to grain, FSPL		Shrinkage	
	Green	12 percent moisture content	Green	12 percent moisture content	Green	12 percent moisture content	Green	12 percent moisture content	Green	12 percent moisture content	Green	12 percent moisture content	Radial	Tangential
			Lb/in.²	Lb/in.²	1,000 lb/in.²	1,000 lb/in.²	Lb/in.²	Lb/in.²	Lb/in.²	Lb/in.²	Lb/in.²	Lb/in.²	Pct	Pct
SOFTWOODS														
Baldcypress	0.42	0.46	6,600	10,600	1,180	1,440	3,580	6,360	810	1,000	400	730	3.8	6.2
Cedar, western red	.31	.32	5,200	7,500	940	1,110	2,770	4,560	770	990	240	460	2.4	5.0
Douglas-fir (coast)	.45	.48	7,700	12,400	1,560	1.950	3,780	7,240	900	1,130	380	800	5.0	7.8
Douglas-fir (interior north)	.45	.48	7,400	13,100	1,410	1,790	3,470	6,900	950	1,400	360	770	5.0	7.8
Fir, white	.37	.39	5,900	9,800	1,160	1,490	2,900	5,810	760	1,100	280	530	3.2	7.1
Hemlock, western	.42	.45	6,600	11,300	1,310	1,640	3,360	7,110	860	1,250	280	550	4.3	7.9
Larch, western	.48	.52	4,900	13,100	960	1,870	3,760	7,640	870	1,360	400	930	4.2	8.1
Pine, eastern white	.34	.35	4,900	8,600	990	1,240	2,440	4,800	680	900	220	440	2.3	6.0
Pine, ponderosa	.38	.40	5,100	9,400	1,000	1,290	2,450	5,320	700	1,130	280	580	3.9	6.3
Pine, sugar	.34	.36	4,900	8,200	1,030	1,190	2,460	4,460	720	1,130	210	500	2.9	5.6
Pine, southern yellow														
Loblolly	.47	.51	7,300	12,800	1,400	1,790	3,510	7,130	860	1,390	390	790	4.8	7.4
Longleaf	.54	.59	8,500	14,500	1,590	1,980	4,320	8,470	1,040	1,510	480	960	5.1	7.5
Shortleaf	.47	.51	7,400	13,100	1,390	1,750	3,530	7,270	910	1,390	350	820	4.4	7.7
Redwood (old growth)	.38	.40	7,500	10,000	1,180	1,340	4,200	6,150	800	940	420	700	2.6	4.4
Redwood (second growth)	.34	.35	5,900	7,900	960	1,100	3,110	5,220	890	1,100	270	520	2.2	4.9
Spruce, Engelmann	.33	.35	4,700	9,300	1,030	1,300	2,180	4,480	640	1,200	200	410	3.4	6.6
Spruce, Sitka	.37	.40	5,700	10,200	1,230	1,570	2,670	5,610	760	1,150	280	580	4.3	7.5
Spruce, white	.37	.40	5,600	9,800	1,070	1,340	2,570	5,470	690	1,080	240	460	4.7	8.2

Table 3.–*Strength values of clear wood in the green and air-dry condition;[1] shrinkage values given to ovendry[2]–continued*

Species	Specific gravity ovendry weight; volume		Modulus of rupture		Young's modulus		Compression parallel to grain, maximum		Shear strength parallel to grain		Compression perpendicular to grain, FSPL		Shrinkage	
	Green	12 percent moisture content	Green	12 percent moisture content	Green	12 percent moisture content	Green	12 percent moisture content	Green	12 percent moisture content	Green	12 percent moisture content	Radial	Tangential
			Lb/in.²	Lb/in.²	1,000, lb/in.	1,000, lb/in.	Lb/in.²	Lb/in.²	Lb/in.²	Lb/in.²	Lb/in.²	Lb/in.²	Pct	Pct
HARDWOODS														
Ash, white	.55	.60	9,600	15,400	1,440	1,740	3,990	7,410	1,380	1,950	670	1,160	4.8	7.8
Beech, American	.56	.64	8,600	14,900	1,380	1,720	3,550	7,300	1,290	2,010	540	1,010	5.1	11.0
Birch, yellow	.55	.62	8,300	16,600	1,500	2,010	3,380	8,170	1,110	1,880	430	970	7.2	9.2
Hickory, pecan	.60	.66	9,800	13,700	1,370	1,730	3,990	7,850	1,480	2,080	780	1,720	4.9	8.9
Hickory, shagbark	.64	.72	11,000	20,200	1,570	2,160	4,580	9,210	1,520	2,430	840	1,760	7.0	10.0
Lauan, red	.44	.48	7,700	11,300	1,380	1,630	3,700	5,890	930	1,220	690	720	3.8	7.6
Maple, sugar	.56	.63	9,400	15,800	1,550	1,830	4,020	7,830	1,460	2,330	640	1,470	4.9	9.5
Oak, northern red	.56	.63	8,300	14,300	1,350	1,820	3,440	6,760	1,210	1,780	610	1,010	4.0	8.2
Oak, southern red	.52	.59	6,900	10,900	1,140	1,490	3,030	6,090	930	1,390	550	870	4.5	8.7
Oak, white	.60	.68	8,300	15,200	1,250	1,780	3,560	7,440	1,250	2,000	670	1,070	5.5	10.6
Sweetgum	.46	.52	7,100	12,500	1,200	1,640	3,040	6,320	990	1,600	370	620	5.2	9.9
Teak	.57	.63	11,000	12,800	1,510	1,590	5,470	7,110	1,290	1,480	1,040	1,190	2.2	4.0
Tupelo, black	.46	.50	7,000	9,600	1,030	1,200	3,040	5,520	1,100	1,340	480	930	4.4	1.7
Yellow-poplar	.40	.42	6,000	10,100	1,220	1,580	2,660	5,540	790	1,190	270	500	4.0	7.1

[1]Based on green strength values and air-dry to green ratios given in ASTM D 2555-70 for domestic woods.
*Expressed as percentage of green dimension as given in Wood Handbook for domestic woods.

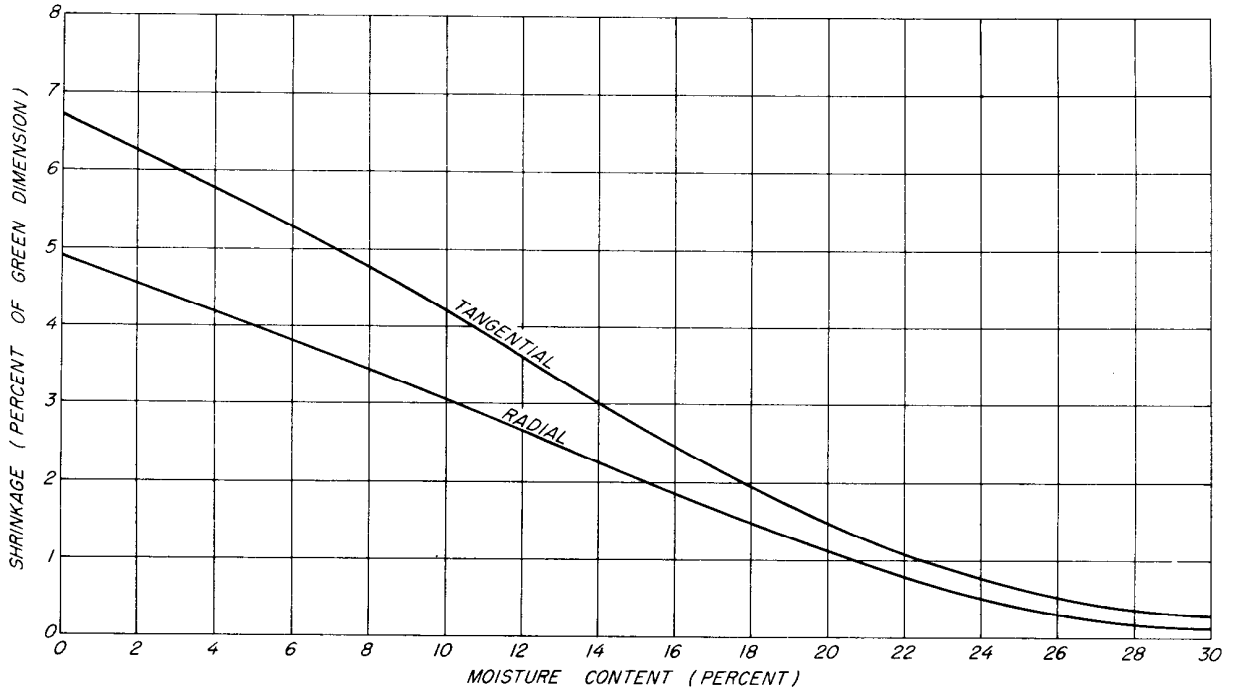

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Figure 30.–Typical shrinkage of lumber with moisture content changes.

Table 4.–*Average relationships between strength properties* of *clear wood and specific gravity*

Strength properties	Specific gravity-strength relation)	
	Green wood	Air-dry wood (12 pet moisture content)
Static bending		
Fiber stress at proportional limit (lb/in.*)	$10,200G^{1.25}$	$16,700G^{1.25}$
Modulus of rupture (lb/in.*)	$17,600G^{1.25}$	$25,700G^{1.25}$
Work to maximum load (in.-lb/in.*)	$35.6G^{1.75}$	$32.4G^{1.75}$
Total work (in.-lb/in.*)	$103G^{2}$	$72.7G^{2}$
Modulus of elasticity (1,000 lb/in.*)	2,360G	2,800G
Impact bending, height of drop causing complete failure (in.)	$114G^{1.75}$	$94.6G^{1.75}$
Compression parallel to grain:		
Fiber stress at proportional limit (lb/in.*)	5,250G	8,750G
Maximum crushing strength (lb/in.*)	6,730G	12,200G
Modulus of elasticity (1,000 lb/in.*)	2,910G	3,380G
Compression perpendicular to grain, fiber stress at proportional limit (lb/in.*)	$3,000G^{2.25}$	$4,630G^{2.25}$
Hardness:		
End (lb)	$3.740G^{2.25}$	$4,800G^{2.25}$
Side (lb)	$3.420G^{2.25}$	$3,770G^{2.25}$

[1]The properties and values should be read as equations; for example, modulus of rupture for green wood = $17,600G^{1.25}$, where G represents the specific gravity of ovendry wood, based on the volume at the moisture condition indicated.

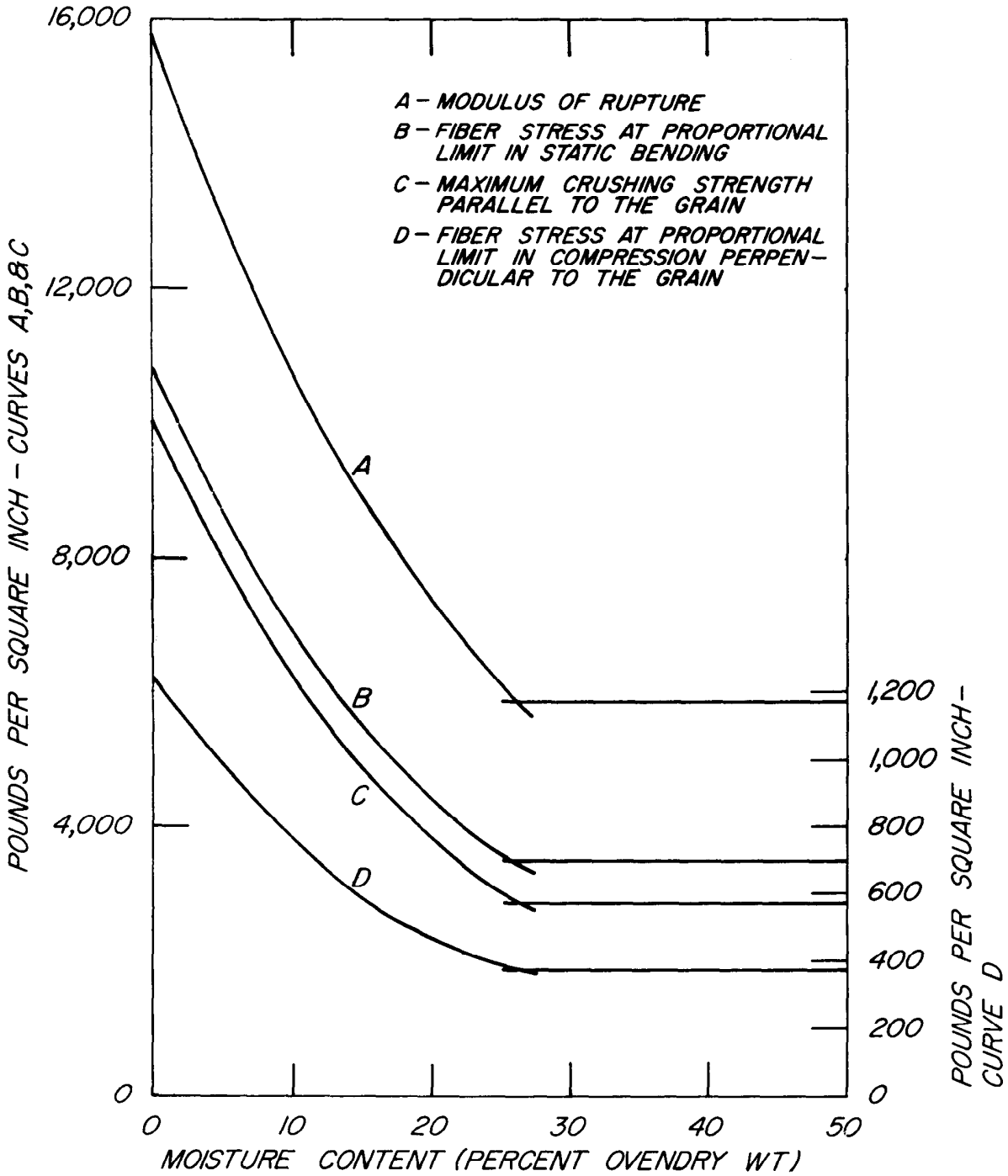

Figure 31.–Effect of moisture content on strength of clear wood.

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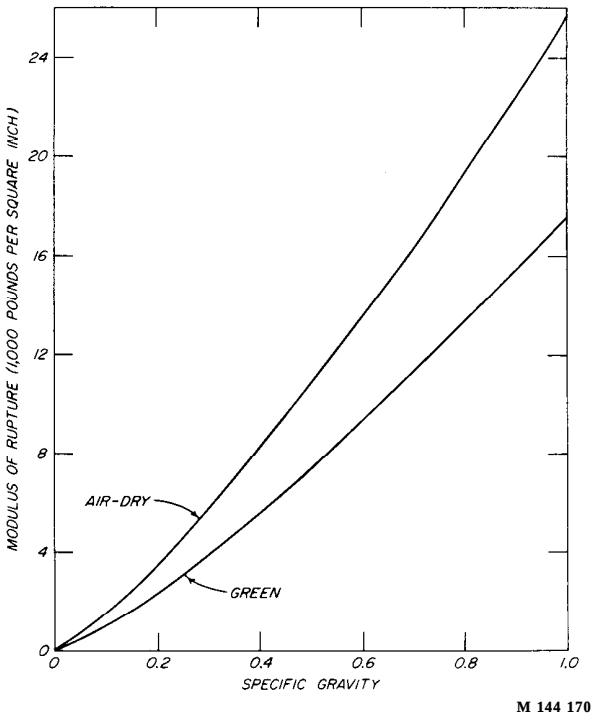

Figure 32.–Effect of specific gravity on modulus of rupture of green and air-dry wood.

vice versa, at approximately the following rates for each 1 percent change in moisture content: Modulus of rupture, 4 percent; modulus of elasticity, 2 percent; compression parallel and perpendicular to the grain, 6 percent; and shear, 3 percent. These changes commence when wood is dried below the fiber-saturation point–25 to 30 percent moisture content in most species. Figure 31 illustrates the relationship for several properties for a wood having a fiber-saturation point of approximately 27 percent.

Density

The densities of typical softwood and hardwood species are shown in table 3. Two values are indicated, one for the green and the other for air-dry volume conditions. Both are based on ovendry weight so the difference reflects the effect of shrinkage alone. Most species used in building construction range between 0.30 and 0.70 in specific gravity based on air-dry volume.

Specific gravity is a good index of the mechanical properties of straight-grained wood free of defects. Average relationships between specific gravity and a number of mechanical properties, based on tests of many species, are expressed by the power functions presented in table 4. These functions are not precise estimators of mechanical properties because the wood of some species contains relatively large amounts of resins, gums, and other extractives that add to weight but contribute little or nothing to mechanical properties. The structural arrangement of anatomical elements within wood can also effect strength.

The relationships between average specific gravity and modulus of rupture values for many species, both green and at 12 percent moisture, are shown in figure 32.

Other Mechanical Properties

Clear wood strength values, both green and air-dry, are given in table 3. Increased values due to drying are clearly shown. Modulus of rupture is a measure of stress at failure in bending. It is also used as an approximation to express clear wood strength in tension parallel to the grain. Proportional limit strength is roughly two-thirds of modulus of rupture. The modulus of elasticity is also given in the table for beams at a span/depth ratio of 14 to 1, and includes the effect of shear deformation. Modulus of elasticity in tension and compression parallel to the grain and free from shear is approximately 10 percent higher.

Knots, cross grain, and other distortions in the grain direction of wood naturally affect the directional properties presented for clear wood in table 3. In particular, strength properties in the longitudinal direction are reduced and longitudinal shrinkage is increased.

Along axes perpendicular to the grain, the modulus of elasticity is only 1/20 (tangentially) to 1/12 (radially) as great. Proportional-limit strength values in compression parallel to the grain are roughly 3/4 the maximum crushing strength values shown in table 3. The lower values shown for proportional limit in compression perpendicular to the grain are only 1/5 to 1/8 as large. The strength values given in the table for shear parallel to the grain are average values at failure and represent the level of bond strength that must be attained if a side-grain bonded joint involving wood as a substrate is to develop the full strength of the material. When loads act in the same plane but in the direction across the grain, failure in rolling shear occurs at about 1/5 to 1/4 the load level shown in the table. Such stresses occur commonly in plywood. Wood is very low in tensile strength perpendicular to the

grain, and stresses in this direction must be held to a minimum. One-third of the value for shear strength is sometimes used as a rule of thumb to estimate failure stress for tension perpendicular to the grain.

The reduced ability of stressed wood members to support loads over prolonged periods of time is well known. Figure 33 shows the relation of strength to duration of load that is used in deriving safe working stresses for wood from standard laboratory test values such as those shown in table 3. The effects of load duration may be attributed to creep characteristics. The increasing deformation of wood with time under constant load, and the immediate and delayed elastic response to the removal of load, are shown diagramatically in figure 34. The permanent deformation or "set" is also shown. Specific data on creep in wood are quite limited, but the amount increases rapidly at stress levels beyond proportional limit in both tension and compression.

Stress relaxation with time under constant strain is the counterpart of creep, and the curves shown in figure 35 serve to illustrate the effect of strain level on the time-dependent behavior of wood. The curves show retention of stress under conditions of constant strain in compression and tension parallel to grain.

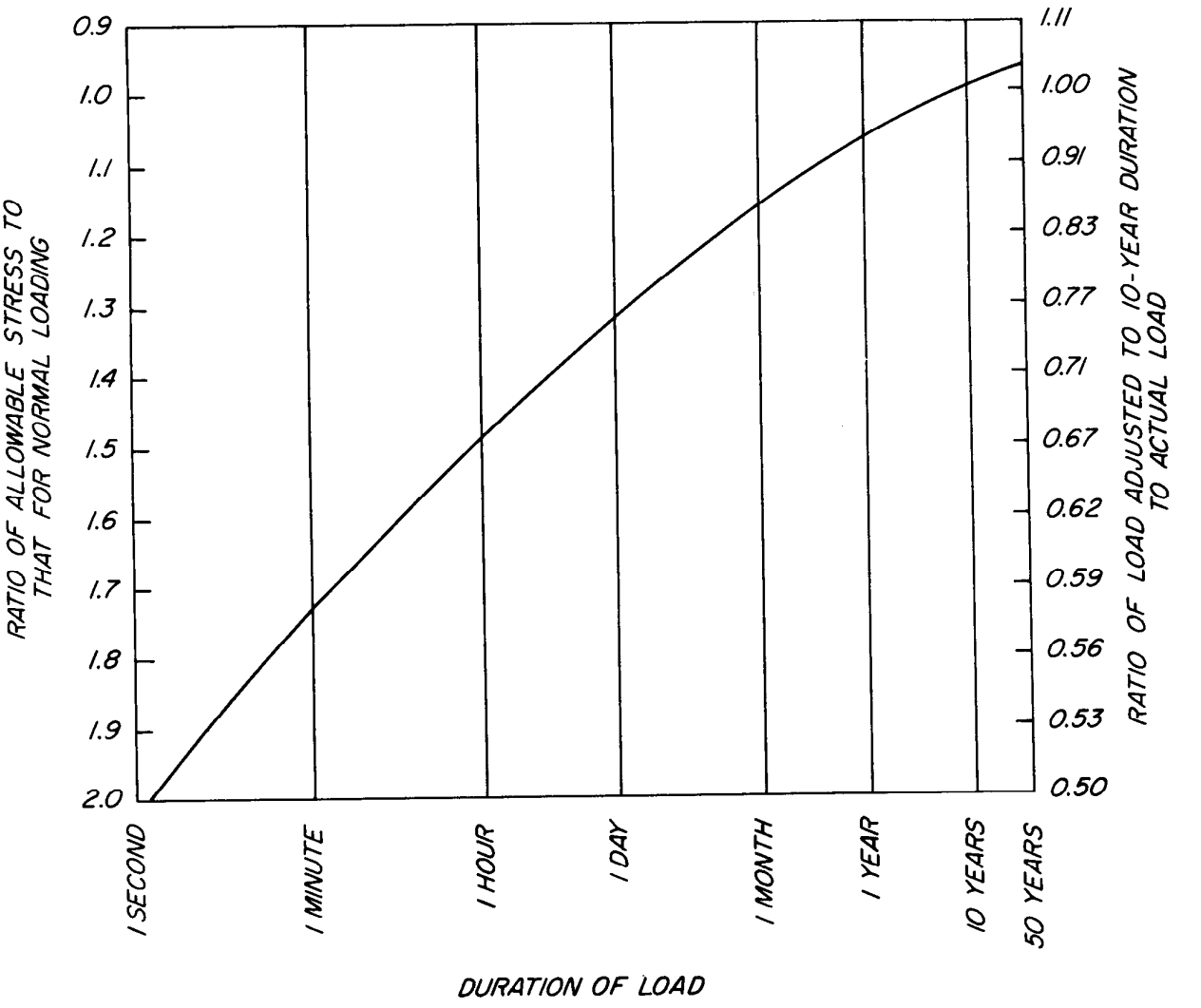

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Figure 33.–Reduction of strength and duration of load.

In the bonding of wood, strains are frequently developed in tension and compression across the grain as a result of restrained shrinkage or swelling.

Plywood

Kinds of Plywood

Plywood is classified as interior or exterior by its ability to withstand exposure to weathering.

Grading of softwood plywood (and of several hardwood plywoods as well) is based on its structural use. The species used in plywood are classified into five groups, principally by modulus of elasticity but also by other mechanical properties. Group 1 (E = 1,800,000 pounds per square inch minimum) includes, among others, coast Douglas-fir, western larch, and southern pine; group 2 (E = 1,500,000 pounds per square inch minimum) includes interior Douglas-fir, California red fir, white fir, western hemlock, and lauan; group 3 (E = 1,200,000 pounds per square inch minimum) includes ponderosa pine and redwood; group 4 (E = 1,000,000 pounds per square inch minimum) includes western red cedar and poplar; and group 5 (E = 1,000,000 pounds per square inch minimum) includes balsam fir and balsam poplar. Reference should be made to the latest softwood plywood standard PS-1 for other species in each group.

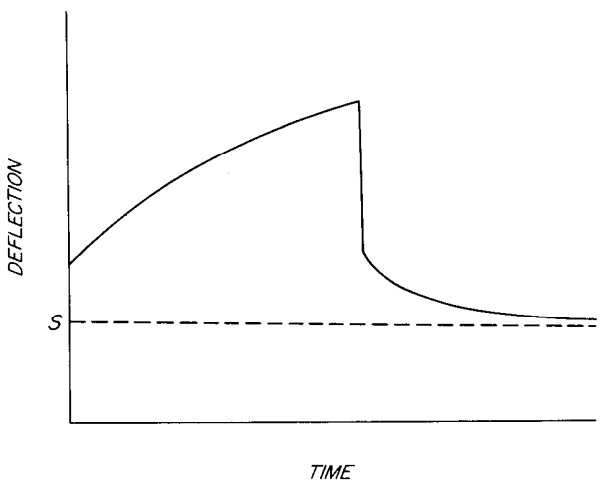

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Figure 34.–Creep characteristics of wood (S represents permanent set).

Veneers themselves are graded from A to D on the basis of increasing size of knots and other weakening defects permitted. The key plies in plywood grading are the face and back plies, with C and D grade veneers permitted as inner plies. For each species group, strength values have been assigned to the individual plies. Softwood plywood construction, is strictly controlled so that section properties essential to design can be assigned to each thickness of plywood.

An identification index used on softwood sheathing panels consists of two numbers. The number to the left indicates maximum spacing over supports when used as roof sheathing; the number to the right indicates maximum spacing over floor supports under average residential loading conditions. For other plywood panels, grade is determined by the grade of the face and back veneers and the species group of these plies (i.e., A-C, group 3). Plywood is manufactured from predried veneer and does not shrink in thickness when adapting to interior conditions. Actual thickness under these conditions corresponds to the designated thickness.

Hardwood plywood is graded more by the appearance of the panel than by its structural performance. Grade categories, which vary somewhat from species to species, include *premium*, *good* for natural finish, *sound* for smooth paint surfaces, *utility* which permits knots and knotholes up to 3/4-inch diameter, and *backing* which permits knotholes as large as 2 inches in diameter.

Softwood plywood in building construction is used for roof and wall sheathing, and subflooring. These applications offer some of the most advantageous opportunities for bonding plywood panels to framing lumber to improve structural performance. In effect the plywood becomes a flange, adding to the section properties of the framing system and greatly improving the rigidity of the roof, floor, or wall. Other uses in construction include floor underlayment, interior wall panels, siding, soffits, fascia, and built-ins of all sorts.

The hygroscopic and rheological properties of plywood are similar to those of solid wood. Most veneer surfaces present no particular bonding problems in plywood manufacture. However, the subsequent secondary gluing to plywood is somewhat more difficult because of surface changes resulting from hot-pressing involved in plywood's manufacture. Thus, sanded plywood is preferred for critical bonding. For less critical uses, rough plywood may be bonded without special treatment, even though contact between

the substrate surfaces is incomplete. The "rolling shear" strength of plywood limits its applications to situations where shear stresses in the plane of the panel are relatively low.

Mechanical Properties of Plywood

The properties of plywood are derived from the solid wood properties of its constituent veneers redistributed according to the particular plywood construction. The effective modulus of elasticity of plywood in bending is essentially derived from that of the plies oriented with grain parallel to the direction of stress:

$$E_p = \frac{1}{I}\sum_i E_i I_i$$

where

E_p is the modulus of elasticity of plywood in bending,
I is overall moment of inertia, and
$E_i I_i$ is the modulus of elasticity and moment of inertia of an individual ply about the neutral axis of the entire cross section.

The moment of inertia only of the parallel plies in a 1/2-inch-thick, five-ply panel, with all plies of equal thickness, is 0.80 x I of the total section. Consequently, as shown in table 5, the effective modulus of elasticity of such a panel of a group 1 species (such as Douglas-fir) parallel to the grain of the face plies is 0.80 x 1,950,000 = 1,560,000 pounds per square inch. Other properties may be calculated from the properties of the individual plies stressed parallel to the grain using the relationships:

$$f_p = \frac{0.85 f_{xx} E_p}{E_{xx}}$$

where

f_p is effective fiber stress in bending of plywood,
f_{xx} is fiber stress in bending of wood in parallel plies,

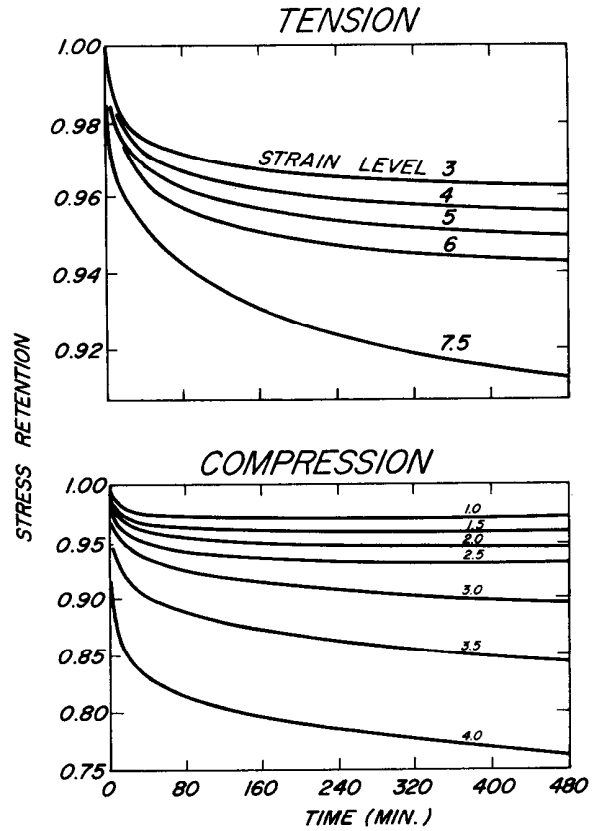

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Figure 35.–Relaxation at different strain levels (in 1,000 micro-inches per inch) in tension and compression in one species of wood.

E_p is modulus of elasticity in bending of plywood, and
$E_{,,}$ is modulus of elasticity in bending of wood in parallel plies.

Similarly, for plywood stressed in tension or compression,

$$E_p = \frac{1}{t}\sum_i E_i t_i$$

where

t is overall thickness, and
$E_i t_i$ is modulus of elasticity and thickness of an individual ply.

Also,

$$f_p = \frac{f_{xx} E_p}{E_{xx}}$$

Table 5.—*Properties of substrates and overlays under typical use conditions*

Substrate or overlay	Specific gravity	Modulus of elasticity	Modulus of rupture	Tensile strength in plane	Compressive strength in plane	Equilibrium moisture content 30 percent relative humidity	Equilibrium moisture content 90 percent relative humidity	Linear expansion 30-90 percent relative humidity	Coefficient thermal expansion
		1,000 lb/in.²	*Lb/in.²*	*Lb/in.²*	*Lb/in.²*	*Pct*	*Pct*	*Pct*	
Douglas-fir clear wood	0.48	—	—	—	—	6.0	20.0	—	—
Parallel to grain	—	1,950	12,400	12,400	7,220	—	—	0.10	2×10^{-6}
Perpendicular to grain	—	100	—	370	790	—	—	2.5-3.9	17×10^{-6}
Softwood plywood[1]	.48	—	—	—	—	6.0	20.0	—	—
(five-ply, 1/2 in., group 1)					4,530	—	—	.22	2.5×10^{-6}
Parallel to face plies	—	1,560	8,430	7,440	2,890	—	—	.36	3×10^{-6}
Perpendicular to face plies	—	390	2,110	4,960	—	6.6	16.6	.40- .50	5.5×10^{-6}
Particleboard					—	6.0	16.0	.25	—
Type 1, medium density,					700- 3,400	6.0	14-18.5	.35- .50	—
class 1 and 2 mat-formed	.59-0.80	250- 400	1,600- 2,400	1,300	2,000- 4,000	4.4	11.0	.20- .50	—
Structural, medium density	.59- .80	450	2,500	—	4,200- 5,300	3.8	11.0	.38	—
Fiberboard, medium density	.40- .80	90- 700	400- 4,000	800- 2,000	—	3.0	9.1	—	—
Hardboard					30,000-48,000	—	—	.10	4.2×10^{-6}
Untreated	.80-1.00	200- 800	3,000- 6,000	1,000- 3,000	—	—	—	.35	8.2×10^{-6}
Treated	.95-1.15	800-1,000	7,500-10,500	4,000- 5,500	—	3.0	9.2	—	—
Paper decorative laminate	1.30-1.40	—	—	—	20,000-40,000	—	—	.15	3.0×10^{-6}
Machine direction	—	2,230	—	18,410	—	—	—	.40	6.1×10^{-6}
Cross-machine direction	—	1,560	—	12,130	500	—	—	—	8.0×10^{-6}
Paper backing sheet	1.30-1.40	—	—	—	—	—	—	—	13.0×10^{-6}
Machine direction	—	2,280	—	25,280	—	—	—	—	6.2×10^{-6}
Cross-machine direction	—	1,510	—	15,160	240	—	—	—	—
Gypsum board	.80	—	—	—	7,200	—	—	—	5.5×10^{-6}
Aluminum	2.7	10,000	—	12,000-80,000					
Steel	7.8	29,000	—	40,000-120,000					
Polyurethane foam	.153	11	—	—					
Concrete	2.2	4,300	—	—					

[1]Calculated as clear wood, not for design use.

where f and E are stress and modulus values in tension or compression.

These expressions have been used to calculate stress values in table 5 to permit comparison with other wood-base substrates. In design, particularly where plywood is combined in a composite section as in stressed-skin construction, plywood is treated, not as a uniform layer, but as a spaced assembly of plies stressed parallel to the grain. These plies are considered to carry all of the stress. Deflections and resisting moments for the entire composite are calculated on the basis of the contribution to section properties made by these plies and also on parallel-to-grain strength and elastic properties of these plies.

The dimensional stability in length and width of plywood is the result of the dimensional stability of wood along the grain and the restraint thus imposed on the attempted shrinkage (or swelling) of the perpendicular plies. With a 1/2-inch, five-ply panel of Douglas-fir, all plies being the same thickness, the widthwise swelling which results from a change from 30 to 90 percent relative humidity can be calculated as follows:

Assume the modulus of elasticity parallel to the grain to be 1,950,000 pounds per square inch and that perpendicular to the grain to be 1/20 as great, and refer to figure 36.

Load in tension (crossbands) = load in compression (face, back, and center ply); subscript "xx" indicates parallel plies, and subscript "z" perpendicular plies:

$$E_{xx}\epsilon_{xx}t_{xx} = E_z\epsilon_z t_z$$

$$20 \times \epsilon_{xx} \times 2 = 1 \times \epsilon_z \times 3$$

$$\epsilon_{xx} = \frac{3\epsilon_z}{40}$$

But

$$\epsilon_z = 0.039 - S$$

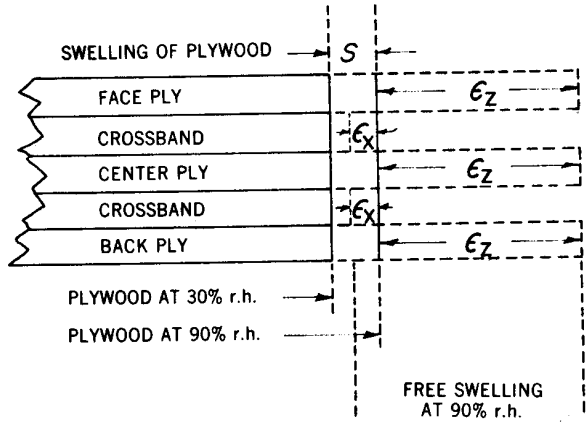

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Figure 36.–Edge of plywood showing elastic restraint of swelling of various lamina in width, either parallel (X) or perpendicular (Z).

where

0.039 is clear wood linear expansion perpendicular to grain from table 5 and

S is linear expansion of plywood perpendicular to face plies.

$$\epsilon_{xx} = S - 0.0010$$

where

0.0010 is clear wood linear expansion parallel to grain from table 5 as shown in figure 36.

Consequently,

$$S - 0.0010 = \frac{3}{40}(0.039 - S)$$

$$43S = 0.157$$

and

$$S = 0.0036 \text{ inch per inch}$$

Swelling (S) = 0.0036 inch per inch, or 0.36 percent, for a change from 30 to 90 percent relative humidity as shown in table 5. This is less than 1/10 the free swelling of Douglas-fir wood across the grain for the same change in moisture content. It should be recognized that this stability is accomplished by the development of compressive

stress in the face, back, and center plies and by a tensile stress in the crossbands. The loads in tension and compression are equal. As long as they are symmetrically distributed about the centerline of the plywood section, the construction is balanced and the panel will remain flat. If the construction were unbalanced, warp would result.

The situation has also been described, somewhat more simply, as the weighted swelling of individual plies, each ply's tendency to swell freely being weighted by its modulus of elasticity and thickness:

In this instance,

$$S = \frac{20 \times 0.0010 \times 2 + 0.039 \times 3}{(20 \times 2) + 3}$$

$$= \frac{0.040 + 0.117}{43}$$

$$= \frac{0.157}{0.43}$$

= 0.0036 inch per inch or 0.36 percent

It should be noted from table 5 that the greatly increased stability in width of plywood is achieved at a slight sacrifice of wood's excellent longitudinal stability in the direction of panel length. The method of calculation assumes elastic behavior and is limited in application to strains within the elastic range. It will be evident that, under this assumption, the plies in plywood are subjected to self-imposed stresses at all moisture contents except that one at which the adhesive bond was formed.

The dimensional stability and mechanical efficiency of plywood are dependent upon the rigidity of the adhesive bond. Working stress values and section properties for conventional constructions of commercial softwood plywood are given in Plywood Design Specifications issued by the American Plywood Association.

Particleboard

Resin-bonded particleboard is made from wood particles of widely varying geometry: Flakes, shavings, splinters, and a variety of milled or ground particles. These are bonded together with heat and considerable pressure by resin adhesives, usually of the urea-formaldehyde type. In the usual platen-formed particleboard, the particles are oriented with their grain direction at random in the plane of the board. The effect is not unlike that of a multi-plied plywood construction. Particleboard thicknesses are commonly in the range of 1/8 to 1-1/2 inches. Particleboard offers the advantage of smooth grainless surfaces in panel form. Applications in structures include floor underlayment, interior panels, wardrobe doors, and a wide variety of uses in cabinets and counters.

Structural Particleboard

Structural particleboard must have two key properties not required in particleboards commonly employed as furniture core stock and floor underlayment: (1) durability and (2) assignment of engineering design properties to insure that panels may carry anticipated building loads even under adverse environmental conditions. Though the underlayment-type particleboards have had inherent strength and stiffness, they have been primarily designed to be "gap fillers" or to have good surface characteristics. Hence the maximum structural properties for the amount of wood used were not sought. Also, urea resin, the binder commonly employed in underlayment particleboards, is not as resistant to water or weather as phenolic resin.

Phenolic resin has been employed in many structural wood applications, such as exterior grades of plywood. So phenolic, or a similarly durable resin, must be employed in a structural particleboard. The Canadians allow the use of such boards as building sheathing, subfloor, and cladding. The U.S. Standard does not specify end use for such boards, but the National Particleboard Association has obtained recognition of such properties for these panels to be used as decking (subfloor-underlayment combination) in mobile homes and factory-built housing. One U.S. manufacturer has obtained recognition of his product by the International Conference of Building

Officials (ICBO) as a satisfactory alternative material to that specified in the Uniform Building Code for roof, wall, and floor sheathing and underlayment. Hence, cities and states using the Uniform Building Code would allow use of this board in buildings.

Mechanical Properties of Particleboard

Mat-formed particleboards with random flake orientation have essentially the same properties in width and length. Particleboards are classified as low, medium, or high density with a corresponding range in strength properties and dimensional stability. Within boards of a particular particle geometry, strength properties and linear expansion increase with increasing specific gravity.

Particle geometry also influences particleboard properties. Two types, 1 and 2, based on degree of moisture resistance of the binder, are also recognized. Type 1, limited to interior applications, is the most common today. The values shown in table 5 are typical for type 1 medium density boards. As may be readily seen, conventional particleboards, even though substantially denser than plywood are not as stiff or as strong as plywood.

Due to their resin content and press-modified surfaces, particleboards manufactured in the United States and Canada are somewhat less hygroscopic than wood at high humidites. Dimensional stability of flake-type particleboards in terms of linear expansion is comparable to that of plywood. Thickness swelling is considerably greater than plywood and depends upon density, particle geometry, and resin content.

Particleboard is commonly overlaid with veneer, hardboard, or decorative laminates having different dimensional stability than particleboard. Stresses are set up in the same manner previously described for plywood; principles of balanced construction apply here as well. Using data from table 5, for example, a 1/2-inch particleboard having modulus of elasticity of 300,000 pounds per square inch and a linear expansion of 0.30 percent is overlaid face and back with a decorative laminate 0.060 inch thick having E = 2,230,000 pounds per square inch and linear expansion of 0.10 percent in the machine direction. What amount of restraint may be expected?

From $E_L ?_L t_L = E\ E_p ?_p t_p$, where subscript *L* indicates laminate and subscript *p* indicates particleboard, we get

$$2{,}230 \times \epsilon_L \times 0.120 = 300 \times \epsilon_p \times 0.50$$

$$268\epsilon_L = 150\epsilon_p$$

$$\epsilon_L = \frac{150\epsilon_p}{268}$$

But

$$\epsilon_L = S - 0.0010$$

where

S is swelling of the composite

and

$$\epsilon_p = 0.0030 - S$$

so,

$$S - 0.0010 = \frac{150}{268}(0.0030 - S)$$

$$S = 0.0017 \text{ inch per inch.}$$

The strain in the decorative laminate is 0.0017 -0.0010 = 0.0007 inch per inch; that in the particleboard is 0.0030 - 0.0017 = 0.0013 inch per inch. The particleboard is stressed in compression approximately 390 pounds per square inch whereas the laminate carries a stress in tension of about 1,560 pounds per square inch. The construction is balanced and so remains flat, but would undoubtedly have warped if the decorative laminate had been applied only to one face. A practical solution approximating balanced construction would be to overlay one face with a decorative laminate and the back with a backing sheet having similar properties (table 5).

Another means for minimizing warp would be to use a nonrigid adhesive such as a rubber-base contact cement that would permit slippage to occur between the overlay and the substrate, thus minimizing the build-up of stress.

Although relatively few studies have been made of the time-dependent characteristics of particleboard, evidence at hand indicates considerably higher rates of creep and relaxation than in solid wood or plywood-possibly as much as 4 to 1. Only at very low levels of stress can elastic recovery from deformation be expected.

Particleboard surfaces are usually sanded in the process of manufacture and are readily bonded with adhesives that are compatible with the binder systems of the board-usually urea resins in the case of type 1 and phenolic-type resins in the case of type 2.

Fiberboards

Building fiberboards of low and medium density are manufactured from high-yield wood pulps and, less frequently, from vegetable fibers such as bagasse and cornstalks. Most fiberboards are made by a wet-felting process analogous to that used in the manufacture of paper. Low-density boards combine thermal insulating qualities with moderate structural strength, and find use as wall sheathing and wallboard. When used as sheathing the usual thickness is 1/2 inch, but other thicknesses from 3/8 to 2 inches are made for other purposes. Acoustical board is a special type of low-density fiberboard. Medium-density fiberboards, including laminated paper wallboards, have superior structural properties such as hardness that adapt them to use as interior wall surfaces, and as drawer bottoms, backs, and dividers in built-ins. Thicknesses generally range from 3/16 to 1/2 inch and sheet sizes up to 4 by 12 feet.

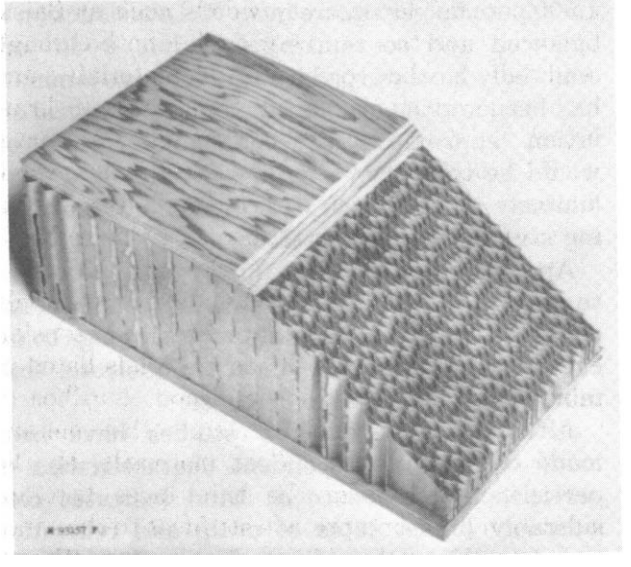

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Figure 37.–Paper honeycomb core in sandwich construction.

Low-density fiberboards with a specific gravity less than 0.40 have relatively little stiffness and strength. Their linear expansion on swelling is also low. Medium-density fiberboards range from 0.40 to 0.80 in specific gravity and their strength properties (table 5) are generally comparable to medium-density particleboards. Hygroscopicity at high humidities and dimensional stability vary with such treatments as asphalt impregnation in manufacture. All fiberboards maintain their structural integrity by basically the same type of fiber bonding that occurs in paper products. Without wet-strength additives, they share with paper a lack of any significant moisture resistance. Like paper, most fiberboards exhibit pronounced time-dependent behavior such as creep and relaxation, and to an even greater extent than particleboard. Under a sustained stretch or compression, stresses die out rapidly and fiberboards take on a "set" condition.

Hardboard

Hardboards are a special kind of fiberboard. They are manufactured to high density by various processes including conventional wet felting which produces the characteristic smooth face and screenback board. Modification of the wet-felting process and the dry air-felting process yields a hardboard with two smooth faces. Tempered hardboard is subsequently impregnated with various drying oils and subjected to a baking treatment for improved strength and water resistance. Thicknesses of hardboard range from 1/8 to 5/16 inch and sheets as large as 4 by 16 feet are available. Uses for hardboard are similar to those for thin plywood. They include interior paneling, exterior siding, doors, cabinetry, crossbands in veneered construction, and facing for plywood. Prefinished panels with decorative scoring effects are used as wall coverings in kitchens, bathrooms, and shower stalls.

Fiberboards that are compressed to specific gravities in excess of 0.80 are designated as hardboards. At specific gravities in the range of 0.80 to 1.00, untreated hardboard exhibits improved properties in strength and stiffness, exceeding particleboards and approaching plywood, as shown in table 5. Equilibrium moisture content is slightly less than for particleboard, with somewhat greater linear expansion. Tempered or treated hardboards exhibit generally improved properties of strength, stiffness, and reduced

moisture pick-up. As with fiberboard generally, the behavior of hardboard over time is far from elastic, with creep and relaxation effects as much as five times greater than those of wood itself.

Surface properties of hardboard, particularly that manufactured with both faces smooth, may not be conducive to adhesive bonding. Light sanding is generally sufficient preparation for bonding. The screen-back surface of wet-felted hardboard presents no particular bonding problem.

Paper Laminates

Resin-impregnated paper is the base of a family of materials used to overlay such substrates as lumber, plywood, particleboard, and hardboard. Paper laminates may be used for masking defects, for decorative purposes, or for their structural properties. For the masking of plywood, a single sheet of paper impregnated with about 25 percent phenolic resin is incorporated with the veneer assembly in hot pressing. For less stable substrates, a single paper sheet would not be effective due to stresses resulting from differential shrinkage and swelling.

Decorative laminates involve several sheets of resin-impregnated base material, frequently paper but sometimes a fabric, which are bonded together at high temperature and pressure to form a dense laminate for subsequent application to the substrate. The resins most commonly used for impregnating the base material are melamine and phenolic resins. The face ply is usually transparent melamine-impregnated paper for maximum effectiveness in protecting and displaying the decorative sheet immediately beneath it. Behind this are several sheets of phenolic resin-impregnated material and a melamine-impregnated backing sheet for balanced construction. A final back sheet of special paper to improve adhesion completes the assembly. Such laminates impart hardness and wear resistance with attractive appearance to countertops and other surfaces that must resist hard wear.

Resin-impregnated paper laminates are the highest density and, generally, highest strength materials in the family of wood-based products. Properties are anisotropic, as in plywood. Paper laminates are valued for a high modulus of elasticity and tensile strength, for very low equilibrium moisture content, and for relatively low linear expansion, as shown in table 5.

The smooth, often glazed surfaces of high-resin content papers may demand a light abrading or sanding treatment in preparation for secondary bonding. In the case of decorative laminates that are manufactured with a special paper back sheet having good bonding characteristics, no special treatment should be necessary.

Structural overlays of resin-impregnated base materials, including paper, textile fabric, and fiberglass fabric, are sometimes used as facing for wood-base substrates in structural sandwich applications. Various resins-including phenol and melamine formaldehydes, polyester, and silicones-are used to impregnate the base materials.

Sandwich Panel Materials

Structural sandwich construction involves the bonding of relatively thin faces of a structural material to a thick core of lightweight material. When such a composite is loaded flatwise as a beam, the faces are highly stressed in tension or compression and the core in shear. The resultant construction is highly efficient in providing strength and stiffness at minimal weight. Plywood illustrates a common facing material for sandwich panels. Other face materials include hardboard, gypsum board, asbestos board, aluminum, steel and other metals, and paper laminates.

Core materials include honeycomb of paper, fabric, or aluminum foil (fig. 37); foamed plastics such as polystyrene, polyurethanes, and polycyanurates; and low-density woods such as balsa. Special properties can be provided both through selection of the core or face materials, and through treatment. Resin treatment of kraft paper for a honeycomb core is used advantageously to improve performance under damp conditions. Applications to which sandwich construction are adapted include roof, floor, and wall panels.

Sandwich construction demands face materials having favorable structural properties in tension and compression. Most of the materials listed in table 5, including wood, plywood, hardboard, paper laminates, aluminum, and other metals, meet this qualification. Core materials, on the other hand, stabilize the thin faces through lateral support, and provide stiffness to the sandwich by spacing of the faces. Tensile strength and modulus of elasticity of the core material are of less importance than its shear rigidity. Foamed

plastics with specific gravities as low as 0.091–comparable to balsa wood-are satisfactory for some core applications. Their mechanical properties are very low as exemplified by polyurethane foam in table 5.

The density of honeycomb cores of resin-impregnated paper, resin-impregnated glass-fabric, or aluminum is controlled by the parent material, cell wall thickness, and by honeycomb cell size (the larger the cell size, the lower the density). Impregnated paper or cotton fabric honeycomb may equal or exceed the strength shown for the honeycomb. Thin aluminum sheets are corrugated and bonded with a metal-to-metal adhesive to form honeycomb cores.

The bond between core and facing is extremely critical in sandwich construction, particularly when faces are relatively thin. It is essential that the contacting surfaces of the faces be receptive to bonding and that the adhesive be compatible with both the core and facing material. Metal surfaces are particularly critical and must be scrupulously clean at the time of adhesive application.

Gypsum Board

Gypsum itself is a mineral with chemical composition $CaSO_4 \cdot 2H_20$. After crushing and calcining to remove part of the combined water, it takes on the characteristics of plaster of paris. Adding water to the plaster of paris produces a plastic mixture which sets to a hard solid through chemical recombination with water to restore its original composition. This is the form in which it appears as the core of gypsum wallboard.

Gypsum board products consist of this gypsum core faced and edged with paper designed to provide firm adhesion to the core. Papers with decorative finishes and other special surfaces laminated to the basic envelope are available. Sheets 1/4 to 5/8 inch thick and in sizes up to 4 by 12 feet are commonly used. Principal uses for gypsum board are as ceiling and interior wall covering in dry-wall construction, sheathing, and as a base for gypsum plasters.

Gypsum itself has a specific gravity of 2.3 in rock form. However, the gypsum core in wallboard is much lighter, about 0.80 specific gravity, as the result of weight control additives such as wood fiber. Only limited data on properties are available for gypsum wallboard but, as shown in table 5, its compressive strength is quite low and its coefficient of thermal expansion two to three times that of plywood. The paper surface is readily adaptable to bonding by conventional wood bonding adhesives.

Concrete

Concrete is a mixture of portland cement, water, and an aggregate of sand, gravel, or crushed rock. The quality of the mix is determined by the quality of the cement paste formed by the reaction of the cement with water. Setting occurs through a hydration reaction involving bonding to the aggregate particles to form concrete. New concrete must be allowed to dry for several weeks before another material is adhesively bonded to it.

Most applications involving the bonding of concrete to other materials are nonstructural and consequently require less attention to control of self-imposed stresses from restraint of dimensional change. Floating, solid wood floors on concrete, for example, depend on adequate expansion joints between wood members to contain the swelling of the wood without restraint. For this application a nonrigid adhesive should be used. Rigid adhesives are limited to combinations of concrete with dimensionally stable materials, or to substrates such as plywood with very limited dimensional change, so that stresses resulting from restraint do not cause adhesive or substrate failure.

Clean, dust-free, and dry concrete surfaces are prerequisite to bonding. Adhesive applications in bonding other materials to concrete frequently occur below grade and may involve critical problems of moisture build-up in service. Thus watertightness and a vapor barrier preferably installed on the soil side of the concrete are needed. Certain concrete surfaces are not suitable for bonding because they offer a crumbly or chalky surface; such defective concrete is occasioned by improper pouring, setting, or mixing.

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CHAPTER 5: ADHESIVES[8]

A number of adhesives are currently being used in the building construction industry in the United States. Their variety can cause a problem in selecting the best adhesive for a particular application. This chapter discusses the more important adhesives, emphasizing the outstanding properties of each. Comments to help in product selection are also included.

Adhesives to be described include both those suited to fabrication under controlled conditions, as in a plant or small shop, and those employed onsite, where conditions such as temperature can vary widely. Bonded products fabricated in plants encompass major components of modular and mobile homes, such as floor decking, wall panels, and trusses; structural timber laminates: stressed-skin panels; sandwich panels; folded plates; box beams; scarf joints; and similar bonded units. Onsite bonding may involve applications where structural performance is critical, as in floor systems (i.e., bonding plywood decking to floor joists) or truss assembly. Less critical applications include bonding drywall or wall paneling to partition studs; bonding underlayment to subfloor; application of high-density plastic laminates; and installing furring strips.

SELECTION OF AN ADHESIVE

Several factors have to be considered to choose the right adhesive for a bonding project. They include durability and strength of the adhesive, kinds of surfaces to be bonded, special job requirements, physical and working properties of the adhesive, and cost considerations.

Durability Requirements

When selecting any construction adhesive, it is important to consider bond durability requirements under the conditions the assembly must meet at its ultimate location. Will the final location of the bonded system be inside or outside? If located inside, will normal temperature and humidity conditions be encountered or will they vary widely? For instance, it is known that roof trusses in houses can be exposed to temperatures of 71° C (160° F) or more. Trusses in commercial or industrial buildings may not only encounter similarly high temperatures, but may also be subjected to humidity conditions exceeding 50 percent relative humidity. If the adhesive is to be exposed to an outdoor environment, what conditions will be encountered? Will a high degree of waterproofing be required? For example, the assembly may be exposed directly to the elements where it will be subjected to alternate wetting from rain and drying from sunshine or heat. Or it may be in a sheltered outdoor location where rainsoaking would be unusual. Perhaps the bondline will be in an assembly protected from direct sunshine or rain, but exposed to extremes of temperature and humidity.

Some bonding jobs have complex adhesive requirements. For example, onsite bonding of plywood floor assemblies may present an initial problem of bonding wet, or even frozen, wood materials, even though the ultimate environment will be normal home temperatures and humidities. Assessment of adhesive durability requirements by a user is simply good practice.

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Strength and Resistance to Deformation

What strength requirements must the adhesive possess? Will the bonded joint be stressed or unstressed? In many construction applications, it is obvious that the joint will be stressed in some fashion. In such instances, an adhesive may be required that will cure to a rigid state and develop strength equal to the wood. On the other hand, an elastomeric or thermoplastic adhesive prone to creep under severe stress may be entirely satisfactory for joints subjected to little or no stress (chapter 2).

Most laymen are not technically skilled enough to analyze the strength requirements needed in an adhesive system. Fortunately, several trade associations have accumulated this kind of information and work closely with their members to assist them in using a suitable adhesive system.

Most adhesive manufacturers are also familiar with various existing governmental specifications and usually offer, as a service to their clients, a list of their adhesives that comply. Some governmental agencies even require the adhesive suppliers to have their products tested by an independent laboratory for compliance to specific standards or specifications before accepting the adhesive system for field use. In addition, many adhesive producers have strength property data on their adhesive products and usually will make this information available to clients upon request. In instances where specific test data are lacking, they will often work closely with clients to submit their recommendations on the most suitable adhesive. Governmental laboratories such as the U.S. Forest Products Laboratory have likewise accumulated a wealth of data on adhesives through the years.

Adhesive Applications

The manner in which an adhesive is to be used and the flexibility in application which it offers are important to its successful performance. First, note the substrates to be bonded. Are they wood, metal, plastic, or a combination thereof? Is the surface of the substrate adequate, or must it be prepared just prior to bonding? What is the moisture content of the wood? Will the adhesive be used in a plant under controlled temperature and humidity, or in a small shop where a lesser degree of control can be exercised on the operation? Or will the product be employed onsite where temperatures, especially, may be uncontrollable? These factors alone or in combination will affect the type of adhesive selected for the bonding application.

What equipment is needed for preparing or applying the adhesive? Some products must be mixed with other ingredients before use; others come ready-to-use. Several adhesives can be applied by several means, others have definite limits of application. Cartridge calking guns offer a convenient way of applying certain adhesives, such as mastics, for onsite bonding. Heavy-bodied casein adhesives are well suited to adhesive applicators, whereas spray techniques afford another convenient means for applying adhesives such as contact cements. Simple bonding jobs may often lend themselves to the use of stiff bristle brushes, mops, or paint rollers to apply the adhesive. Thin-viscosity products can also be readily applied by such simple means as plastic squeeze bottles. Hot melt adhesives applied in the molten form generally require special manual or automatic applicators. For most plant manufacturing conditions, mechanical equipment such as mixers and roll spreaders are preferred because they lend themselves to automated or semiautomated production line techniques, resulting in greater and more uniform productivity (chapter 6).

Many adhesives require a minimum pressure period or clamping time while cure or set is attained. Thus, it is important to know the adhesive's curing characteristics. Plant production procedures can often utilize hydraulic pressure, air bag or air hose pressure, or clamp pressure. For onsite bonding, nails, staples, screws, or similar fastening methods usually provide adequate pressure. Very viscous or tacky adhesives can sometimes hold assembly components together momentarily until pressure can be applied (chapter 6).

What is the setting time of the adhesive and what limitations might be encountered in its application? Adhesives such as elastomeric contact types have sufficient cohesiveness to bond immediately, through contact pressure alone, provided that severe mechanical stresses are not introduced. However, the final cure is not realized for several days afterwards. Many of the thermosets require a curing period under pressure at room temperatures for a period of several hours before the bonded assembly can be safely handled.

The setting or bonding of some adhesives (i.e., epoxies) can be delayed by keeping them cool. Also, the curing speed for some adhesives can be substantially shortened if it is possible to use heat to increase the actual bondline temperature. This is frequently done in plants, where conditions sometimes lend themselves to the use of steam, radiant or resistance heat, or radiofrequency (RF) energy as the heat source. Such heat must be capable of reaching the bondline effectively, not just the wood itself.

Some thermoplastic resin emulsions, such as polyvinyl acetates, usually require much shorter periods of cure at ambient temperatures to attain their minimum cure, generally an hour or less under pressure, compared to several hours for typical thermosetting-resin systems. Hot melt assembly adhesives attain strength rapidly on cooling, and are therefore appropriate for assembly line operations or where short bonding time is desirable.

Many adhesives are critical to temperature conditions and may not be too well adapted for use where temperatures are too high or too low. Curing temperatures under 16° C (60° F) can forbid the use of many adhesives now on the market.

Adhesive Physical and Working Properties

Most commercial adhesives for the building construction industry are available in powder, liquid, or solid forms. As a rule, adhesives sold in powder form have to be dispersed in water before they are ready for use. A casein adhesive is typical. For other types, such as some of the thermosetting-resin systems, catalysts or hardeners must be added. Some liquid products are sold in ready-to-use condition, requiring only that they be spread on the material to be bonded. These products may be moderate-viscosity liquids or very viscous mastic materials. Illustrative of lower viscosity adhesives are contact cements and polyvinyl acetate emulsion adhesives that can be pumped or sprayed. Mastic products are heavy-bodied, viscous adhesives that lend themselves more to troweling or extrusion from a cartridge or pressure gun. Hot-melt adhesives are sold as a solid product and must be melted for application.

The working life of an adhesive may also have a bearing on its selection. As a rule, products that are sold in ready-to-use form have a working life of many hours as long as the manufacturer's instructions are followed for handling and storage. Precautions should be observed to keep containers tightly closed when not in use. This prevents undue loss of solvents or volatile components, or pick-up of moisture from the atmosphere. Care should also be taken to clean spreading or handling equipment after use to preclude accumulation of hardened adhesive.

Adhesives that have to be mixed at the time of use, particularly those involving a hardener or catalyst, usually have a limited working life. This can range from 1 to 8 hours at 20° to 30° C (68° to 86° F) for room-temperature-setting adhesives to overnight for hot-pressing formulations. Working life decreases as the temperature of the mixed adhesive increases. Incorporation of a catalyst or hardener triggers a chemical reaction in the adhesive mix that terminates with the setting or curing of the mixture.

Note also the ambient temperature at which the adhesive can be employed and cured. Generally, four ranges of adhesive bondline curing temperatures are recognized in the industry: first, cold-setting systems that will cure under 20° C (68° F); second, room-temperature-setting systems that cure at 20° to 30° C (68° to 86° F); third, intermediate-temperature-setting mixes that cure from 31° to 99° C (87° to 211° F); and fourth, hot-setting adhesives that require a temperature in the bondline above 100° C (212° F) to cure.

Storage life or shelf life of an adhesive may also be important to the user. Most products are formulated to remain in a usable condition for a period of a few weeks to many months, depending on the specific storage temperature conditions encountered. For the most part, storage temperatures of 20° to 35° C can be tolerated by a majority of adhesives. The life of most adhesives can be prolonged by storing at cooler temperatures of below 20° C (68° F), but above freezing conditions. Some emulsions must be protected from freezing. Conversely, where temperatures exceed 35° C (95° F), the shelf life may be materially shortened. For guidance, most manufacturers list storage data on container labels or in their technical literature.

Other factors influencing adhesive selection are whether the product has an objectionable odor during use; presents a fire hazard during its application; possesses potential danger of staining substrates such as wood; or gives a permanently dark-colored bondline. What constitutes an objectionable odor is difficult to define since one individual may tolerate a situation that is not ac-

ceptable to another. Certain adhesives do possess distinct odors stemming directly from chemicals or solvents utilized in their manufacture; however, where adequate ventilation exists in a plant or onsite, a vapor problem and danger of flammability are minimized. Contact cements may pose such hazards because they often contain solvents that are overpowering in odor and present a fire hazard if applied in confined, unventilated areas. Also, some individuals may be allergic to certain adhesives. The risk of dermatitis can be greatly minimized by the use of gloves and by periodic washing of hands.

Staining of wood sometimes occurs when certain adhesives are applied to a particular species of wood. Fortunately, most adhesives do not cause this condition; those that are prone to staining can often be employed in such a manner as to virtually eliminate the problem. For example, some grades of casein adhesives will stain wood species such as oak or redwood. A change to a different formulation, usually containing a lower level of alkaline chemicals, will reduce the staining.

Adhesive mixes that cure to a dark bondline which is exposed to view in the final assembly may be objectionable when a natural finish is to be applied. Resorcinol adhesive mixes may cause this condition. The amber-colored resin can be combined with a light-colored catalyst when preparing the adhesive mix to disguise the dark color to some degree, but not completely. The best alternative is to use a lighter colored adhesive, such as a melamine urea, providing it meets other use and performance requirements.

Cost Considerations

Cost will also influence the choice of an adhesive. Several things should be kept in mind regarding adhesive costs. First, although adhesives vary widely in price, purchase price alone is generally a poor indicator of the actual adhesive cost. Some products come in ready-to-use form, need no mixing, and their costs are readily apparent. Others incorporate additional ingredients in their preparation that may affect the overall cost. For example, a powdered casein adhesive generally requires the incorporation of 2 parts water to 1 part adhesive by weight, thus giving an adhesive mix substantially lower in cost than the original unit purchase price of the casein adhesive.

Secondly, the amount of the adhesive mix required to do a satisfactory bonding job should be considered. A good common denominator for expressing this is in terms of pounds of adhesive mix needed to bond 1,000 square feet of single bondline (glueline) surface, often abbreviated as #/MSGL. Application rates vary considerably among different adhesive systems. Most manufacturers cite spread ranges for their products in technical literature or on container labels. Once the user has determined his adhesive mix cost and has knowledge of spread rates required for his bonding project, he can very accurately arrive at this theoretical bondline cost.

Thirdly, the cost of labor must be considered. If mixing numerous ingredients for an adhesive takes a fair amount of time, it will obviously cost more to prepare than a simple two-component system. Likewise, a ready-to-use adhesive that might initially cost the purchaser more to buy could end up being more inexpensive to use because of the labor savings effected. The degree of difficulty in cleaning equipment with any given adhesive must also be considered because this affects total labor costs and production continuity.

Finally, consideration should be given to the cost of the adhesive system in relation to the overall cost of the assembly being bonded. It is rare that the actual cost of an adhesive mix exceeds more than a minimal portion of the total cost of the building unit. It is not unusual for a more expensive adhesive to substantially contribute to the speed or ease of manufacture of an assembly, resulting in lower total cost for that unit than might otherwise be attainable.

Selection Guide

The more completely a user assesses the various aspects of his potential bonding job, the better are his chances of selecting the proper adhesive. Even where outside assistance is solicited by the user from an adhesive supplier or manufacturer, both user and advisor must clearly understand the nature of the bonding application to come to a sound decision on the choice of adhesive.

Surely, selecting an adhesive product can be confusing. With this in mind, two tables are being included to present helpful information. Table 6 presents typical physical and working properties for the more important adhesive systems now in use in the building construction field. Table 7 lists the typical application-and-use conditions for each adhesive. These tables are guidelines only. Obviously, the manufacturer's instructions must be followed closely to insure a successful bonding job.

Table 6.–*Building construction adhesives-physical and working properties*

Types of properties	Synthetic thermoset			Synthetic thermoplastic				Casein
	Resorcinol-formaldehyde	Melamine-formaldehyde	Epoxy	Resin emulsions	Elastomeric contact	Elastomeric mastic	Hot melt	
Physical form commercially available	Liquid	Liquid, powder	Liquid	Liquid, powder	Liquid	Liquid	Solid	Powder
Shipping container	Bulk, drum, pail, and small cans	Drum	Drum, pail, and small cans	Bulk, drum, pail, and small cans	Drum, pail and small cans	Drum, pail, small cans, cartridge	Drum, pail	Drum and small cans
Shelf life at 21° C (70° F)	3 to over 9 mo	Less than 3 to over 9 mo	3 to over 9 mo	Less than 3, up to 9 mo	Less than 3, up to 9 mo	Less than 3, up to 9 mo	Over 9 mo	3 to over 9 mo
Mix additives	Catalyst or hardener	Catalyst or hardener, water, fillers, or extenders	Catalyst or hardener	None, or catalyst, or hardener and water	None	None	None	Water
Working life at 21° C (70° F)	1 to 6 h	1 to over 6 h	Under 1 h to 6 h	Over 6 h	Over 6 h	1 to over 6 h	Over 6 h	1 to 6 h
Spreading equipment	Roller spreader, brush, or extruder	Roller spreader	Trowel, brush, or paint roller	Roller spreader, spray, brush, or paint roller	Roller spreader, spray, curtain coater, trowel, brush, or paint roller	Pressure gun, trowel, or cartridge	Roller spreader, pressure gun, or curtain	Roller spreader, extruder, brush, or paint roller

Table 6.–*Building construction adhesives-physical and working properties–continued*

Types of properties	Synthetic thermoset			Synthetic thermoplastic				Casein
	Resorcinol-formaldehyde	delamine-formaldehyde	Epoxy	Resin emulsions	Elastomeric contact	Elastomeric mastic	Hot melt	
Assembly time tolerance at 21° C (70° F)	60 to 90 min, maximum	Up to 8 h, maximum	20 min, maximum	20 min. maximum	60 to 90 min, 90 maximum	20 min, maximum	Seconds or less	60 to 90 min, maximum
Pressure application and typical pressure–lb/in.[2]	Mechanical press, nail bonding; 25 to over 100	Hydraulic press, 100 to 200	Pneumatic clamps, nail bonding; 25 to 150	Mechanical press; 50 to 200	Nip rolls, air press, nail bonding; 25 to 100	Nail bonding; 25 to 100	Nip rolls, pneumatic clamps; 25 to 150	Mechanical press, nail bonding, 25 to 200
Adhesive cure temperature	20° to over 100° c (68° to over 212° F)	31° to over 100° C (87° to over 212° F)	Below 20° to 30° C (below 68° to 87° F)	Below 20° to over 100° C (below 68° to over 212° F)	20° to 30° C (68° to 86° F)	Below 20° to 30° c (68° to 86° F)	Above 100° C (above 212° F)	Below 20° to 30° C (below 68° to 86° F)
Cure or setting time of adhesive[1]	4 to 16 h; under 10 min above 100° C (212° F)	Under 10 min above 100° C (212° F)	1/2 to 16 h	Under 1/2 to 16 h	Immediate use	Immediate use or under 1/2 h	Immediate use	4 to 16 h

[1]Cure time here is that lapse of time at 21° C (70° F) after mating the adherends under pressure application, but before the assembly can be moved or pressure released.

Table 7.–*Building construction adhesives-typical application and use conditions*

Applications and uses	Synthetic thermosets			Synthetic thermosplastic				Casein
	Resorcinol-formaldehyde	Melamine-formaldehyde	Epoxy	Resin emulsions	Elastomeric contact	Elastomeric mastic	Hot melt	
Interior and exterior applications	Primarily exterior, some interior	Primarily exterior, some interior	Interior and exterior	Primarily interior, some exterior	Primarily interior	Primarily interior	Primarily interior	Primarily interior
Suitability for stressed joints	Yes	Yes	With mechanical fasteners only	With mechanical fasteners only	No	With mechanical fasteners only	No	Yes
Heat resistance of bondline	To 66° C (150° F]	To 66° C (150° F)	To 66° C (150° F)	To 43° C (110° F)	To 43° C (110° F)	To 43° C (110° F)	To 43° C (110° F)	To 66° c (150° F)
Strong-as-wood bond strength	Yes	Yes	Yes	In some instances	Usually not	Usually not	Usually not	Yes
Spread rates[1]	50 to 100 #/MGSL	35 to 50 #/MGSL	35 to 50 #/MGSL	35 to 50 #/MGSL	35 to 50 #/MGSL	200 to 300 #/MGSL	100 to 150 #/MGSL	50 to 100 #/MGSL
Structural timbers	Yes	–	–	–	–	–	–	Yes
Stressed-skin panels	Yes	Yes	–	–	–	–	–	–
Folded plates	Yes	–	–	–	–	–	–	–
Ridge beams	Yes	–	–	–	–	–	–	–
Box beams	Yes	–	–	–	–	–	–	Yes
Moldings	–	–	–	Yes	Yes	–	–	Yes
High-density plastic laminates	Yes	–	–	Yes	–	–	Yes	Yes
Finger and scarf joints	Yes	Yes	–	–	–	–	–	–
Sandwich panels	Yes	Yes	–	–	–	–	–	–
Treated wood	Yes	Yes	–	–	–	–	–	–
Kitchen units	–	–	–	Yes	Yes	–	–	–
Furring strips	–	–	Yes	–	–	Yes	–	–
Parquet floors	–	–	Yes	–	–	Yes	–	–
Drywall and paneling	–	–	–	Yes	Yes	Yes	–	–
Underlayment	–	–	–	Yes	–	Yes	–	Yes
Plywood floors	–	–	–	–	–	Yes	–	Yes
Gusset plates	–	–	–	–	–	Yes	–	Yes

[1] #/MSGL = pound solids per thousand square foot single bondline.

TYPES OF ADHESIVES AVAILABLE

The various products to be discussed are divided into two broad groups, synthetic adhesives and natural adhesives. The synthetics are further subdivided into thermosetting and thermoplastic adhesives.

Synthetic Adhesives

Synthetic adhesives employ specific chemicals that are reacted, or simply mixed, under precise factory conditions to obtain a resinous or adhesive product. Their modes of manufacture and varied chemical composition result in a large group of adhesives possessing a wide range of properties. These synthetic adhesives are similar to typical commercial plastics and are generally manufactured by the same plastics industry.

Thermosetting resins are converted by chemical reaction through catalysts or heat at the time of use to a hard, infusible, insoluble state. The reaction is not reversible once cure is obtained.

Thermoplastic adhesives, on the other hand, are generally resin systems that are completely reacted as supplied. Their application involves only physical change, such as film forming through loss of solvent or melting and solidification on cooling. Such adhesives are generally reversible in that the solid bondline can be reliquefied by heat or solvent action. Most thermoplastic adhesives tend to deform under stress or when subjected to heat. This deformation is called creep.

Thermosetting Adhesives

Resorcinol-Formaldehyde Resins

This type of adhesive is produced from two primary chemicals: Resorcinol, a reddish brown, flaky material, and formaldehyde in a water solution. (Formaldehyde is a gas which in water solution is called "formalin".) Complete reaction of resorcinol with formaldehyde yields a resinous, stable solid (i.e., the fully set adhesive). During manufacture, the amount of formaldehyde added is not enough to permit the reaction to go to completion. Mixing the adhesive before use simply entails adding sufficient formaldehyde to complete the reaction. The resultant resorcinol resin is a dark amber sirup consisting of resin dispersed in water and alcohols, having a viscosity under 1,000 centipoises at 21° C (70° F) and resin solids of 50 to 65 percent.

Three kinds of resorcinol formulation are commercially available. One is a straight or unmodified resorcinol-formaldehyde resin utilizing only the prime chemicals of resorcinol and formaldehyde. Another is a resorcinol-phenol combination in which a minor amount of lower cost phenol has been incorporated with resorcinol and formaldehyde into the resin system for economy. A third type is a phenol-resorcinol product in which a larger amount of phenol has been incorporated into the resin system to substantially lower the cost. In general, an increase in phenol content in the adhesive requires an increase in temperature for adequate curing.

All three types of resins are commercially available only in sirups. They are usually sold in drum containers, but can be bulk handled if volume warrants. The liquid resins possess good shelf life when stored at 21° C (70° F). Straight resorcinols are extremely stable and will keep for a year or more. The phenol-modified blends have shorter, but still ample stability, such as 3 to 9 months at 21°C (70° F).

A resorcinol adhesive is normally sold as a two-component system comprised of the liquid resorcinol resin and a powdered hardener. The latter is generally a tannish or brown-colored, free-flowing powder that usually possesses a pungent odor due to the presence of a formaldehyde-containing ingredient. Some manufacturers also offer on a limited basis the use of liquid formaldehyde as the hardener for certain resin formulations.

It is important that the proportion of resin and catalyst be weighed or accurately measured in order to obtain a proper adhesive mix for application. Equipment described in chapter 6 is adaptable for plant application. For onsite use, a small portable mixer or even manual mixing is usually adequate.

Resorcinol mixes tend to be exothermic (to rise in temperature) after mixing of the hardener with the resin. When large batches are prepared, water-jacketed mixers and spreaders should be used. Precooling the liquid resin prior to admixing the catalyst will also help keep the mix at a cool temperature and thus prolong its working

life. On the other hand, very cold resin should not be applied as the chemical reaction may be too slow for proper cure. The adhesive manufacturer's directions should be carefully followed in using these adhesives.

The mixture is chemically activated after the hardener has been mixed with the liquid resin and will set after a period of time to a hard insoluble state that is irreversible. The time the adhesive remains unset after mixing is referred to as working life, or pot life. Most systems exhibit a working life of from approximately 1 to 6 hours at 21° C (70" F). If operating temperatures are higher, the working life will be materially shortened. Precautions may be necessary to keep the mix cool to avoid premature setting. Resorcinol adhesives are generally formulated to cure at room and intermediate temperatures. For certain applications, however, they can be modified to also cure under cold-setting or hot-setting conditions.

Resorcinol adhesives can be applied to substrates in several ways. When the adhesive is used in a plant, a mechanically powered roller spreader with appropriate roll grooving offers a convenient and precise method of application. Some timber-laminating plants employ an apparatus to extrude the adhesive onto the stock in lieu of a roller spreader.

When this adhesive is employed on a construction site, a stiff bristle brush or paint roller will suffice to apply the adhesive. Moisture content of the stock being bonded should be monitored and controlled. Bonding can be accomplished with wood moisture content in the range of 12 to 18 percent. However, assemblies destined solely for interior use and bonded under controlled plant conditions generally give the best joint performance when stock moisture content is 6 to 12 percent.

Assemblies bonded with a resorcinol adhesive system must be held under pressure for several hours to allow sufficent time to cure the bondline. As a rule, cure times of from 4 to 16 hours are needed for room or intermediate bondline temperatures. When high bondline temperatures are involved, set times can be reduced significantly, often to a matter of minutes, depending on the assembly involved. Conversely, with exceedingly low bondline temperatures the cure time must be lengthened by several hours beyond room-temperature bonding requirements.

In factory operations, pressure can be obtained by means of a hydraulic press, I-beams and turnbuckles, C-clamps, pneumatic clamps, and jigs (chapter 6). Suitable pressure for bonding applications onsite is usually obtained simply through the use of mechanical fasteners such as nails, staples, or screws.

Resorcinol adhesives provide waterproof bonds that resist attack from weather and chemical reagents, and that are impervious to microorganisms and insects. They are one of the few adhesives that can offer this performance when cured at room or intermediate temperatures.

One of their most important uses is for structural timber laminates. The large, unwieldy members take time to lay up, and require the long assembly-time properties that a resorcinol mix can provide. The bulky nature of a timber laminate does not lend itself to hot-pressing or hot-setting techniques. However, a number of timber laminating plants have shortened the curing process by isolating the processing area to provide external heat and humidity to the clamped assemblies. This is accomplished by getting heat to the inner bondlines as high as 70° C (158° F) over a period of several hours.

Resorcinol adhesives are also used to bond other building components such as stressed-skin panels, plywood box beams, and even scarf joints, since the adhesive properties required are quite similar in many respects to those for timber laminating. Resorcinols are likewise used to bond dissimilar materials such as high-density plastic laminates or metal sheets, when properly primed, to cellulosic substrates. All of these assemblies are manufactured in plants under fairly well controlled conditions.

Resorcinol adhesives can also be employed for such onsite applications as box beams and small roof trusses, providing that ambient temperatures are adequate for proper curing of the bondline and that adequate pressure can be applied.

Resorcinols will effectively bond preservative- and fire-retardant-treated wood. This includes both oil-soluble and water-borne preservative-treated woods. Very few other adhesives can effectively bond such a variety of chemically treated wood materials. Care should be exercised to prepare the stock surface properly for bonding. This is usually accomplished by planing or sanding the substrate just prior to the bonding operation to remove foreign material that could interfere with getting good joint strength. The

adhesive manufacturer's instructions should be followed quite closely here.

In summary, resorcinols provide durable, waterproof bonds at room- or intermediate-temperature curing conditions; give excellent joint strength in highly stressed bonded assemblies; mix easily because only two components are involved; and can bond many chemically treated woods.

Disadvantages of resorcinols include a pressure period of several hours to realize minimum cure; a minimum bondline temperature of 21° C (70° F) for most critical applications; a dark-colored bondline that might preclude some uses; and comparatively high cost, particularly for unextended formulations.

Melamine-Formaldehyde Resins

Melamine-formaldehyde resins are a condensation product of two principal chemicals, melamine and formaldehyde. For cost savings, some copolymer products are prepared with urea to yield a melamine-urea-formaldehyde resin. Most such adhesives are produced in spray-dried powders, white or tan in color, to obtain adequate storage stability. Liquid versions possess too short a shelf life for extended commercial use, although a few are now being sold. All melamines produce a highly water-resistant to waterproof bond and a bonded joint that is light in color. Melamine adhesive powders are sold in standard fiber or metal containers, and exhibit good storage characteristics in excess of 12 months at 21° C (70° F).

Some melamine powders are sold with fillers and catalysts already incorporated, thus requiring only the addition of water to prepare the mix. Other powders and liquid products require the addition of a catalyst and possibly a filler ingredient at the time of use. The manufacturer's mixing directions should be explicitly followed. Since melamines are used almost exclusively in plants, the conventional mixing and spreading equipment described in chapter 6 is generally utilized. An applicator-wheel device, which is part of the dielectric generator setup, is used to spread the adhesive on stock for finger-jointing work.

Melamine adhesives require heat to properly set the bondline; hence, they are solely a hot-setting type of adhesive. Generally, bondline temperatures greater than 71° C (160° F) are required to give the degree of cure necessary to realize optimum bond strength. Because melamines respond very well to radiofrequency current for curing, they are used extensively in scarf- and finger-jointing applications where rapid bondline cures can thus be obtained. These thermoset-type adhesive systems set to a hard, rigid bondline that gives joint strengths as strong as the wood itself; thus, they can be used for joints that will be highly stressed without much risk of adhesive failure.

Straight melamine-resin adhesives give a bond that will withstand exterior elements for many years on untreated wood and is resistant to attack by micro-organisms. They can be used to bond wood that has been treated with mildly acidic fire-retardant chemicals, but are not too effective in bonding preservative-treated stock or highly acidic fire-retardant-treated wood. Light-colored melamine bondlines blend in quite well with the natural color of most woods, which leads to their preference for certain bonding jobs over the darker color resorcinols. Melamine-urea adhesives provide durable bondlines, more so as the proportion of melamine increases. Resins with at least 50 percent melamine are usually considered adequate to produce exterior-type joints on untreated wood.

The principal application of the melamines in the building construction field is for bonding scarf and finger joints in factory-type operations. Long lengths of individual lamina for structural timber trusses or beams are obtained by scarfing together shorter stock. Dimension lumber, particularly 2 by 4 studs, can also be produced from shorts via scarf-jointing techniques.

In summary, advantages of straight melamine adhesives are ability to give light-colored, waterproof bondlines and excellent cure characteristics under high frequency current. The main disadvantages are the need to cure the bondline by hot-setting techniques, thus limiting applications, and the need to prepare the adhesive mix at time of use.

Epoxy Adhesives

Epoxies find only limited use as a construction adhesive for wood. Epoxy adhesives are formed by the reaction of epichlorohydrin with bis-phenol in the presence of sodium hydroxide. The finished resin is normally a viscous liquid of 100-percent solids content, which is combined with a separate hardener at the time of use. Both resin and hardener are stable for months when stored

separately at 21° C (70° F). The epoxy resin and hardener provide a 100-percent reactive mixture; consequently, with no solvent or volatile evolution, they possess good nonshrinking characteristics.

The adhesive mix is prepared at the time of use by mixing the resin and hardener together in the proper proportions. The hardener is usually one of the polyamine compounds, with specific ones selected to give a pot life varying from a few minutes to several hours at 21° C (70° F). The mixed adhesive tends to be highly exothermic, and hence small batch mixing is best unless special cooling is provided.

Epoxies exhibit good dry strength in wood-to-wood bonds, but only fair bonds where the assembly is subjected to prolonged high moisture and water soaking conditions. They provide excellent bonds to most metals and ceramic materials. The nonshrink characteristics and heavy viscosity of the adhesive provide excellent gap-filling properties and make it ideal for bonding poorly fitted adherends where bondlines thicker than 0.005 inch must be tolerated.

Epoxy's principal use in building construction is bonding wood onsite to other materials, such as furring strips to concrete or other aggregate substrates. Epoxies can also be employed as a grout or putty. Bondline strength developed in epoxy-bonded wood joints will usually be less than that of solid wood itself. Hence, epoxy systems are not generally recommended for wood joints that will be highly stressed, as in structural timber laminates, because there is a risk of failure at the bondline and substrate interface. However, epoxies do possess excellent thermal stability and are impervious to attack from both microorganisms and strong reagents. Undoubtedly they will find more applications in the building construction industry in the future.

Thermoplastic Adhesives

Thermoplastic adhesives used for building construction are similar in several respects. They are not recommended for bonded joints that will be highly stressed because most of them are susceptible to creep. They are generally sold ready to use. Further, shelf life of the adhesive is from 3 to 9 months at 21° C (70° F), provided that the storage containers or use tanks are kept closed.

Polyvinyl-Acetate-Resin Emulsions

These vinyl acetate adhesives are commonly known as resin emulsions, or simply as "white glues." They are manufactured by polymerizing vinyl acetate monomer and stabilizers either alone or with other polymers to form copolymers. This process produces an emulsion in which many small adhesive particles are suspended in a protective colloid. Vinyl acetates generally come in liquid form, although at least one manufacturer markets a spray-dried version.

Vinyl acetates are normally recognized by their white to tan colors, range in viscosity from very thin to thick (1,000 to 20,000 centipoises at 21° C (70° F)), and are often characterized by a sweet or an "acid" odor. Formulations vary in solids content. Most unmodified products have 50 to 55 percent adhesive solids; extended versions usually have a total solids content of 40 to 50 percent.

The typical resin emulsions are usually sold in standard containers, but lend themselves to bulk handling and can be readily pumped from one point to another by conventional means. Most products possess good shelf life of from 1 to 12 months at 21° C (70° F). Formulations having limited stability can be stored in cool areas to prolong their shelf life. However, freezing should be avoided.

Most resin emulsions come in ready-to-use form and thus require no mixing. However, some varieties, generally referred to as cross-linking resin emulsions, are now commercially available in two or more component systems that possess a higher degree of durability than previously exhibited by unmodified emulsion adhesives. Cross-linking type vinyl acetates require some period of mixing. Most of these systems have an emulsion adhesive and liquid catalyst as components. Sometimes a third ingredient in the form of a filler is incorporated to control mix consistency. All ingredients are readily mixed and applied by conventional equipment.

Two-component systems undergo a chemical reaction after mixing and will set after several hours. Most are formulated to allow from 6 to 24 hours' pot life at 21° C (70° F). Higher ambient temperatures will shorten this time.

Vinyl resin emulsions are used to a large extent in plants under reasonably controlled operating

conditions. For onsite applications, squeeze bottles, paint rollers, or stiff bristle brushes offer convenient means of application. Some formulations are also adaptable to spraying. Care should be taken not to incorporate air into the adhesive mixture during high speed spreading. This causes foaming and loss of solvent from the emulsion, allowing skinning or film formation. Moisture content of stock being bonded should ideally be 4 to 12 percent to coincide with the ultimate interior use of the bonded assemblies.

Most polyvinyls are compounded for room-temperature-curing conditions and possess very fast setting times, usually from 1/2 to 1-1/2 hours at 21° C (70° F). Curing with these adhesives depends upon a partial loss of solvent, usually water, into the substrate, allowing the adhesive particles in the emulsion to coalesce and form a film (the cured bondline). Such systems also possess short assembly times of 20 minutes or less, thus requiring quick pressure application on the assembly. Some products can be employed as cold-setting adhesives at temperatures as low as 10° C (50° F), but care should be taken to select the correct products for bonding temperatures under 21° C (70° F). At low temperatures, a condition known as chalking might occur with certain emulsions, causing a poorly bonded joint. The dry adhesive takes on the appearance of chalk because the particles do not coalesce in the normal fashion.

Crosslinking formulations can be used as intermediate or hot-setting adhesives, resulting in short cure cycles amounting to a few minutes. Some of these products also cure rapidly under dielectric heat. Resin emulsions require pressure during their cure to keep components properly mated. Plant and shop operations utilize typical hydraulic and air pressure equipment while onsite jobs usually resort to mechanical fasteners for pressure.

Emulsion adhesives have found widespread use in mobile and modular home manufacture. Here immediate strength and stiffening of the assembly is needed, but long-term strength is not required because nails or other fasteners are adequate. The ease of use and quick-setting characteristics of emulsion adhesives are appealing features for bonding decking to floor joists, wall panels to studs, and components to kitchen units; for laminating countertops; and for other assembly steps in this type of structure. Also, some moldings for interior use are now bonded in place with vinyl acetate emulsions.

Emulsion adhesives are capable of providing joint strengths approaching the strength of wood itself. However, these products, being thermoplastic in nature, are not generally recommended where the bonded joint will be highly stressed. The bondline is prone to creep unless auxiliary fastening agents are used. This condition can be aggravated if the bonded joint is also subjected to temperatures exceeding 49° C (120° F) for any prolonged period. Resin emulsions provide excellent dry strength at temperatures below 43° C (110° F), but only limited water resistance. With newer formulations now being marketed, particularly crosslinking types, many of these shortcomings are being eliminated. Long-term field experience should determine how well bond permanence is retained.

In summary, resin emulsions offer the advantage of being ready to use or requiring only limited mixing, of applying easily, of setting rapidly at room temperature, and, generally, of curing to a colorless bondline. Their disadvantages are several. They tend to creep in stressed joints, are even more subject to deformation at temperatures above 49° C (120° F) for sustained periods, and possess only fair water and moisture resistance. Newer crosslinking types possess properties that are minimizing these disadvantages.

Elastomeric Adhesives

This broad class of adhesives is finding growing acceptance in the building construction field. Elastomeric adhesives were introduced for installing tile in 1935, and some of the original installations are still in good condition. Elastomerits for attaching cork and other types of thermal insulation became prominent in the late 30's, and varieties for installing gypsum wallboard were introduced in 1950. Nevertheless, the expansion of this class of products has been so rapid in recent years that not so much is known about their properties and applications as with some other adhesives here described.

Elastomeric adhesives contain an elastomeric material, such as natural and reclaimed rubber, or synthetic rubbers-neoprene, polyurethane, styrene-butadiene (SBR), styrene-butadiene block copolymers (S-B-S), or butadiene acronitrile (nitrile)-and consequently give a nonrigid and somewhat flexible bondline. The relative rigidity or flexibility of the adhesive is a variable which can be controlled by proper compounding techniques. The basic elastomer is only present in suf-

ficient quantity to act as an effective binder, or "backbone," of the elastomeric system. For simplicity, the elastomeric adhesives that are employed in construction can be divided into two broad groups, contact adhesives and mastic adhesives.

Contact Adhesives

Contact adhesives, often called contact cements, contact-bond adhesives, or dry-bond adhesives, are spread on all mating surfaces of the adherends and partially dried. At this time they will adhere to similar adhesive-coated surfaces instantaneously upon contact.

Commercial forms of contact cements are usually low-solids, low-viscosity solutions that are of either a solvent base or an aqueous base. The solvent-base contact cements incorporate volatile solvents such as methyl ethyl ketone to obtain fast release of the solvent from the adhesive film after spreading on a substrate, but prior to mating components.

Solvent-base contact cements pose hazards of fire and explosion as well as of toxic-fume poisoning when they are used in confined spaces. They should be used in well-ventilated and nonflammable areas. Use of cements with chlorinated solvent, can eliminate the fire and explosion danger, but leaves toxic fume hazards. Aqueous-base systems will eliminate fire hazards due to flash ignition of fumes and will somewhat, reduce the danger from fume-inhalation, although they too may contain volatile constituents and should be used in well-ventilated areas.

Aqueous-base contact cements are also low-viscosity systems, but are generally slower drying than the solvent-solution products and lack the early green strength, quick grab, and-in most cases--the ultimate physical bonding characteristics of solvent-based systems. Other general disadvantages of aqueous-based products include package instability, poor freeze/thaw resistance, and-often-limited shelf life.

Mention should be made here of a category of elastomeric adhesives which are similar in some respects to the contact cements, but which have their own distinct properties. Included in this category are such products as duct-liner adhesive, aerosol spray adhesives, and general-purpose elastomeric liquid adhesives. These products are normally applied in the same manner as contact cements, but will allow for movement to position the substrates for correct alinement after contact, whereas contact cements have a high degree of grab and bond instantaneously on contact.

Contact cements produce their bondlines as liquids of low viscosity and low adhesive spreads, and hence are suitable only in well-fitted, thin bondlines. Where substrates are very porous, a second coat of contact cement may be needed on each surface to insure sufficient, adhesive film thickness. Application should be at ambient temperatures of 21° to 32° C (70° to 90° F) for best results. Assembly times should be held as short as possible after drying–2 hours at maximum. Brief contact pressure, required to get an optimum bond, can be obtained by power-driven nip rolls, manual roller, block and hammer, air press, or similar techniques. Because of the quick bond that a contact cement affords, machining and trimming of the final assembly can proceed almost immediately.

Contact cements are often used in modular- and mobile-home construction for applications where close-fitted joints are possible, and usually where only moderate strength is required. However, it, is possible to compound neoprene systems to form very strong bonds, exhibiting shear values in excess of 400 pounds per square inch with wood, and in which failures often occur in the substrates. Frequent applications for contact cements are in fabricating countertops with high-density plastic laminates and for bonding dissimilar substrates. They are also used for double-laminating gypsum wallboard.

Only limited performance criteria for contact adhesives are available from the forest products industry and various governmental agencies at, this time. Since their use has been primarily confined to laminating high-density plastic or metal sheets to rigid substrates, adhesive suppliers have worked out performance details directly with the users. Two primary requirements are generally recognized. One is the contact adhesive's ability to provide limited heat, resistance, such as to endure the heat of hot pans placed on countertops without exhibiting delamination. The other requirement, particularly for bonding plastic laminates, is to resist, delaminating at edges because of substrate dimensional changes due to changing moisture conditions, particularly when the fabrication was originally made at low relative humidities.

Mastic Adhesives

Mastic adhesives are very viscous materials, usually from 100,000 to 300,000 centipoises at 21° C (70° F), and are composed of rubber, resins, filler, and solvents. The solvents are generally organic volatiles which readily evaporate or diffuse to set the adhesive, although aqueous-base mastics are available and are increasing in popularity, due in part, to continuing safety restrictions regarding fire hazards which are being imposed by government agencies and insurance companies.

Mastic adhesives normally are applied to only one surface of the two components to be bonded. They can be used at ambient temperatures as low as freezing if the adhesive itself has been stored for the previous 24 hours at or near room temperature. This ability to bond cold substrates is a distinct advantage for onsite bonding. Some assembly time is advisable before mating components to allow evaporation of solvents in the system, although this is not mandatory. Mastics usually possess good wet tack and will adhere to a variety of substrates. Because they are heavy-bodied in consistency, they provide good gap-filling properties. This is important for onsite bonding where poor fitting joints are encountered. Mechanical fasteners such as nails or staples are employed when bonding onsite to maintain rigidity in the assembly until the adhesive has set.

Mastic adhesives are employed to bond plywood decking to floor joists in bonded floor systems, and wall panels and dry walls to studs. Mastics offer advantages when used in nail-bonding floor systems, since they permit longer joist spans and wider spacing of floor joists due to their stiffness, with resultant savings in construction costs. They also help prevent squeak due to loosening floorboards. In vertical drywall or wall-panel installations, a minimum of nails is required because of good wet tack inherent in mastics. However, drywall ceilings, because of the dead weight factor, do require nail-bonding. Other types of mastic adhesives are used to apply parquet flooring to concrete floors.

Mastics in completed joints usually will not reach full cure until from 2 to 4 weeks after fabrication, although formulations with full-cure times of as little as 24 hours can be produced. Although mastics should be applied liberally, in thicknesses ranging from 1/32 to 1/4 inch, excessive adhesive in the joint will reduce green-strength development and ultimate bond strength. Generally, all types of elastomeric adhesives should be utilized only in joints that are not highly stressed, but adhesive-bonded modular units are capable of withstanding stresses of transit (racking) and erection.

Performance standards for mastic adhesives include American Plywood Association Specification AFG-01 (ASTM D 3498) covering requirements for field-bonded floor systems; USAS A136.1 for setting ceramic tile; and ASTM C557 for adhesive-nail-on installation of gypsum wallboard. All of these performance standards require that the bond-joint meet, a variety of test conditions while maintaining certain minimum performance properties.

Advantages and Disadvantages of Elastomerics

Contact cements lend themselves very readily to application by spraying, roller coating, or trowel, while mastic adhesives are readily applied by trowel, pressure gun, or putty knife. Both types of adhesives are sold in 5-gallon pails or 55-gallon drums. Some manufacturers of mastic adhesives are now selling this product in convenient but, more expensive cartridge packs having a capacity of 1 quart or less. The cartridges are designed to fit, into a standard calking gun so that the adhesive can be easily applied in bead or ribbon form on one of the two adherends being bonded. The cartridges are disposable when empty.

Both contact and mastic adhesives give non-rigid bonds and, by most criteria, yield lower levels of strength than thermosetting wood adhesives. However, elastomerics are free from the problems of embrittlement upon aging which affect, some thermosets, and often form more shock- or impact-resistant joints. Even though elastomeric adhesives do impart, some heat resistance, adequate for many applications, they do not begin to approach the level of heat resistance of the thermosets. Also, they may be less resistant to oxidation unless protected with an efficient, antioxidant in the formulation. Generally, water resistance of the elastomeric film is adequate, but the bonded joint must be sufficiently strong to resist internal stresses that occur within the bonded assemblies from dimensional changes in the substrates (swelling and shrinking).

In general, elastomerics have the advantages of being ready to use, easy to apply for construction purposes, economical in overall cost, particularly with the mastic types, and of requiring only minimal and brief pressing during cure. As disadvantages, many elastomerics should be used only in well-ventilated and fire-safe areas; organic solvents must be used to clean up equipment with solvent-solution compositions; elastomerics may creep in stressed joints; and many have low heat-resistance.

Hot-Melt Adhesives

Although hot-melts do not find much use at the present time in building construction, their use is increasing because they offer many unique properties. Hot-melts are constituted of ethylene vinyl acetate polymers, thermoplastic rubbers (block copolymers), or similar synthetic polymers, formulated with other additives such as rosin and similar thermoplastic materials. The present commercial form of these adhesives is a solid that is sold in a pelleted, chunk, stick, or rope form. Hot-melts possess shelf life of at least 6 months at 21° C (70" F). The adhesive requires no preparation for use, but is melted in suitable equipment and is conveyed to the application site by specially designed hot-melt application equipment, such as heated applicator wheels, reverse rolls, pressure guns, and curtain coaters. The technology of hot-melt adhesive formulation and application is developing rapidly toward faster bonding and higher speed production under the stimulus of antipollution laws and economic incentives.

Hot melts are applied on substrates in molten form at temperatures of 121° C (250° F) to 232° C (450" F). Components must be mated in a matter of a few seconds to obtain optimum bond qualities. The adhesive, being thermoplastic, sets by chilling, which occurs very quickly on the cooler material being bonded. Cold stock chills the adhesive film prematurely and can give poor adhesion. It is desirable, for this reason, to have substrates at room temperature conditions–21° to 32° C (70° to 90° F)–for good bonding results. Generally, adhesive is applied to only one of the two mating surfaces. Pressure is obtained by nip or pressure rolls and is of sufficient duration to permit the bondline to cool and thus develop sufficient cohesive strength. Bonded assemblies can be trimmed immediately if desired.

Hot melts are utilized in modular and mobile homes to install plastic and veneer edge bands to counter or sink tops, to seal and bond roof assemblies, and so forth. Equipment is now available to laminate high-density decorative laminates directly to substrates in factory operations. Hot melts are excellent for obtaining quick spot-weld types of bond while a second but slower curing, more durable adhesive is used to develop a more permanent bond.

Hot melts, being thermoplastic, are prone to creep, lack solvent resistance, and generally do not exhibit good heat resistance above 49° C (120° F), although new polymers are being developed to permit use up to 66° C (150° F) or higher. Open pot temperatures above 205° C (401° F) will usually cause thermal degradation, although in closed applicators or with special formulations somewhat higher temperatures may be used.

Natural Adhesives

Natural adhesives are so called because their principal ingredient is derived from natural sources rather than synthesized chemically. As a group they represent the oldest adhesives known to man; in fact, it has only been since just before World War II that synthetic adhesives have found widespread use. Only the casein adhesives are of importance today in the building construction field, although some discussion is also included on animal adhesives.

Casein Adhesives

Casein adhesives have been used in the United States for many years. They came into prominence during World War I when they were employed extensively in the manufacture of wooden airplanes. These adhesives remained the dominant wood adhesive in this country until the late 1930's when urea-formaldehyde resins were introduced as the first synthetic products.

Casein is a dry-powder, proteinaceous material that is derived from skimmed milk. Most of the raw casein now used in the United States is imported from Argentina, New Zealand, Australia, and Europe; no commercial quantities are now produced domestically. The casein adhesive is prepared by dry blending the raw casein with several alkaline chemicals, and at times with extenders. These ingredients are varied to give compositions designed to do specific bonding jobs.

For example, some are formulated to give quick setting; others are capable of long assembly time: and some less alkaline formulations will minimize or prevent staining on certain woods.

Casein adhesives are normally sold as dry blends. Storage life will be many months at 21° C (70° F) so long as containers or bags are kept tightly closed and the adhesive is not exposed to high humidity or wet conditions. The adhesive mix is prepared by dispersing the powder in water. Normally, one part powder to two parts cool water by weight is the ratio employed. A few minutes after mixing, a typical casein will become thick and, in some instances, unspreadable. At this point the mix is going through a chemical reaction peculiar to casein adhesives. No water should be added for thinning. A stand time, or rest period, of about 15 minutes should be allowed, during which the mix becomes lower in viscosity. Then the adhesive is agitated again for a few minutes, after which it is ready to use. For plant use, conventional mixer equipment is utilized; for onsite use, a small portable mixer or manual mixing in a bucket will be adequate.

Caseins usually possess a working life of from 3 hours to overnight at 21° C (70° F). As a rule, the fast-setting formulations have the shorter pot lives. Some casein mixes do not gel or solidify at the end of their pot life as with thermoset or elastomeric adhesives, but thin noticeably and become watery. When this condition occurs, the mixture is unusable and should be discarded.

Casein adhesive is readily applied to the adherends by conventional equipment in plants and shops, although some timber laminators have adopted an extruder for this purpose.

Casein adhesives are formulated to cure at room temperature as well as at cold-setting bondline temperatures. Many caseins have the ability to bond wood adequately at temperatures as low' as the freezing point of water. Intermediate- or hot-setting bondline temperature conditions do not accelerate the cure rate of casein adhesives significantly, and it is rare that caseins would be utilized under these conditions.

Caseins, like most rigid-curing adhesives, require a pressure-period during the setting process. They can be formulated to cure in from 1 to 16 hours at 21° C (70° F). Where bonding is done onsite, mechanical fasteners are the sole means of holding members together until the adhesive cures. Large assemblies such as trusses should stand at least 24 hours after bonding before trimming and finishing operations.

Casein adhesives provide adequate bonds for many construction purposes. One of their important applications is in bonded structural timber laminates where they are employed along with resorcinols as the two principal adhesives. Their properties of excellent heat resistance (up to 70° C or 158° F) and long assembly-time tolerance (as long as 1-1/2 hours at 21° C or 70° F) make them particularly adaptable for bonding large laminated trusses and beams. In addition, the rigid bondlines provide joint strength comparable to wood itself and are capable of withstanding internal stresses that often develop in such assemblies.

Caseins are also utilized for onsite bonding jobs despite the inconvenience of mix preparation. They readily bond stock in the 12 to 18 percent moisture content range that is characteristic of construction lumber, and can cure at temperatures as low as 0° C (32° F). This low-temperature-setting characteristic may also be used to advantage in plants or shops that find difficulty in maintaining the minimum temperature of 21° C (70° F) which is desirable for many synthetic adhesives. Most caseins also possess good gap-filling properties in joints. This factor can be important in construction work where poor-fitting joints result in bondlines exceeding the normal 0.005-inch thickness.

Casein adhesives find diverse applications in plants where they may be used to bond a variety of assemblies: Plywood box beams, sandwich panel constructions, flat stress-skinned panels, gusset plates on roof trusses, and floor assemblies. High-density plastic laminates and hollow core flush doors likewise are bonded with caseins. Certain formulations possessing good wet tack and fast cure are ideal for assembly bonding. Onsite applications include such items as roof trusses, beams, and floor decking assemblies.

Although the most water-resistant of the natural adhesives, casein adhesives possess only fair water-resistance by modern standards, and should not be used in assemblies that will be exposed to the elements or to conditions where the wood moisture content remains above 16 percent for extended periods of time. Because caseins are proteinaceous matter, they are susceptible to attack by fungi and mold. Many construction formulations incorporate a preservative that protects the bondline somewhat against microorganism attack.

In summary, some of the advantages of casein adhesives are: Excellent adhesive joint strength;

rigid bondlines capable of withstanding internal stresses; ability of bondlines to withstand temperatures up to 70° C (158° F) at moderate relative humidities; setting of the adhesive at bondline temperatures as low as freezing; and good gap-filling characteristics. Disadvantages that can be cited are: Need to prepare the mix for use and to allow "stand time" while it undergoes chemical reaction; need to incorporate a preservative to reduce attack by micro-organisms; and poor resistance to soaking and sustained high relative-humidity conditions.

Animal Adhesives

Animal adhesives are commonly referred to as animal glues or hide glues. Although they are among the oldest adhesives known to man, they no longer enjoy widespread use, having been replaced by synthetic adhesives with superior properties. Nevertheless, they are still preferred by some craftsmen for special bonding jobs. The main constituent in the adhesive is collagen, a proteinaceous material derived principally from hides and bones. Most animal adhesives are sold in a solid form and have to be dispersed in water, then heated in a jacketed kettle at 37.5° to 60° C (100° to 140° F), at which temperature they are applied to the substrate. The adhesive sets hard upon cooling, much like a hot-melt adhesive. The hot, molten adhesive does possess good wet tack and this characteristic leads some craftsmen to still prefer its use for assembly work, as in the furniture industry.

The hardened adhesive gives a strong dry bond. The bondline will weaken, however, if exposed to temperatures over 37.5° C (100° F), high moisture conditions, or water soaking. Consequently, animal glues are confined to interior applications where normal ambient temperatures and normal relative humidities are encountered. Typical bonding applications are for assembling kitchen units, edge bonding lumber, edge banding, and laminating small lumber parts for furniture use.

Adhesives of Secondary Importance

Two other adhesives should also be briefly mentioned because of their importance in the forest products industry, even though they do not lend themselves directly to construction applications. These are the urea-formaldehyde and phenol-formaldehyde resins, both of which are thermoset synthetic products.

Urea-formaldehyde systems find widespread application in the manufacture of products for the building construction field, such as hardwood plywood and particleboard, as well as in furniture manufacture and numerous specialty applications. These resins are one of the most versatile products used in the wood-bonding field. The most popular form is sold as a liquid, although dry powders are also available. Most products require the addition of a catalyst at the time of use, and often the incorporation of suitable fillers and extenders. The adhesive systems are quite economical in cost, and the bondlines can be cured either at room temperature or at higher temperatures, depending on the specific formulation. They are not adaptable for cold-setting cure conditions encountered in onsite bonding jobs; hence their use is confined essentially to plant or shop.

Most assemblies bonded with urea-formaldehyde mixes are intended for interior use because the bondlines are not fully waterproof, only highly water-resistant. Fortification with waterproof adhesives such as melamine-resins will provide a waterproof bondline, but then the adhesive must be cured by heat. Bonded joints can be subjected to stressed conditions where normal ambient temperatures and humidities are encountered. Some bondline degradation can occur under prolonged conditions of high temperature (above 60° C or 140° F) and high relative humidity (above 50 percent).

Another important class of adhesive in the wood-bonding industry is the phenol-formaldehyde resins. These products are used in the production of softwood structural and sheathing plywoods important to the home building industry. Phenolic bondlines are waterproof and are capable of withstanding exposure to the elements. Most phenol-formaldehyde adhesive systems require hot-setting to cure the adhesive. This limitation confines this class of adhesive to closely controlled operating conditions in plants and virtually eliminates its use as an onsite product.

Phenol resins are available in liquid and powder forms. The liquid variety is the most used due to its economy, ease of handling and storage, and versatility in properties. Phenolic bonds are not only waterproof but provide joint strengths as great as the wood itself, thus permitting use in highly stressed bonded joints. Phenol-formaldehyde bondlines are resistant to high temperature and high humidity conditions; likewise, they are

quite impervious to attack by various microorganisms. Despite their being limited to hot-pressing applications, tremendous amounts of phenol-formaldehyde resins are used annually in the production of softwood plywood.

Learning More About Adhesives

This chapter should make clear that a variety of adhesives are commercially available for building construction. It is impossible to cover in detail the properties of the various brand-names now sold. Where more information is desired on a specific formulation, it is suggested the manufacturer be contacted directly or the matter discussed with your local distributor. It is important to follow the manufacturer's directions for using an adhesive. These can be found either on the container label or in separate technical literature.

BACKGROUND MATERIAL

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CHAPTER 6:

EQUIPMENT FOR FABRICATION[9]

Choice of equipment for fabricating with adhesives will directly influence bonding effectiveness and cost. Adhesives may be chosen or rejected for a construction application depending on whether or not inexpensive equipment is available for use with them. Likewise, adhesives that require expensive, complex equipment will not be adopted unless compensating advantages are offered. Equipment should be selected for simplicity, ease of application, ruggedness, and portability. Some or all of the following operations may require equipment: (1) Storing, (2) mixing, (3) pumping, (4) applying, and (5) pressing.

STORING

Storage facilities required for adhesives will depend on the type of adhesive, the volume requirements, shipping costs, and other factors.

For adhesives with a long storage life, large containers may be used. Of course, the larger the purchases, the larger the storage facilities required. Many producers of adhesive-bonded wood products operate tractor-trailer units which may leave their plant with merchandise but would normally come back empty. In such instances, a returning tractor might simply bring back a tank-trailer of adhesive, which could remain in use as a portable bulk-storage facility.

On the other hand, some plants prefer smaller containers to facilitate handling, even though their total volume might justify larger ones. For instance, the location of adhesive usage in the plant may dictate the use of portable containers rather than to pump long distances from a tank truck or central storage. Furthermore, container-packaged adhesives may save on freight charges because they can be conveyed by conventional truck-trailers; freight charges on tank-trailer shipments are higher since no back-haul is possible with them.

The decision of whether to use drum or bulk storage facilities should include consideration of the f.o.b. point, comparative freight rates for bulk and drums, and return freight cost (if portable hulk containers are being considered).

Permanent Storage Systems

Permanent bulk-storage facilities are usually custom fabricated. The dimensions of an internal bulk tank will depend on the head room and floor space available. Placement of the tank on an elevated platform to provide for gravity feed may eliminate the need for a pump. Even though separation may not occur in the adhesive in storage, slow agitation can prevent skin formation when evaporation occurs into the enclosed air space over the liquid. With water-based adhesives, skin formation can be reduced by saturating the incoming air with water vapor. A bypass should be provided to permit the escape of air when the tank is being filled.

The tank should have a drain at the bottom and a manhole at the top to facilitate cleaning. A liquid-level gage may be needed although some fiberglass tanks have enough translucency to see the liquid level through the tank. In this case, the

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side of the tank should be calibrated in gallons with indicator marks.

The permanent storage tank should exceed the expected tank truck deliveries by 10 to 20 percent to allow for variation in delivery schedules. Normally, 3,000- or 4,000-gallon total capacity trucks are available. Tank trucks are available with one or more compartments. A compartmented tank truck can deliver several different adhesives to one plant or the same adhesive to several plants in the same vicinity.

Portable Storage Systems

Portable bulk liquid storage tanks are essentially of three kinds-fiberglass, metal, and rubber. The metal and fiberglass ones are normally fitted with a manhole in the top and a 2-inch bung at the bottom. For shipping, a plug is put in the bung. After attaching a full opening 2-inch valve, the plug can be cut out and removed. Available tank sizes are approximately 250 and 500 gallons.

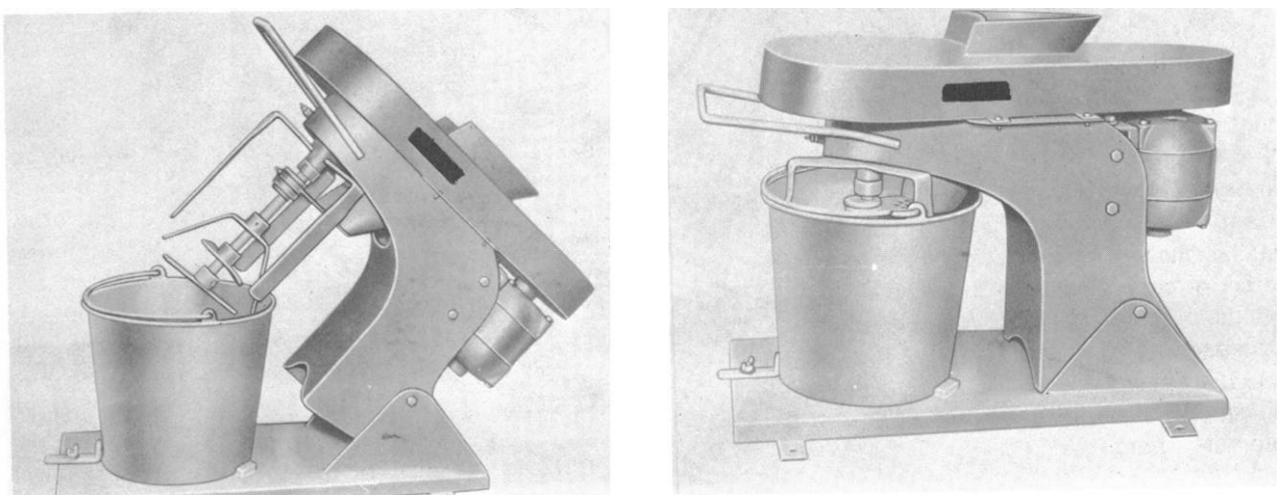
Collapsible rubber containers are available in 55- , 375- , 500- , and 1,000-gallon sizes. When empty, they can be collapsed and rolled up. For example, a filled cylindrical 500-gallon container is 48 inches in diameter by 89 inches long but collapses to 36 by 72 by 9 inches. The use of these containers allows a company truck to haul merchandise one way with a small space devoted to empty tanks and then return to its plant filled with adhesive. Each container can hold a different adhesive, or the whole truckload can be the same adhesive. Before shipping solvent-based adhesives in rubber tanks, a test should be made to determine if the rubber of the container reacts with the ingredients of the adhesive.

Pressure tanks, such as used in finishing systems, can be used to supply extrusion, spray, and other application units. These tanks are portable and do not require a pump to use in the distribution system. For large volumes, this is not as feasible as pumping directly from the drum.

MIXING

Mixing an adhesive may be required to correct a separation on storage or to incorporate a catalyst, solvent, or reactant. Many adhesives are formulated with a number of ingredients dispersed in the liquid. When these materials are dispersed rather than dissolved, there is the possibility of separation. Therefore, before use, simple mixing should be performed. This mixing may be done in several ways with drum-stored adhesives: (1) by removing the head of the drum and stirring mechanically, (2) by rolling the drum across the floor, or (3) by placing the drum on a roller for a period of time.

When adding catalyst, it is important that all of it be mixed uniformly throughout the resin. Motorized mixers are made specifically to mix resins and catalysts (fig. 38). They are suitable for mixing most adhesives having a viscosity not exceeding 10,000 centipoises and having a working life of at least 15 minutes. Some catalyst additions blend readily and may be stirred into the resin with paddles, by hand. Mixing can be done



M 139 449

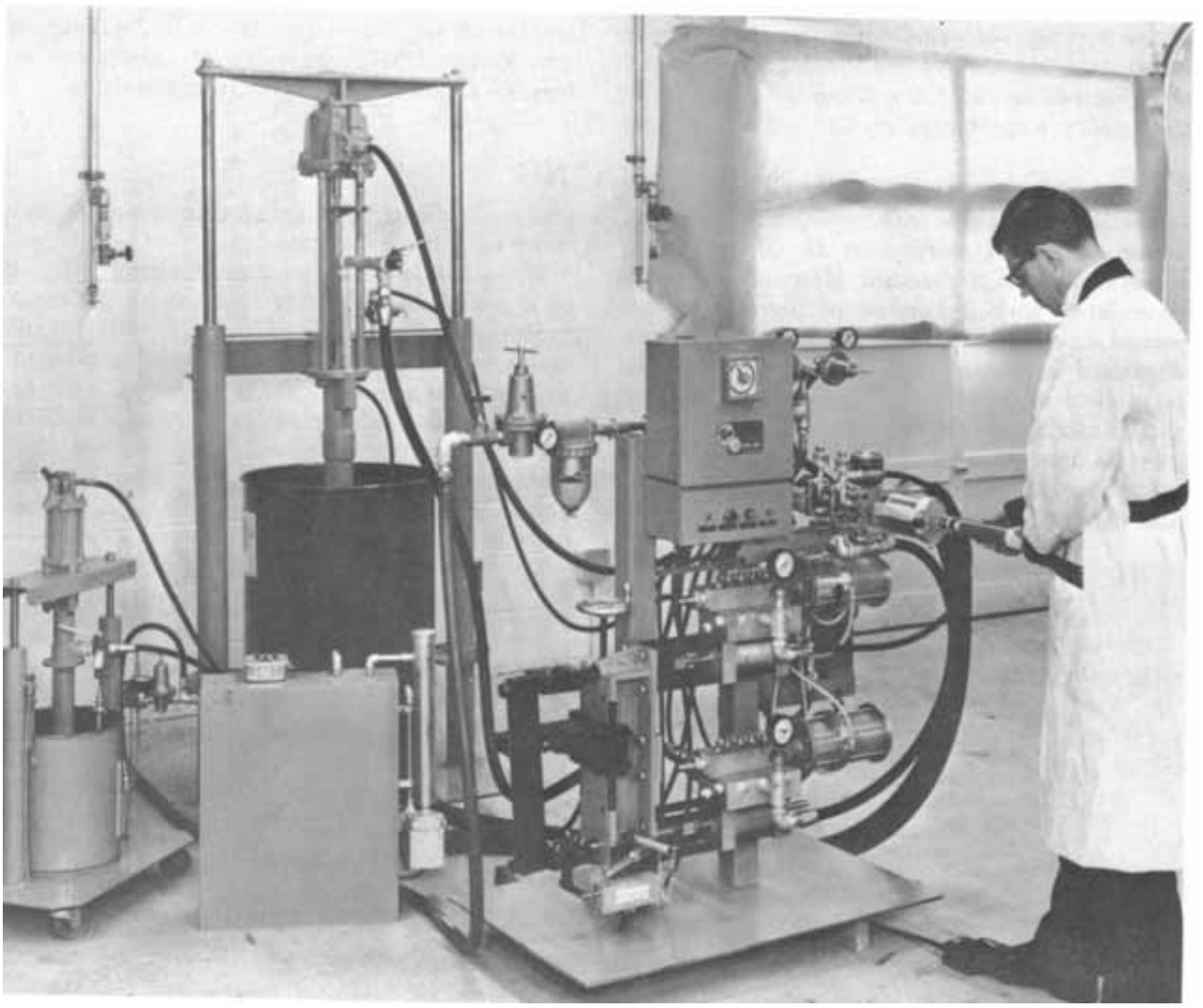
Figure 38. –Mixer for blending adhesive components in a container, which in turn is carried to a spreader or work site.

in a bucket, which can be used to carry the resin to the point of application. Whatever the additive, a sifter should be available to break up lumps of dry material before addition to liquids, thus preventing lumping in the mixture as with casein adhesives.

Automatic metering and mixing equipment (fig. 39) is desirable for mixing adhesives with a working life of from seconds to 15 minutes. The heads on these devices open readily for cleaning (fig. 40). In addition. an automatic flushing device is incorporated to prevent the resin from setting in the head. Very short-life materials in the head must be flushed very frequently. The two adhesive components are fed into the head separately and mixed just prior to being extruded. A proportioning device is used with the head to give the proper proportion for the two materials to he mixed. Another type of mixing head, the static mixer (fig. 41), has no moving parts and mixes the two components as they combine and pass through a tube filled with baffles.

PUMPING

Adhesives can be dispensed from drums by either gravity flow or pump. A number of manufacturers make air pumps which will fit into the 2-inch bung in the head of a drum. Sometimes



M 139 451

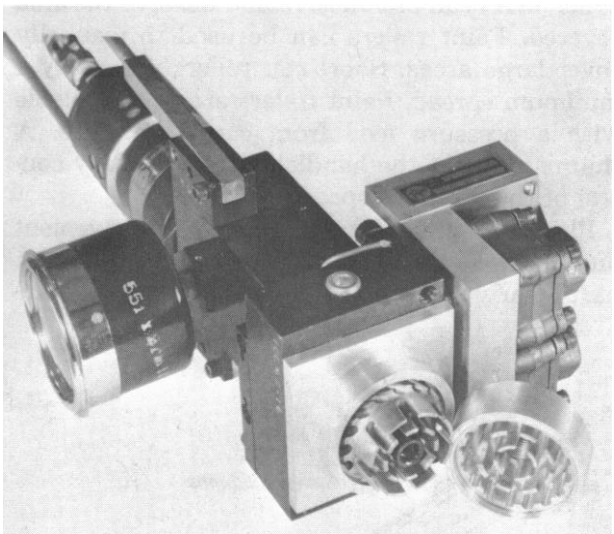
Figure 39.–Automatic metering and mixing equipment for two-part rapid-reacting adhesive systems.

these are combined with an agitator in an airtight head. By choosing a suitable ratio of air pressure to desired fluid-line pressure, liquid with viscosities up to several hundred thousand poises can be pumped. For mastics, a follower plate needs to be used to decrease evaporation and prevent cavitation.

Certain adhesives will not withstand high mechanical shear. There are a number of pumps which can be used with these mechanically sensitive materials. Among these are the air pumps mentioned above.

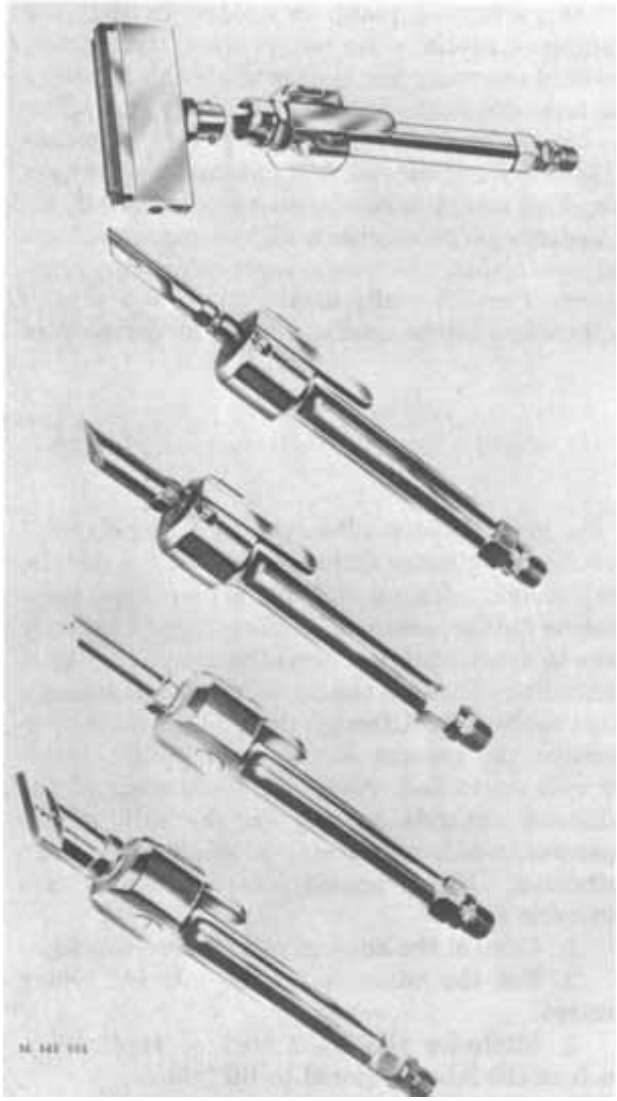
A positive screw conveyor pump for liquids is self-priming up to 28 feet of lift on the suction side. It will handle high viscosity liquids or mastics. Delivery is proportional to speed. Because of the screw action, there is no pulsation of flow.

A positive rotary pump can handle a wide variety of viscosities with no pulsation. Because it is a positive displacement pump, a pressure relief



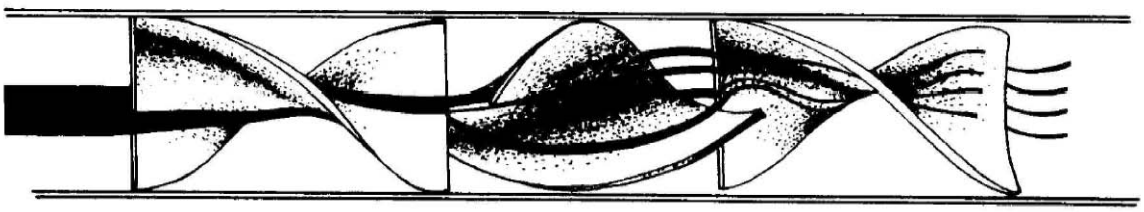
M 141 913

Figure 40.–Open mixing head for automatic metering and mixing equipment.



M 141 551

Figure 42.–Adhesive applicators with special tips control placement of adhesives as a continuous ribbon or as a bead to bottoms or sides of grooves, on adjoining shoulders, on narrow flat surfaces, or in corners.



M 141 869

Figure 41.–Material flow through static mixing head. The material. extruded from the left, is alternately split and rotated by the baffles for thorough blending.

valve should be provided if there is any possibility of flow stoppage.

The peristaltic pump is unique in that the pumped material does not contact the moving parts of the pump (except for the hose). The flexible hose material available is the only restriction on the solvent, abrasive, or corrosive materials which may be pumped. Mechanical shear is very low. This design tends to give a pulsating flow.

Centrifugal pumps have slightly more mechanical shear than the other types of pumps mentioned. They normally handle only low viscosity liquids. and can be used when only moderate head pressure is encountered. Centrifugal pumps provide a steady flow, and can be made of a wide variety of materials to accommodate corrosive or abrasive adhesives.

Gear pumps can be used with mechanically stable materials. They provide a steady flow of material. They are inexpensive, rugged, and provide positive displacement. They can handle low to high viscosity materials. A bypass with a pressure relief valve should be provided if there is any possibility of constriction or stoppage of flow.

APPLYING

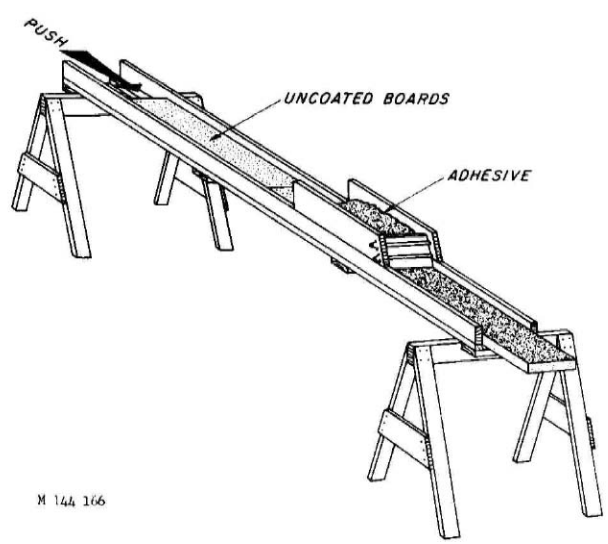
For low-viscosity adhesives such as polyvinyl acetates, applicator and spreader devices may be very simple. Many mobile home plants use polyethlene bottles, pressure oil cans, mops, or simply cans to apply a bead or film of adhesive. A plastic sprinkling can (with the nozzle removed) makes a good applicator. Although this equipment is inexpensive, the amount of adhesive applied cannot be well controlled. Also, the positioning of the adhesive depends entirely on the skill of the operator, which may result in skips or too little adhesive. More sophisticated devices are desirable to:

1. Control the amount of adhesive spread.
2. Put the adhesive on the member where desired.
3. Minimize the labor cost of application, such as the labor required to fill bottles.

Pressurizing the system-using an air pump to move adhesive through a piping system to the job-will reduce labor cost and also make it possible to attach an applicator head to attain the other goals mentioned above. Such an applicator head can apply five beads of adhesive to a 1-1/2-inch stud at a controlled rate (regulated by air pressure) with a guide at the side of the head to position it on the stud. Different types of heads are available. Some are equipped with rollers to spread the adhesive. Others are contoured to fit shaped surfaces (fig. 42). Some finger joint applicators use such a pressurized spreader with a head that mates with the fingers and has holes in the head to apply the adhesive. The wood fingers trip a valve as they pass this head and thus receive the adhesive.

Manual application of adhesive may be adequate in many situations. To visually determine the adequacy of the adhesive spread, press a panel on a bead of adhesive and observe the area covered. Paint rollers can be used to manually cover large areas. Short-nap rollers will apply a minimum spread. Paint rollers are also available with a pressure feed from central storage A thumb valve in the handles allows for easy control of the adhesive spread.

Plastic (polyethylene) bottles are a convenient and inexpensive means of applying adhesives, particularly those which are water based. The sol-



M 144 166

Figure 43.–Push-box for applying mastic to styrofoam insulation and similar materials.

vent in solvent-based adhesives may soften the bottles or diffuse through the walls, thereby changing in composition. The bottles come in a wide variety of shapes, sizes, and mouth openings. Various shaped tips are also available. Because the plastic tips wear out faster than the bottles, metal tips which allow accurate control of placement and volume of adhesive can be used.

Pressure oil cans are often useful for accurate control of placement and volume of adhesive. By shaping the end of the spout, the bead shape can be controlled. By flattening the end of the spout, soldering the end, and drilling holes in the side, adhesive can be applied to the interior walls of a groove. These cans are not suitable for high viscosity, acidic adhesives, or those with a short working life.

When rigid insulation, styrofoam, urethane, or similar material is installed onsite, a simple mastic coater called a push-box is often used (fig. 43). The site mechanic can quickly fabricate a push-box using available materials. The rigid sheet materials are pushed under a reservoir of adhesive located at the midpoint of the trough. A free-floating scraper blade removes all but a thin film of adhesive as the materials pass out of the spreader. Materials must be passed through continuously; when not in use a "blank" board is left in place to prevent loss of adhesive.

Because of the high viscosity of most adhesives, applicator brushes should have stiff bristles to control the adhesive spread. Pressurized brushes with a thumb valve are available for use with a pressurized system. Brushes are particularly well adapted to spreading adhesives on contoured or irregularly shaped surfaces. Trowels are suitable for spreading mastics over large areas, such as floors. They come with a wide variety of serrations in order to control the spread. The manufacturer of the mastic will often suggest the appropriate trowel to use for a particular application. High-viscosity materials, such as mastics, may be spread by trowels or paint rollers as in the spreading of linoleum paste.

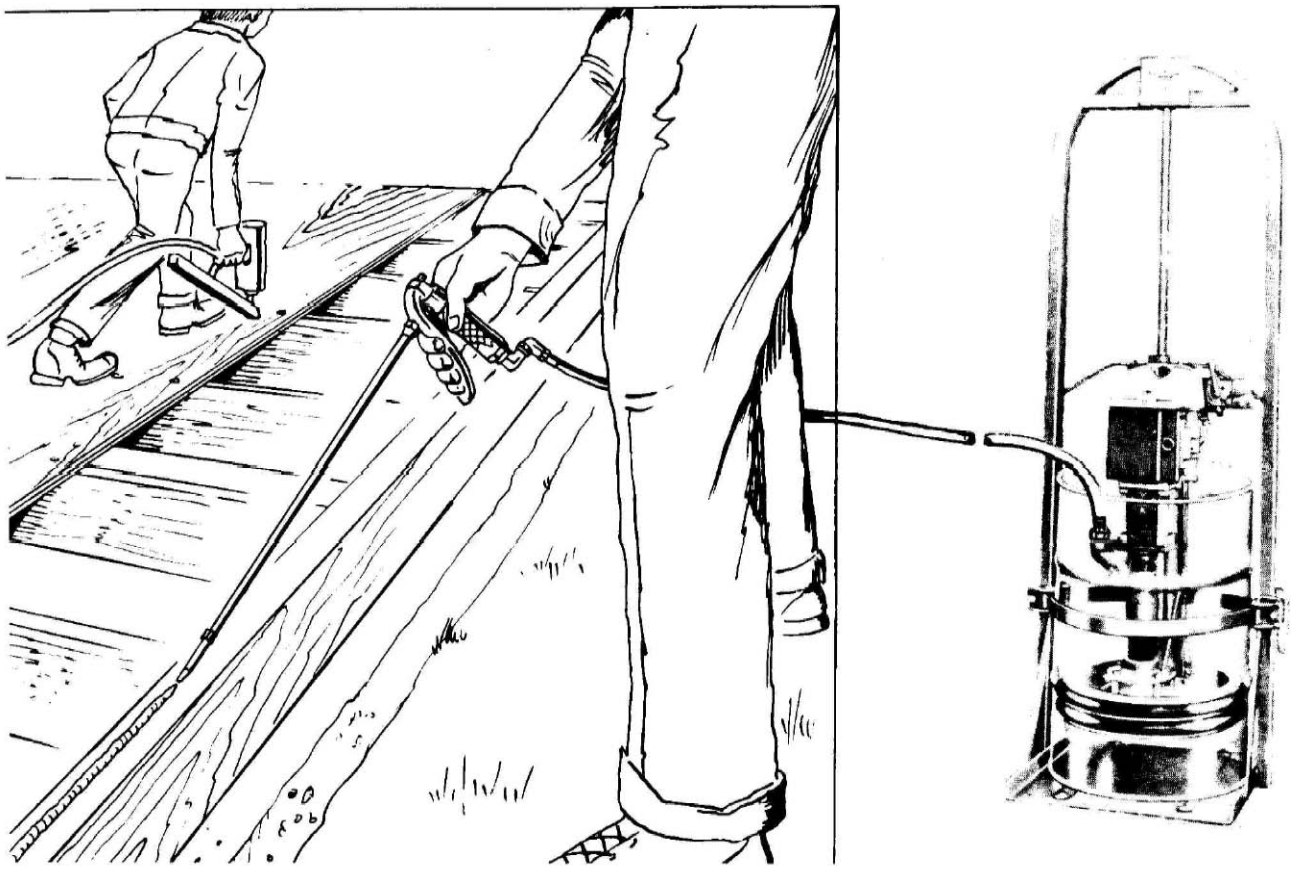
Many mastics are available in cartridges. Application may be made from a hand-operated calking gun (usually ratchet-operated). For larger production work. air-operated guns are available to apply a steady bead of adhesive. These are self-contained except that they need to be attached to an air pressure source. This could be an air line or a pressure cylinder because consumption of air by the guns is minimal.

Both hand- and air-operated guns for mastics are available which are bulk loading. Bulk-loading handguns are frequently reloaded from 5-gallon or smaller buckets. The air-operated variety (fig. 44) are equipped with a Venturi valve which supplies a vacuum to the air line for rapid reloading. Conditions such as degree of vacuum and viscosity of adhesive will regulate the speed of filling quart guns, but it is a matter of seconds usually, not minutes.

Pumping systems can be used for pressurizing guns fed from bulk containers (fig. 45). The viscosity of the mastic, the size of the hoses, the

M 141 553

Figure 44.–An air-operated bulk-loading gun for mastics can be loaded by removing the tip and attaching the barrel to a follower plate in the pail.



M 90877

Figure 45.–Special heavy-duty pumps may be used to dispense mastics.

distance to be pumped, the volume to be pumped, all influence the design of the system. The size and shape of the bead can be regulated by the orifice and the pressure in the fluid line.

The most common method of spreading adhesive for laminated timber is by use of the "extruder" which applies the adhesive in closely spaced narrow strips on only one face of the member (fig. 46) Such spreading permits handling the individual laminates without removing the adhesive. Also, the allowable assembly time may be somewhat longer than is obtained with roller spreading. Assembly time is usually based on a partial open condition where individual laminates are not in contact during the entire assembly period.

Hot-melt adhesives find many applications where very brief setting time is an advantage. Hot-melts are often applied by automated extruders (fig. 46) in plant-bonding operations. Portable hot-melt guns are also available which make possible rapid bonding of assemblies.

Mechanical Spreaders

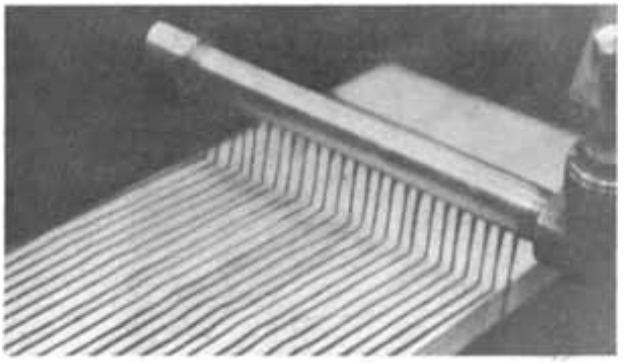
Mechanical adhesive spreaders, such as roller spreaders, usually reduce the labor cost over manual devices. Flat surfaces can be spread by either one-roll or two-roll spreaders. A double-roll spreader can spread two flat surfaces at one pass. This can be two faces of a core or one face of each of two cores. Each of the two spreader rolls is serviced by a doctor roll. The adhesive is held in the nip between spreader and doctor rolls (fig. 47).

Single-roll spreaders may be constructed with (1) a doctor roll with adhesive held in the nip (bobtail) between doctor and spreader rolls, or (2) a single roll which dips into a tank of adhesive. The bobtail type with adhesive retained in the nip is essentially one-half of a double-roll spreader.

The simple dip-type roll uses either a scraper blade or a small roll pressed against the larger to control the spread. Covering this roll with a thick wool felt (1) allows a closer control of the amount of adhesive applied and (2) provides a more

uniform spread in spite of any slight unevenness in the surface being spread. These wool, seamless felts can be positioned by sliding over the end of the roll. When soaked in hot water, they will shrink up to 20 percent in circumference. For spreading tongues or grooves, a short nap fabric, shrunk on the roll, will coat adhesive over the complete tongue or groove. Only a tightly woven fabric with bound ends and edges should be used. In contrast to the felt, a wool fabric sleeve will shrink very little and, therefore, must be made very little larger than the roll being covered.

Contoured metal rolls can be made to spread adhesive on shaped pieces, such as moldings. The scraper must be shaped to fit the roller contour in order to be effective in controlling the spread. Although most rollers are designed to spread adhesive on horizontal substrates, rollers for vertical applications are available. Higher viscosity adhesives will climb a vertical roll if the doctor blade follows the contour of the roll upward in the direction of rotation, as a helix. Another type of roller for spreading vertical surfaces consists of a cone (often truncated) whose axis is 45° to both the surface of the adhesive and the edge of the substrate. The horizontal face of the cone dips into the adhesive while the vertical face applies it to the vertical face of the substrate.



M 138 390

Figure 46.–Extruder applicator applies beads of adhesive to a lumber substrate.

The specification on the grooving of rubber-covered spreader rolls is dependent on the adhesive, the weight of spread to be used, and the substrate. When spreading adhesive onto flexible materials a buttress thread is desirable on the spreader roll (fig. 48). Because of its configuration, it will "lay over" when pressure is applied between the roll and the stock being bonded. This squeezes the adhesive from between the threads.

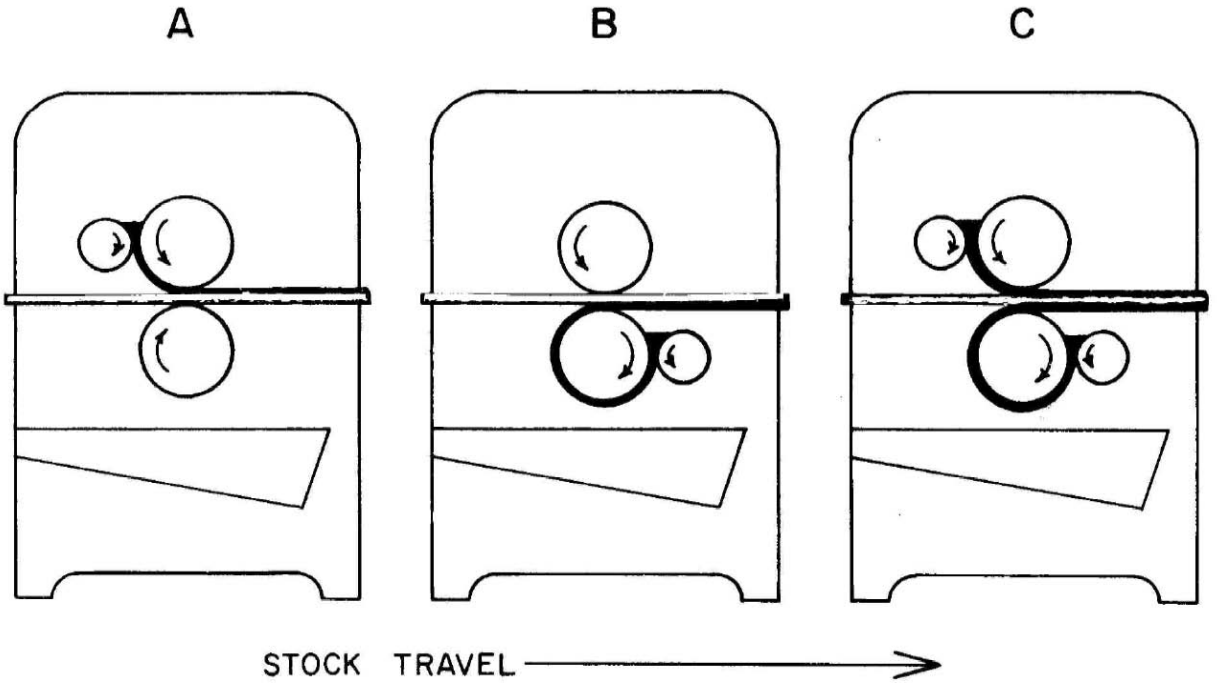


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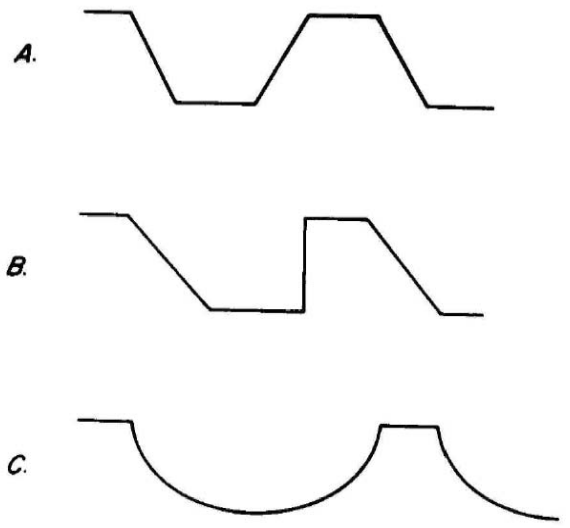
Figure 47.–Roller arrangements in three kinds of mechanical adhesive spreader: A. single-roll spreader for top spread; *B*, single roll spreader for bottom spread: C. double-roll spreader.



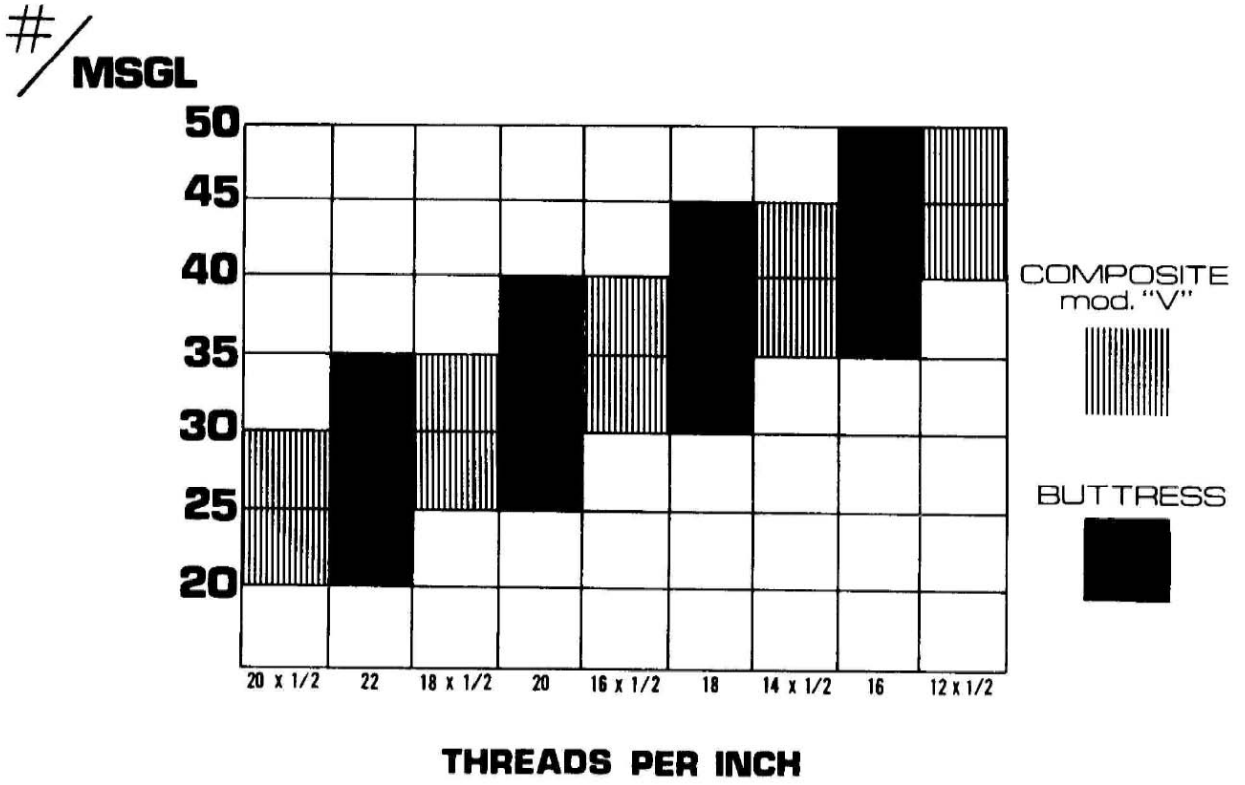
M 141 759

Figure 48.–Profiles of typical grooves on spreader rolls. *A*, acme, composite or modified "V": *B*, buttress: *C*, "U".

As the roll leaves the stock, the thread will stand upright and in so doing will spread a uniform and even adhesive film. On stiffer materials-like particleboard, lumber, or plywood, such as found in flush doors and countertops-a much stiffer roll grooving may be desirable. A pattern such as composite grooving will compress the rubber slightly rather than distort the grooving when substrates varying in thickness are run through the spreader. This reaction will yield a more consistent spread with less variation in thickness than will the buttress thread.

Approximate spreads which will be obtained with different thread densities are shown in figure 49. By choosing a grooving that will deposit a slightly greater spread than is desirable, the required spread will still be obtainable when wear occurs. The spread with a given grooving is dependent on the viscosity of the adhesive. Using a higher viscosity adhesive will decrease the spread, because less liquid adhesive will transfer to the substrate.

Spreaders can be equipped with pumping systems to supply adhesive semiautomatically from



M 139 452

Figure 49.–Adhesive transfer to stock as affected by configuration and frequency of the grooves. (Spread rate in pounds per 1,000 square feet of single bondline.)

a drum or central reservoir. Recirculating pumps are also available to keep the adhesive homageneous. For adhesives with a limited working life, water-cooled doctor rolls are available. In some cases, as when applying contact cement to both core and face or back, a two-position sensing device is available which will automatically adjust to the proper substrate thickness. A typical two-roll spreader for solvent-base contact cement is manufactured with an automatic two-position roll adjustment, hooded exhaust system, recirculating pump, and viscosity-indicating device.

Surfaces should be dustfree before spreading thin face materials. Dust can be removed by a rotating brush attached to a suction system.

Portable Roller Spreaders

Portable roller spreaders are available for applying adhesive in narrow widths to horizontal surfaces such as joists (fig. 50). The adhesive flows by gravity from a reservoir through an adjustable width slit onto a spreading wheel.

SPRAY APPLICATION

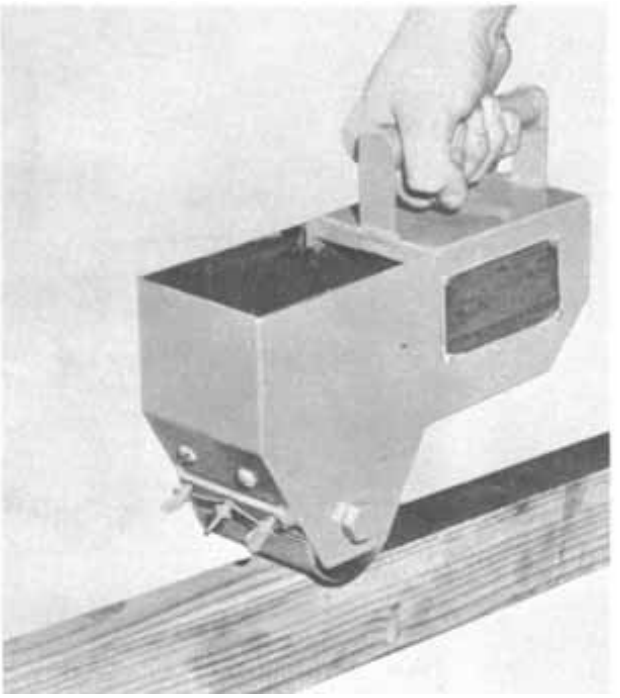
Spraying atomizes the adhesive into tiny drop lets before depositing it on the surface. Although most adhesives which do not contain lumps or large suspended particles can be sprayed, contact cement is probably the most commonly sprayed adhesive used in the construction industry. Regardless of the type of spray equipment used, the droplets of solvent-based contact cement are deposited as small dots which form a webbed or fragmented flecked surface. On the other hand, water-base contact cement yields a smooth homogeneous surface as would a lacquer.

Spray coating equipment is most useful for applying adhesives to varied types of substrates, and particularly those that vary in thickness or contour. This portable equipment can be moved to the object. With manual operation. retouching is simple and the edges of tops are easily coated. Manual equipment is less expensive than some automatic or semiautomatic systems. Disadvantages of spraying include a poorer pattern with solvent-based cements than with water-based, slower application than with roll or curtain coating. and dependence on the ability of the operator. Adhesive spray systems can be classified as air atomization systems, either syphon or pressure type, or as airless systems. Both types can be used with heaters to decrease drying time and may also be used in automatic equipment. In air systems there is more waste and less uniform spread than with airless spraying.

Air Atomization

With air atomization, the adhesive is either forced or sucked out of a fluid line where it is atomized by the impingement of two or more fine streams of air. The atomization is affected by the relative flow rates of air and adhesive, the number of jets and direction of the air, and the viscosity and surface tension of the adhesive.

A spray nozzle consists of two parts: Fluid nozzle and air nozzle, sometimes referred to as fluid tip and air cap. The air nozzle atomizes the fluid stream from the fluid nozzle into a fine spray. Nozzle orifices are available from 0.022 to 0.500 of an inch in diameter. Size of the orifice needed for a given job is determined by the viscosity of the adhesive being sprayed and the amount of flow needed to meet a given rate of production, In general, au orifice diameter of 0.022-0.028 is used



M 139 432

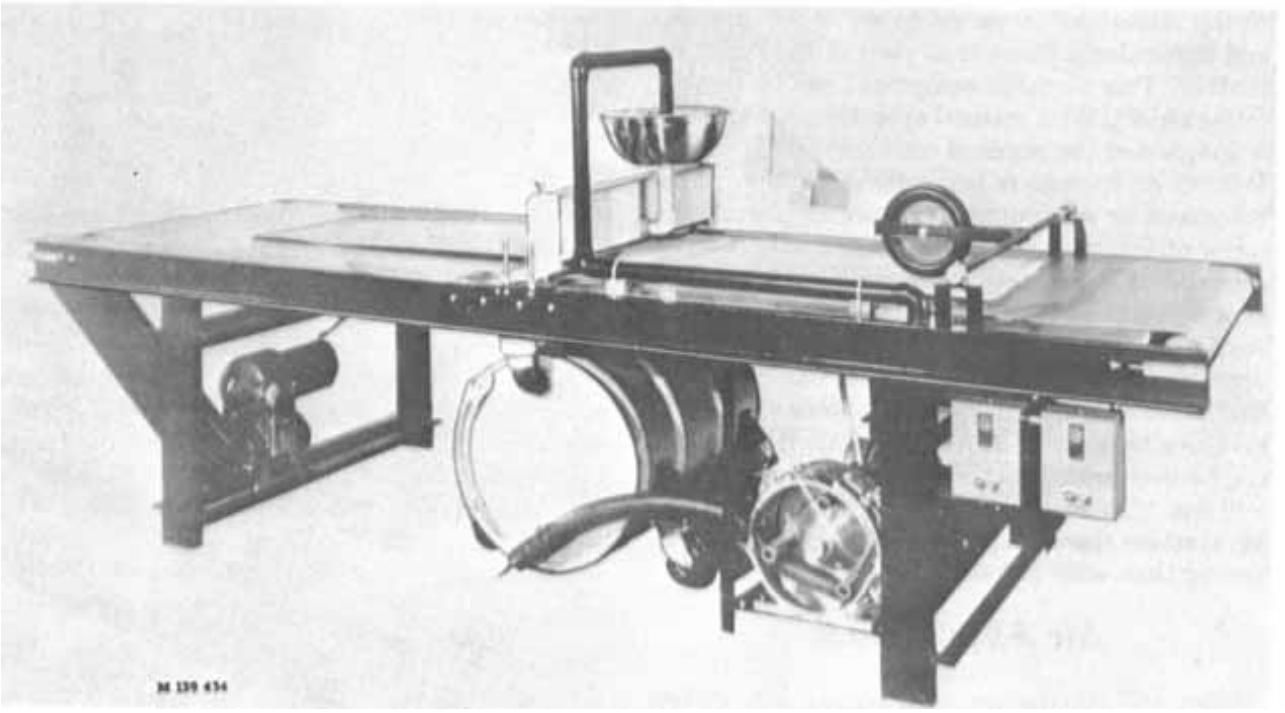
Figure 50.–Portable spreader applies adhesives to installed joists or to wall framing before erection

for thin viscosity fluids and of 0.059-0.070 inch for medium viscosity fluids. For example, with a fluid of a medium viscosity, orifice ranges of 0.028- to 0.040-inch diameter will normally deliver 2 to 6 ounces per minute.

It is frequently more satisfactory to use a multigun setup to achieve higher rates of application than to use a larger fluid nozzle. Viscosity can be decreased by heating the adhesive or reducing the viscosity by suitable solvents. Either method will increase the delivery rate. The heating also speeds the drying rate and, consequently, the production rate. Solvent dilution decreases the solids content as well as the viscosity and, therefore, may increase the amount of adhesive delivered to the substrate very little. If too much adhesive is being ejected for the desired atomization, it can be controlled by: (a) the fluid control knob, (b) pressure in the fluid line, and (c) the orifice size of the fluid nozzle. Another approach may be to increase the air cap pressure, if possible, to get better atomization of the fluid. Pressures greater than 18 pounds per square inch are usually not desirable as the adhesive comes from the gun at too high a velocity. A large volume of air supply is required for air atomization guns.

Using a spray gun properly will not only produce a better coating but also save considerable adhesive. The body of the spray gun should be held perpendicular to the surface as nearly as possible and drawn across the surface at a uniform rate and distance from the substrate. Tilting the gun from the perpendicular will cause the contact cement to bounce from the surface and be wasted. Arcing the gun instead of holding it at a uniform distance from the surface, will vary the coating weight inversely to the distance of the gun from the surface. Swaths across the surface should overlap to prevent undercoating areas and to compensate for any unevenness in the uniformity of the spray pattern. The swath should be started beyond the end of the panel; the gun should be triggered just before coming to the panel so that the gun is spraying when it starts across the substrate.

Sometimes an extra pass is given to the edge, if the coating weight in the center has been light. to insure that a good bond results at the edge. Thirty pounds per thousand square feet should be the minimum spread for quality work with solvent-based contact cement containing 18 percent solids. This minimum will vary inversely with the percentage of solids.



M 139 434

Figure 51.–Curtain coater with pump transfers contact adhesive from drum to overhead reservoir at the center, where it is extruded as a curtain on the high-pressure laminate.

Airless Spray

With an airless spray, atomization occurs by the sudden release of pressure as the pressurized cement goes through a fine nozzle and encounters the ambient ah. The extremely high fluid pressure required may vary from several hundred to thousands of pounds per square inch. It can be compared to the spray from a water hose. No air is required in the atomization. (An air jet may be available on the gun to clear dust from the surface before coating.)

Some of the advantages of an airless spray include:

1. Reduction of overspray. No air is carried with the cement to bounce it off the surface. This reduces over-spray on both the substrate and the booth.

2. Saving of makeup air. Because no air is going through the gun, no demands are made on the air compressor except for the small amount on the pump to supply the pressure. This may be important in a plant in which the available pressurized-air supply is already overtaxed.

Heating the contact cement, with both air and airless systems, is effective in reducing viscosity for better atomization and, also, in reducing the drying time. Such a setup can easily cut the dry ing time in half with a minimal investment, making possible a more efficient work flow. However, water-base contact cements are relatively unaffected by heating before spraying.

The hose material for water-base and solvent-base systems may be different. Before shifting from one type of adhesive to another, hoses should be checked to make sure they are suitable for the particular cement being used.

Most air-spray guns are equipped so that partial pressure on the trigger releases air only, for cleaning the surface to be sprayed.

CURTAIN COATING

In a curtain coater, the material to be coated passes through a falling curtain of adhesive. Normally, one belt brings the substrate up to the curtain, while a belt, traveling at the same speed as the first belt, picks up the coated piece just beyond the curtain and carries it away, possibly to the next operation on the production line. Between the belts is a gap where the curtain of adhesive falls into a collector, or trough, for return to a reservoir. From there, it is recirculated to the manifold from which the curtain falls.

There are two types of curtain coalers. In one the liquid is pumped into an unpressurized reservoir and, after passing several distributors (frequently dams of various shapes, positions, and sizes) to make the flow uniform, the adhesive passes over a weir by gravity to form a curtain. In the other (fig. 51). the adhesive is pumped into an overhead closed reservoir (usually pressurized) and extruded through a variable-width slot in the bottom. The flow can be regulated by varying this slot width. With this type of curtain coater, any floating foreign materials or foam will collect on the surface and have less tendency to flow into and break the curtain.

With either type, foreign objects mixed with the adhesive will interfere with proper operation. It is extremely important with any system to use a screen between the trough and the pump to remove these particles. Deposited film weight can be increased by increased pump speed or slower conveyor belt speed. No adjustment is needed to adjust to different widths, thicknesses, or simple contour difference. By tilting the belts, the leading **edge** can be coated as well as one side edge. Very high speeds (several hundred feet per minute) are easily obtainable. A brush cleaner can be mounted just ahead of the curtain to remove any dust.

Some precautions should be taken with certain materials when using a curtain coater. With some fragile latexes, pumps with low shear should be used. These might include positive screw conveyor pumps, positive rotary pumps. or peristaltic pumps. With some adhesives, a centrifugal pump is satisfactory. Excessive agitation in contact with air should be avoided with materials which foam easily. Foam can cause defects in the curtain. Piping lines should not leak air at joints or packings. Undue turbulence should be avoided in the receiving trough and the reservoir. Curtain breaks will cause skips on the coated piece.

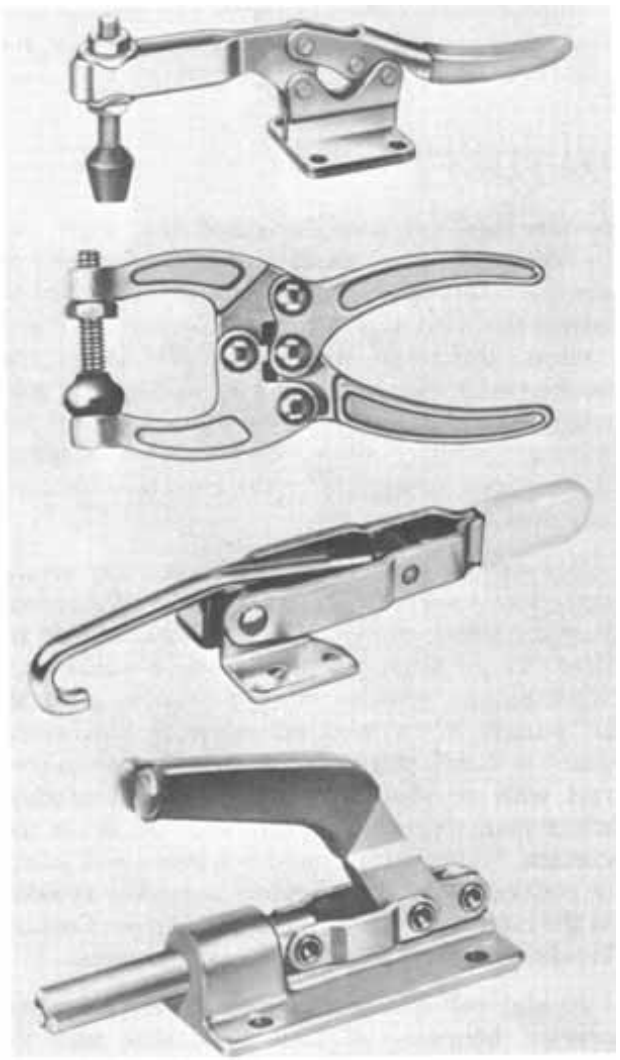
At high belt speeds a device needs to be used to prevent bouncing of thin substrates such as laminated backing sheets when going through the curtain. Such bouncing will cause skips or uneven coating weights.

PRESSING

The purpose of pressure is to bring the parts snugly together after the adhesive is applied and to hold them until the adhesive has attained adequate strength. Generally the thinner bondline makes the stronger joint. However, excessive pressure may force too much of the adhesive from the joint, reducing the strength. Sometimes allowable pressure is limited by the danger of telegraphing of the substrate or marring its surface if a wide variety of pressing equipment is available.

Manual Edger or Assembly Clamps

Small, lightweight assembly clamps (fig. 52), sometimes called eccentric mechanical or toggle clamps, are usually mounted in a fixture. This fixture may be stationary, or on a merry-go-round to pass in front of the operator. Pressure can be applied in three different directions by suitably mounting the clamps.



M 141 554

Figure 52.–Toggle clamps are designed to apply pressure in different ways.

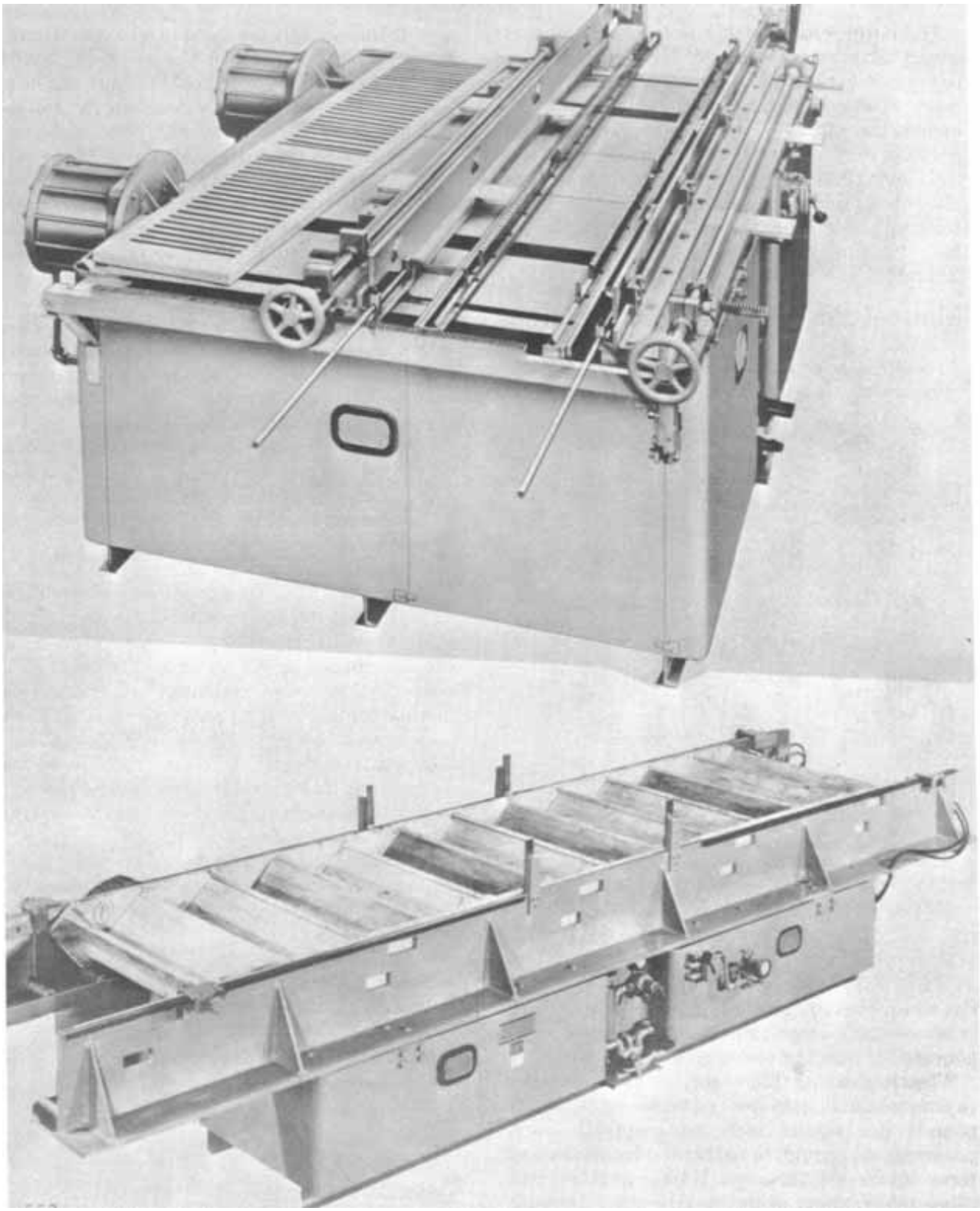
Air-operated clamps are available in the same sizes as the manual ones. These have the advantage of being faster to close, of permitting more latitude in dimensions for the piece being bonded. and of easily regulating the amount of pressure applied so long as the air pressure is continuous and uniform (fig. 53). Various designs of C-clamps are available (fig. 54). Bar clamps (fig. 55) apply side pressures on panels. For the manufacture of beams, mechanical devices such as a chain clamp may be used. A band clamp (fig. 56) can apply pressure to odd-shaped pieces.

Clamp carriers are often used for rapid production of panels or posts (fig. 57). These consist of sets of bar clamps of appropriate design mounted on an endless chain or belt, or radially on a huh. The rotation of sections may be manual or powered. These clamp carriers may be equipped with an air holddown to flatten the panel before application of edge pressure. The operator activates an overhead air cylinder to apply pressure on a bar. pressing panel tightly against the back of the clamp before edge pressure is applied. This method provides a flat panel with no pounding into position by hammering. The cylinder is mounted on an overhead track to be used with each clamp. The overhead track can be sloped so that on release of the air cylinder it rolls out of the way.

The use of impact wrenches on a clamp carrier will speed the operation and insure uniformity of clamping pressure, regardless of the operator. These wrenches can also be used to advantage in tightening various single clamps. The attachment of heavy beams (either wood or metal) to the clamps of a carrier will distribute the pressure more evenly, when thin lumber, such as 4/4 lumber face-bonded for posts, is clamped.

Flat or Laminating Presses

A number of pressing devices have been developed for laminating flat sheet materials, such as bonding thin plastic sheets or veneers to thick,



M 141 552

Figure 53.–Assembly clamps: Top–applies edge pressure with holddowns to make louvered doors: bottom-far assembling stairs.

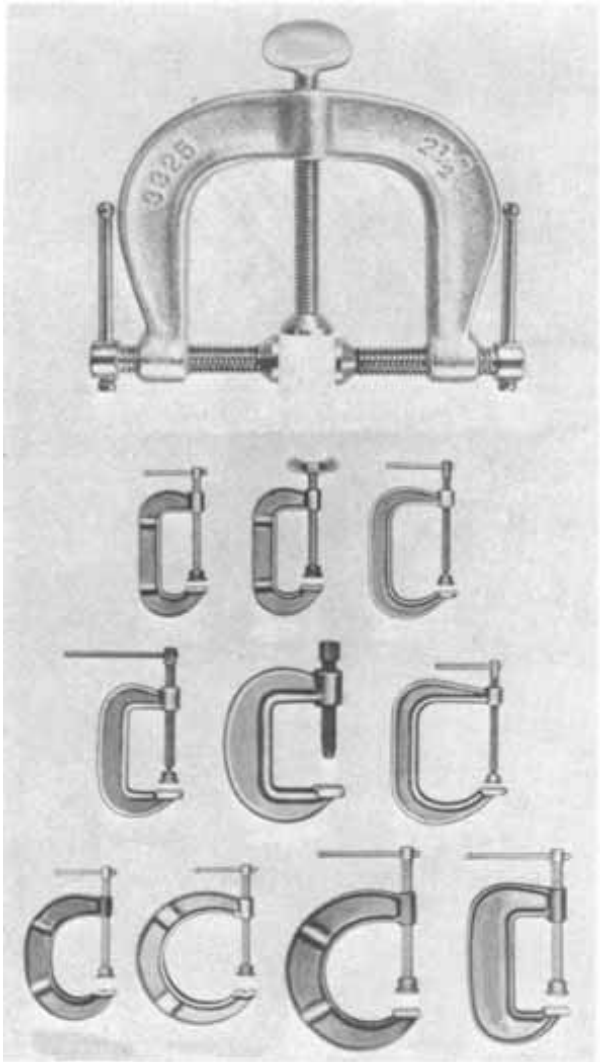


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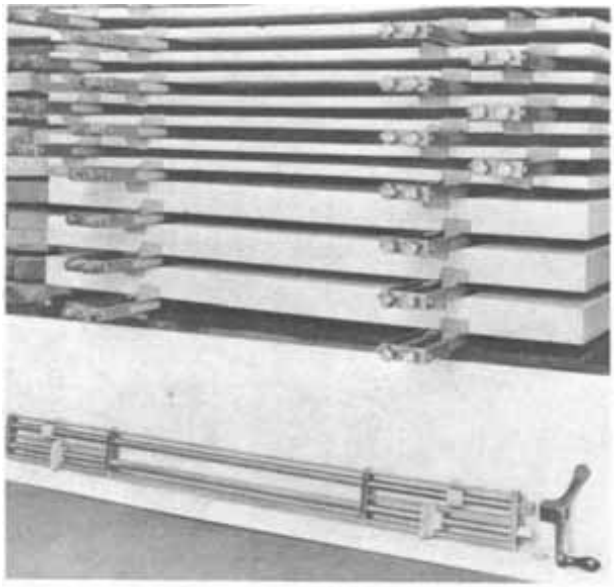
Figure 54.–C-clamps are made in a variety of sizes and configurations for different purposes.



M 139 457

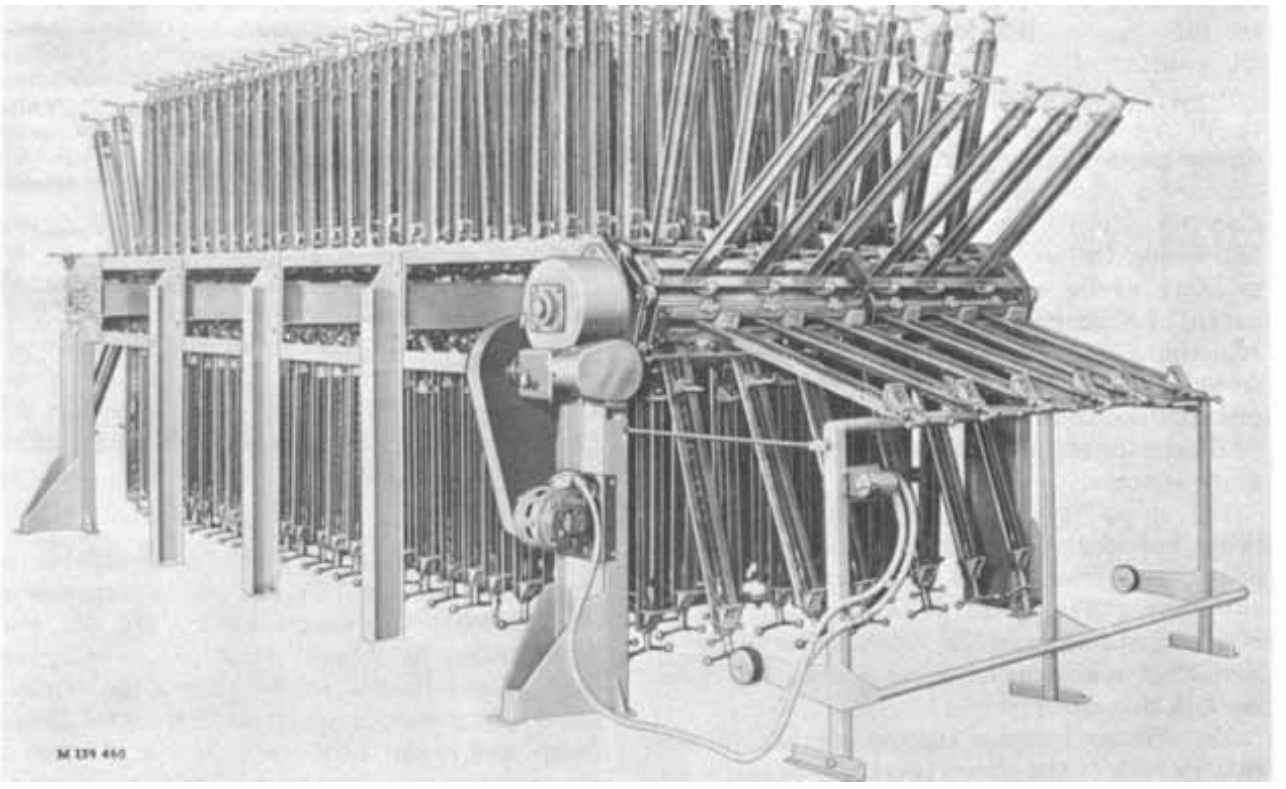
Figure 55.–An integrated stack of drying. adhesive-bonded panels is being held in double-bar clamps. The clamp itself is shown at bottom.

M 139 440

Figure 56.–Band clamps apply pressure to odd-shaped assemblies.

flat cores. This equipment is of interest because it is occasionally employed in bonding panel components for building construction.

When laminating thin veneers or other overlays to core material, only low pressures of 25 to 100 pounds per square inch are required. Such pressures are enough to flatten the laminates and force out excess adhesive. Higher pressure will cause telegraphing of the surface characteristics of the core through a thin decorative surface. This telegraphing becomes more pronounced when the finished surface is glossy. Therefore, with a



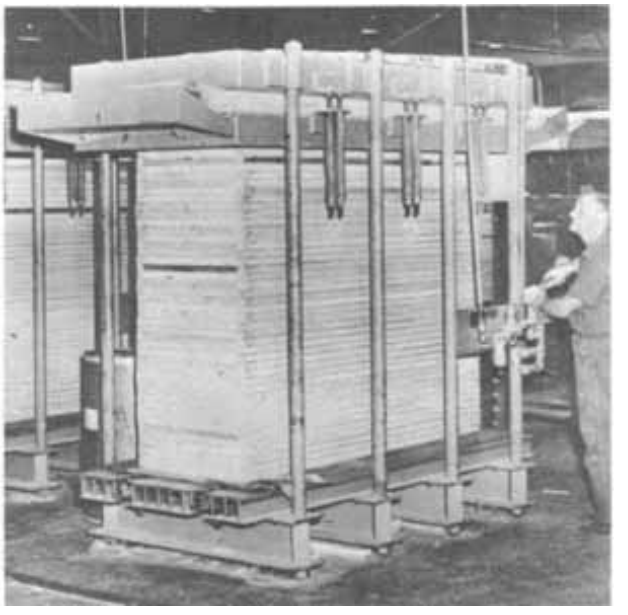
M 139 460

Figure 57.–A motorized 60-section clamp carrier allows adequate time for adhesives to set before release of pressure.

glossy surface, close control of pressure is needed to make a tight joint (squeezing out *all* the excess adhesive), but to avoid telegraphing. It is always important that pressure be uniform over the surface to avoid areas of inadequate pressure.

A number of pressing devices have been developed for application of pressure to flat surfaces, for laminating flat sheets to wood-based cores, and to manufacture hollow-core doors. Many adhesives, such as urea, resorcinol, or polyvinyl acetate resins, require an extended period of clamping before the adhesive has set adequately. With these adhesives, therefore, the press should:

1. Maintain an even pressure over the entire surface,
2. Maintain a controlled and determinable pressure,
3. Maintain pressure for a predetermined period of time,
4. Be quickly loaded and unloaded, and
5. Adjust to different stack heights.



M 139 456

Figure 58.–Inflation of air hose at top of press applies pressure to stacked panels.

Many clamping systems used by the construction industry do not meet the above criteria and are thus causing inferior products or excessive labor costs.

A laminating press may apply force by using air or hydraulic (oil) pressure or mechanically driven gears. Pressure can be applied by the air expansion of a series of hoses (e.g., 4-inch diameter) laid parallel in the air hose press (fig. 58). When the air is bled from the hoses the pressure is released. This type of press has disadvantages of limited height of platen travel, and sometimes of a varying pressure. It does provide a relatively inexpensive press with easily applied pressure and is quick opening and closing. Figure 59 illustrates the principles of construction for an air-hose press.

The air-pod press is similar to the air-hose press, but applies air to bags or pods rather than hoses. It permits greater platen travel than with air hoses and supplies more uniform pressure with variations in stack height. This press is somewhat more expensive, but is also quick opening and closing.

The opening between the top and bottom platens in both of the above two types is easily adjusted by raising or lowering the top head. Pressure regulation for both is made by regulating the air pressure applied and is limited to the air pressure available.

Some presses may use tension springs to return the movable platen. Others may have one or more air cylinders on the top of the press to raise the movable platen, and a few have their hoses at the bottom of the press and depend upon the weight of the load to exhaust the air from the hoses.

The hydraulic press uses a pump to apply oil pressure on a ram. The clamping pressure is indicated and maintained by the oil pressure. Higher pressures and greater platen travel can he provided by hydraulic presses than with the air presses above. A stack shorter than the reach of the hydraulic ram is usually compensated for by inserting a dummy filler stack. Hydraulic presses are more expensive than the air presses but are also more suitable for heavy-duty pressing. Air presses are for room-temperature-curing adhesives, whereas hydraulic presses can be modified for hot pressing.

Hydraulic and air presses are available as singleopening. multiopening. or multisectional presses. With a five-section press (fig. 60), four sections can be pressed while one is being unloaded and reloaded. In this case, if the required presstime is 40 minutes, 8 to 10 minutes should be allowed to build the stack. In the selection of an adhesive, a minimum of 40 minutes pressing time and at least 10 minutes closed assembly time are required under the operating conditions specified.

For methods of calculating pressures applied by air-hose or hydraulic presses, see chapter 9.

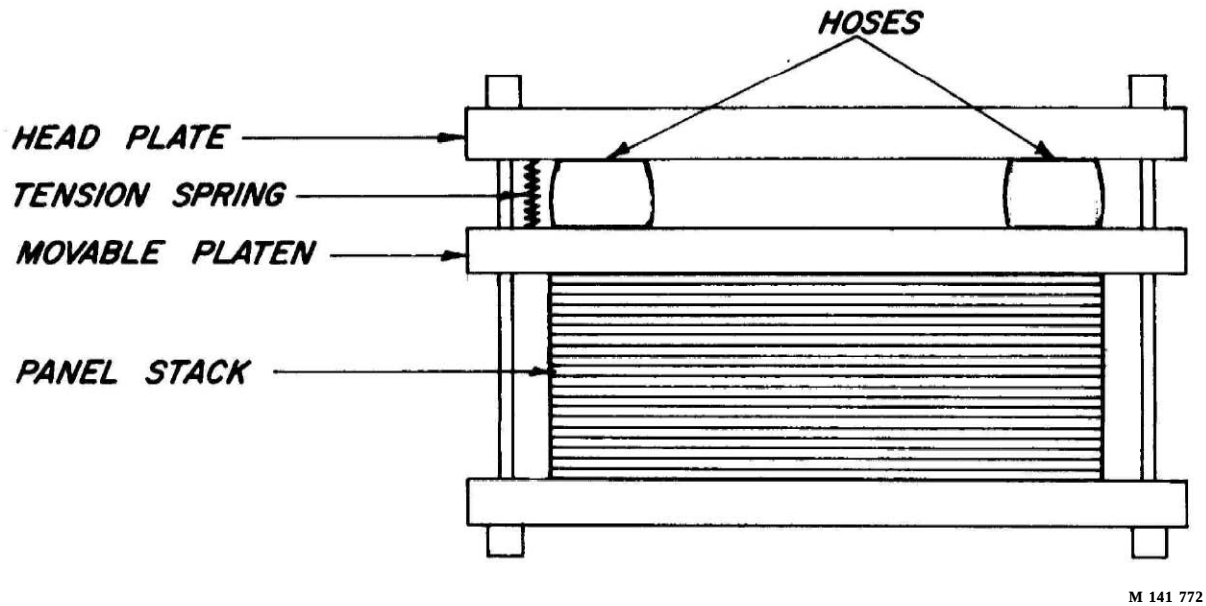


Figure 59.–Principles of air-hose press construction.

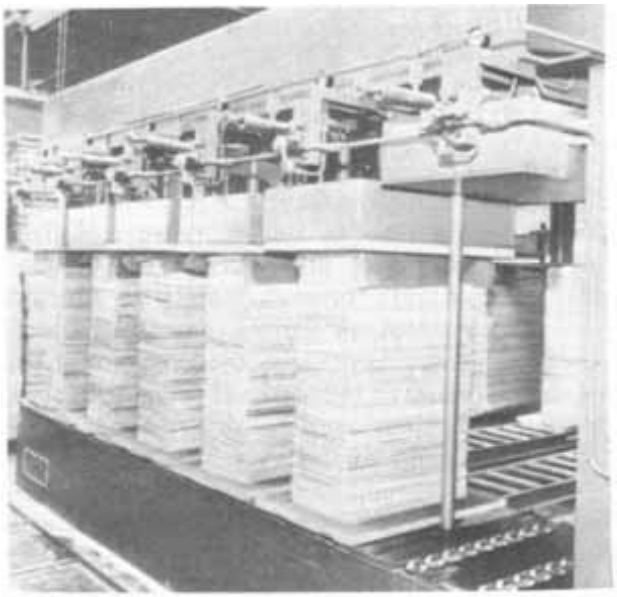


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Figure 60.–A hydraulic press can apply pressure to one or more sections of panels at a time.

Pressing Large Sections

Several different pressing methods have been designed for pressing large stressed-skin components. The simplest of these is cold pressing by chain clamp presses. In this method, the bonded components (all of the same size) are stacked as high as assembly time and ceiling height permit. The chain clamps consist of beams, top and bottom, to distribute pressure uniformly over the joints with connecting chains which are tightened to apply pressure. These beams may be channels (e.g., 6 inches) welded back-to-back with a spacer between. The pressure is applied by tightening a nut on a bolt welded to the end of each chain. Impact wrenches can be used to uniformly tighten the nuts. In cold clamping, it is important that the temperature of the wood and room be warm enough to cure the particular adhesive in the clamping time allowed. Clamping time can be decreased by rolling the assembly into a hot room at 38° to 49° C (100° to 120° F).

The pressing procedure can also be speeded by inserting small wires or metal bands into the bondline for resistance heating when an electrical current is applied. This normally requires fairly high amperage cm-rent at low voltages (110 volts or less). The amount of current should be regulated to keep the heat below the char point of the wood. When thin metal bands are used in this technique, the adhesive must bond equally well to the metal and the wood; and the metal (usually aluminum) must be of uniform thickness to avoid differences in electrical resistance.

Nonmetallic platens, with nichrome wire inserted in rabbeted grooves, or electrical conducting rubber sheets, can be used as resistance heaters (fig. 61). For safety when using electrical resistance heating, extreme care is necessary to insulate adequately between the heating elements with electrical supply lines and the other parts of the equipment.

The time in a hot press is dependent on a number of variables including:

1. Platen temperature,
2. Distance to the deepest bondline,
3. Initial temperature of the wood,
4. Species (primarily density of wood).
5. Moisture content of the wood,
6. The type of adhesive, and
7. The particular catalyst system.

Only experience will define the minimum presstime suitable. Adhesive manufacturers should be consulted on specific curing conditions for their products in each application. Table 8 is presented only to give a starting point for trial on the particular system under consideration. This table was developed for a crosslinking polyvinyl acetate emulsion adhesive, and the presstimes are somewhat shorter than needed for urea, resorcinol, or melamines.

M 96844F

Figure 61.–Curing adhesive in joints with continuous rubber pad heated with low-voltage electric current.

Table 8.–*Suggested hot-press cycles using lumber or particleboard core and a crosslinking polyvinyl acetate emulsion adhesive*[1]

Distance to deepest bondline	Platen temperature, °C (°F)					
	71 (160)	82 (180)	93 (200)	104 (220)	116 (240)	121 (250)
Inch						
1/32	1 minute, 40 seconds	1 minute, 25 seconds	1 minute, 10 seconds	55 seconds	50 seconds	40 seconds
1/16	1 minute, 50 seconds	1 minute. 35 seconds	1 minute, 25 seconds	1 minute, 10 seconds	1 minute, 5 seconds	1 minute
3/32	2 minutes, 30 seconds	2 minutes, 5 seconds	1 minute, 50 seconds	1 minute, 35 seconds	1 minute, 25 seconds	1 minute, 20 seconds
1/8	3 minutes, 20 seconds	2 minutes, 50 seconds	2 minutes, 25 seconds	2 minutes, 5 seconds	1 minute, 55 seconds	1 minute, 45 seconds
5/32	4 minutes	3 minutes. 25 seconds	3 minutes	2 minutes, 35 seconds	2 minutes, 26 seconds	2 minutes, 15 seconds
3/16	4 minutes, 40 seconds	4 minutes	3 minutes, 35 seconds	3 minutes, 10 seconds	2 minutes, 56 seconds	2 minutes, 40 seconds
7/32	5 minutes, 26 seconds	4 minutes, 45 seconds	4 minutes, 16 seconds	3 minutes, 50 seconds	3 minutes, 35 seconds	3 minutes, 20 seconds
1/4	6 minutes, 25 seconds	5 minutes, 30 seconds	5 minutes, 10 seconds	4 minutes, 40 seconds	4 minutes, 20 seconds	4 minutes

When pressing a stack of panels it is important that the cores and veneers are uniform in thickness. A variation of over ±0.005-inch thickness should not be tolerated. Platens *must* be flat and parallel. Defects in platen flatness may be caused by wear, such as from loads riding in and out of the press. If so. a flat caul board (1-in. plywood sheet) should be put on the bottom of every load. Platens must also remain flat and parallel when the full load is applied and when platens are heated.

The stack must also be high enough so that the platen is applying the registered load to the stack. If, at the end of platen travel, little or no pressure has been applied to the stack, the purpose of pressing has been lost. Prepressing can be used to compress wavy veneers so that a full stack can be put in the press.

Roll Laminating

Nip or pinch rollers may be used with contact cements to bring brief pressure on the assembly. These are normally power driven. Nip rollers (fig. 62) may consist of two solid or segmented rubber rolls (like washing machine wringer rolls) with a gap between the rolls somewhat less than the thickness of the panel to be pressed. The rubber should be sof enough to adjust to contours of the panels.

A frequent cause of delamination problems with contact cement is inadequate pressure. A nip roll can apply enough pressure if designed and used properly. Many manual methods, such as manually rolling or tapping with a hammer, do not give adequate pressure for good bonds. The

sooner pressure is applied after the cement has dried, the lower the pressure required to make a satisfactory bond. The time between spreading and pressing, as specified by the adhesive manufacturer, should not be exceeded.

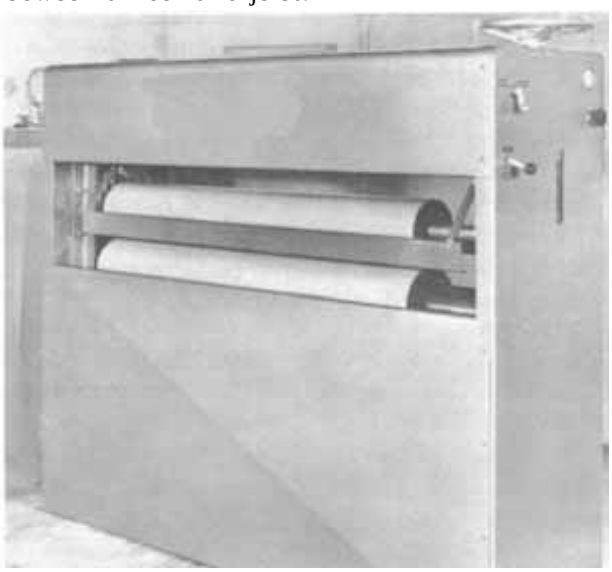
Postforming

Postforming equipment is required to make curved surfaces with high pressure laminates. A postformer heats the postforming grade of high-pressure laminate to the proper temperature and gradually molds it by suitable rollers to the desired shape as it is carried through the machine on a moving belt. The contact cement will have been applied to both surfaces and dried before going through this machine. If the temperature of the laminate is too low, it will crack on bending. If the rollers are not set properly, the laminate will not be brought down to the core with enough pressure to make a good bond.

Other methods used for postforming are usually batch methods. They consist of surface heating the laminate with strip or quartz heaters and then bending with mechanical clamps to the proper shape. If the press is a hot press, the flat part of the top can be set at the same time as the formed edges. Heat-setting adhesives, rather than contact cements, are frequently used with such equipment.

NAILING OR STAPLING

Nails and staples are frequently used in conjunction with adhesives in the assembly of large building sections, such as the joining of interior and exterior walls to studs, floors to joists, ceilings and roofs to trusses, and gussets onto truss members. The selection of both the mechanical fasteners and the adhesive will depend on the purpose each is to serve, the design of the structure, and the durability requirements. For example, the stresses between a gusset plate and the webs and chords in a roof truss may be much higher and subjected to higher temperatures than beween a floor and joist.



M 139 458

Figure 62.–Roll-lamination press with two solid rubber rolls.

In such nail-bonding operations, nail spacing must be determined to provide adequate and uniform pressure as much as possible over the entire joint area. If the main strength of the assembly is to come from the bonded joints, the staples and nails need be only of such a size and placed with such a frequency as to provide satisfactory bonding pressure. If the adhesive is used only to provide a minor structural addition to the assembly, larger and more frequent fasteners will be needed according to accepted building practice with mechanical fasteners only.

The basic power-driven stapler or nailer may be adapted for specialized uses. By mounting a nailer on a long counterbalanced mechanical arm, a man walking upright over the floor can nail the floor to the joists. Likewise, a series of staplers can be mounted on a carriage with wheels. This runs on a pair of rails parallel to and just beyond a wall section. Staplers so mounted can be tripped simultaneously to staple a wall material to the entire stud at one time. By moving the machine down the track and stapling each stud in turn, the wall section can be quickly completed. Floor panels can be prefabricated in a similar fashion.

Shooting staples or nails from a gun does not necessarily draw the joint up tight as happens when using a hammer. Because a thin bondline is desirable, adequate pressure must be applied adjacent to the point being nailed or stapled. This is particularly important when panel materials are not entirely flat. Standing on the floor adjacent to the point of nailing will usually bring it down

tight. In fastening wall materials to framing in a vertical position, a tighter joint will result if pressure is applied with the hand next to the point of stapling.

Properly selected staples may cause less splitting than nails, particularly near the end of a piece.

MATERIALS USED IN EQUIPMENT

The materials selected to handle adhesives should not be attacked by them or contaminate them. This includes each part of the equipment contacting the adhesive, including such minor items as gaskets. Because most adhesives are proprietary products, the discussion, of necessity, will have to be in general terms. emphasizing points which may be troublesome.

Water-Based Adhesives

Some hoses used to conduct solvent-based adhesives will not handle water-based adhesives. If a change is to be made from solvent-based to water-based adhesives, check for the suitability of the hoses with the hose or equipment manufacturer.

The acidity of the adhesive will influence the selection of metals in equipment construction. Acid adhesives (with a pH less than 7.0) should not be used with iron or steel unless the part is expendable and the iron corrosion has no adverse effect on the adhesive. Because pH is a logarithmic function, as the numbers decrease the corrosion effect increases rapidly. For instance, although 6 is only a little mire corrosive than 7, 5 is much more corrosive than 6. Such items as iron barrel pumps, mixing buckets, or valves, because of their low cost as compared to their usefulness, may be considered expendable for use with acidic adhesives. Tinned containers or zinc-plated parts do not appreciably delay the corrosion of iron by acidic materials, because of the thinness and porosity of the coating. Aluminum may not be satisfactory for adhesives of high alkalinity such as certain phenol resins or for those of moderate acidity such as polyvinyl acetate or some urea resins. Stainless steel should be used in pumps for water-based adhesives. Epoxy coatings are suitable for coating iron or steel reservoirs, although these coatings may need frequent replacement.

Solvent-Based Adhesives

Iron, steel, or other metals may be used for most systems containing only organic solvents as vehicles. Plastics may be used if they are not either softened or hardened by the system (such as by leaching of plasticizer). Plastics should be tested even when changing proprietary adhesives to others of the same type. Equipment gaskets should also be tested. If not done, frequent replacement of gaskets may be a cause of aggravation and of downtime.

Polyethylene containers (plastic bottles) can be used for water-based adhesives but usually are not suited to solvent systems. These containers may not be softened by some solvent systems, but may be so porous to the solvents as to make them unusable for storage. Dried adhesive is easy to clean off of teflon- or polyethylene-coated equipment. Coating the equipment with wax or a thin coating of oil will supply a temporary release coat.

Copper or copper alloys should never be used with neoprene-based or epoxy-resin adhesives as they may be instrumental in causing a deterioration in the bond quality and durability.

CHAPTER 7:

GENERAL BONDING TECHNIQUES[10]

The quality of any adhesive bond depends both on the selection of the proper adhesive for the application and on the bonding conditions under which that adhesive is used. The best adhesive in the world will not produce consistently high-quality joints if it is used improperly. In practice, more of the poor joints encountered are the result of poor bonding conditions than of some deficiency of the adhesive, provided the proper adhesive was selected. The quality of joints is, then, a responsibility of both the adhesive user and the adhesive manufacturer.

The degree of control necessary in the bonding process will depend largely on the structural requirements of the actual joints. Joints where high strength is required for structural integrity, such as where they are continually highly stressed, should be distinguished from other joints where such high requirements do not exist, such as where mechanical fastenings are also used and will adequately carry the loads in service.

For high-strength critical joints, bonding conditions must be carefully controlled, and only rigid, high-strength, and durable adhesives should be used. For example, bonds in horizontally laminated timber beams or arches must be high-quality throughout. On the other hand, bonds between interior plywood facings and conventional wood-frame walls are not normally expected to be highly stressed, although the facings must be firmly held in place. Joints holding such facings do not normally involve the structural integrity of the building. Yet in prefabricated panels, mobile homes, and some modular units, this bond is expected to provide substantial resistance to racking, buckling, and other distortions, especially during movement and erection.

Most adhesives discussed in this handbook were initially developed to fabricate various wood products in plants. Until the advent of the mastic construction adhesives, adhesives were not developed for onsite construction. Earlier adhesives were intended primarily for use in thin bondlines of approximately 0.005 inch between well-fitted joints requiring accurate machining of surfaces and the use of pressing equipment. The following discussions of bonding techniques will cover processes to produce high-quality joints in plant fabrication, with additional comments on variations and problems in the use of the same adhesives in small shops or onsite.

Although the general bonding process is quite similar for the different classes of adhesives, each type requires somewhat different bonding conditions. The sections that follow are intended only to offer general guidelines for good bonding techniques, and not as a substitute for the specific instructions provided for each product by the adhesive manufacturer.

[10]Written by Richard F. Blomquist, Southeastern Forest Experiment Station. USDA Forest Service, Athens, Ga.

PREPARATION OF ADHERENDS FOR BONDING

To obtain strong, uniform, adhesive-bonded joints, preparation of the surfaces to be bonded is necessary. To provide the necessary degree of adhesion, the surface to be bonded should be clean. Generally, it should be smooth and well-fitted to the adjacent surface to permit economical. thin bondlines. Good fitting will also provide maximum opportunity for the applied pressure to distribute the liquid adhesive over the entire joint area. The resultant even spreading will help assure good adhesion.

Wood and other adherends which change in dimension with changes in moisture content must be properly conditioned before bonding. Metals and other adherends that change in dimension because of thermal changes should generally be at ambient room conditions when bonded to minimize induced stresses in resultant joints and undesirable distortion of bonded assemblies.

Moisture Conditioning

Moisture-induced dimensional changes in lumber-swelling and shrinking-can stress bonded joints severely enough to cause premature adhesive failure in lower quality joints, or even failure in the wood with higher quality joints. Such dimensional changes also cause undesirable warping in bonded-wood assemblies, as in warping of flush doors and various types of sandwich or stressed-skin building panels. As a general rule, lumber should be conditioned before bonding to the approximate moisture content expected during service so as to minimize internal stress. Conditioning of substrates is generally not done to meet adhesives requirements; most wood adhesives give adequate adhesion over a rather wide range of wood moisture content below the fiber saturation point.

To condition lumber, simply store it at the same ambient temperature and humidity as it will generally encounter in service. All faces should be exposed to good ventilation, either by stickering or other means. The time required to condition any piece of lumber will vary in terms of its density and dimensions, with a minimum of 48 hours suggested for nominal l-inch boards and a proportionately greater time for thicker pieces (chapter 4). As a general guideline, wood for interior use in a building, such as cabinetry and trim, should be at about 6 to 8 percent moisture content. Wood to be exposed to exterior conditions should be at about 12 to 14 percent moisture content. These are averages from various locations in the United States and from summer to winter conditions.

From a practical standpoint, softwood dimension lumber used for wood-frame houses is required by certain grading rules to be below 19 percent moisture content; other rules still permit green lumber. A maximum of 19 percent moisture content is not too unreasonable for southern pine or Douglas-fir lumber for framing, and such lumber can be used for bonding without further conditioning. Wood for interior applications should be at lower moisture contents as indicated above.

Conditioned lumber should be protected against significant moisture-content increases due to rain and high humidity between manufacture and use. This is particularly important with lumber for bonded constructions and for interior use. If concern exists regarding the dampness of stored lumber, moisture-meter testing is appropriate and redrying should be considered.

Manufactured wood-base products, such as plywood, hardboard, particleboard, and paper-based plastic laminates, will also swell and shrink with changes in relative humidity. Because many of these products are manufactured in hot presses, the hygroscopicity of the wood substance may have been changed and be less than normal wood. Hence the equilibrium moisture content of such products will he different (and usually lower) than for lumber (table 2). Thus if the lumber moisture content recommended for an interior application is 6 to 8 percent, moisture content for particleboard or plastic laminate in that situation should probably be somewhat lower.

Most wood adhesives do not bond well to green lumber: that is, wood above the fiber-saturation point (chapter 4). So-called free water present in green lumber may cause dilution of adhesives after spreading. This causes excessive penetration which can result in unsatisfactory joints. It should be possible to develop new adhesive systems or modify present ones to bond green lumber. However. because of the undesirable dimensional changes and internal stresses in-

duced when such wet wood is bonded and put into service, no significant efforts have been made to develop such bonding techniques. A good goal is always to have such wood-based products in equilibrium with the average temperature and relative humidity expected in service.

Preparation of Surfaces

Lumber and Solid Wood

The principal requirement for preparing wood joint surfaces is to have the wood machined smooth and flat, with opposite faces parallel. Surfaces with high and low spots make it difficult to obtain a uniform, thin bondline with roller spreading, and increase the difficulty of distributing uniform pressure over the entire joint area. Very thin adhesive areas on the high spots result in poor quality, starved joints because of excessive squeezeout under pressure. Also, the adhesive which fills the low spots will develop strength slowly, may shrink away from the surface during hardening, and thus can attain only inadequate contact and poor adhesion. Unduly thick bondlines require more adhesive and will increase costs while decreasing joint quality. Generally, an ideal bondline is about 0.005 inch thick for other than gap-filling adhesives.

Adhesives usually cost more per pound or per cubic inch than doss wood itself, so it is generally not economical to use an adhesive in thick bondlines. Often, it is easily possible to provide better fitted joints where thinner bondlines are obtainable. Some compromise may have to be made between good machining and adhesive spread rates. Somewhat thicker bondlines can be tolerated if adhesives are formulated to hold their position in such bondlines without sagging in spreading, or shrinking when the adhesive hardens and develops strength. Casein adhesives, for example. can provide some gap-filling properties in certain formulations. (Mastic-type adhesives are the best performing in thick bondlines, and can form a bondline of up to 1/4 inch without loss of strength.)

Wood surfaces should be machined properly to avoid torn surface fibers. Adhesion is mainly a surface phenomenon. Torn surface fibers are likely to cause poor joints, because such fibers easily pull loose under stress. Most woodworking adhesives will not penetrate into the wood enough to rebond torn fibers effectively. Hence rough-sawn surfaces are to be avoided. Knife-cut surfaces, as produced by planing or jointing, are ideal.

Modern mill-sawing equipment is usually capable of providing adequate surfaces when saws are kept sharp and in good adjustment. Thus it might be feasible to rip 2 by 4's into 2 by 2's for wall framing on a well-maintained straightline ripsaw, and then to adequately bond the sawn surfaces to plywood without planing or jointing. On the other hand, surfaces produced by sawing and planing on the construction site are likely to be questionable for high-quality joints unless special attention is given to proper sharpening, tool maintenance, and operation.

When preparing wood surfaces for bonding, it is generally recommended that conditioned wood be used. and that final surfacing be done just before bonding. If wood is machined many days before bonding, changes in moisture content may result in warp, destroying the smooth, flat surfaces needed. Premachined, softwood lumber that is still reasonably flat and smooth can be bonded satisfactorily with many modern adhesives.

Some species of wood, particularly those with high extractive contents such as pitchy pines, tend to undergo surface changes that are not well understood and that are sometimes referred to as casehardening: such surfaces can be difficult to wet with adhesives. Poor wetting characteristics reduce the actual adhesion and may result in poor or erratic joints. Casehardened lumber should be resurfaced prior to bonding if high-quality bonds are required. It is usually possible to detect undesirable surface conditions for bonding by placing a drop of water or ink on the surface in question. If the drop spreads rapidly and penetrates the surface there is likely to be good wetting and adhesion of the adhesive. If the drop remains, resurfacing is probably desirable.

Wood treated with preservatives and fire retardants sometimes is difficult to bond. This is particularly true of lumber treated with oil-borne preservatives, primarily those dispersed in solvents such as fuel oil. They evaporate very slowly and tend to retain an oily layer on the surface. Resurfacing just before bonding will remove the oily surface layer. Because oil will diffuse back to the surface again, the wood should be bonded soon after resurfacing. It may be desirable to wipe particularly oily surfaces with clean rags and a volatile solvent, such as gasoline or mineral spirits, just before bonding.

Most waterborne chemical treatments for wood, either preservatives or fire retardants, will

not cause serious problems in bonding as far as initial adhesion is concerned. However, some of these chemicals may affect subsequent curing. Such wood should be redried properly after treatment and conditioned before bonding, just as is untreated wood. If crystals of treating chemicals are present on the dried surface, they can be brushed off just before bonding. If the grain is too rough or is raised by the treatment, the surface may be lightly sanded, being careful not to sand through the treated layer.

Lumber prone to warp or distort because of abnormalities, such as compression wood in softwoods or tension wood in hardwoods, should be avoided in bonding where high-quality joints are critical. Such lumber may distort severely in service. If so, excessive stresses will be introduced in the bonded wood piece which may break either the bondline or the wood itself.

Plywood, Hardboard, Particleboard, and Plastic Laminates

These materials are manufactured in hot presses under considerable pressure. Such pressing may cause undesirable changes in the surfaces which render them difficult to wet with the adhesive, and which will result in poor adhesion in later assembly operations. These surface conditions are another form of casehardening. Fortunately, sanding such panel materials in the subsequent manufacturing process usually removes the condition. Softwood plywood in construction grades is not commonly sanded and seldom presents a casehardening problem. When the backs of hardboard, particleboard, plastic laminates, and some plywood panels are to be bonded to other materials, it may be necessary to lightly sand the joint areas with either hand sanding or with power equipment to expose fresh wood before bonding.

Hardboards, plywood, and particleboards may have been sanded in the mill. The back sides of most paper-base plastic laminates are usually factory-sanded to provide a surface that pro. motes adhesion. Difficult-to-wet surfaces can be detected by noting the spread of a drop of water or ink. Light sanding should correct any casehardening which is detected. Excessive sanding may create an irregular surface of high and low spots and should be avoided.

Metals

The principal need in preparing metals for bonding is a clean surface. It should be recognized that metals are commonly coated with an oily layer as an aid in rolling the sheet or film, or as a protective coating during storage and shipment. Oils may vary considerably in composition and be of either a vegetable or mineral base. Oily surfaces can usually be cleaned adequately with a solvent such as carbon tetrachloride, acetone, benzene. gasoline, or other low-boiling hydrocarbon solvents. Be careful of fire in working with such flammable solvents and do not inhale the vapors!

Cleaning with soaps or other detergents in water is also useful, but the surface must then be rinsed well with water and redried before bonding. Solvents must be clean and clean wiping cloths used; otherwise, the contaminated solvent or cloth may just spread the oils over the surface. Special metal-cleaning systems are used when high-quality metal joints are required, as in aircraft manufacture where corrosion of the metal surface under the adhesive film is to be avoided. Such special treatments are not normally required for bonding metals for lightly stressed joints in building applications, but must be considered where critical high-strength joints are required.

PREPARATION OF THE ADHESIVE

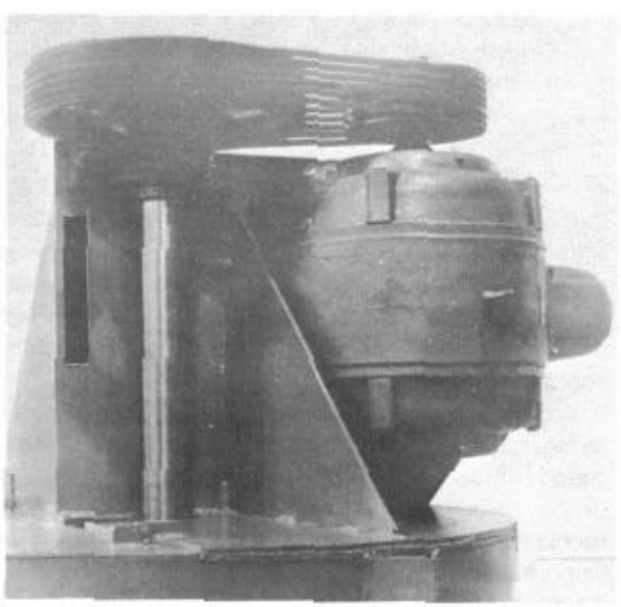
Most adhesives tend to deteriorate on long storage. This is particularly true of adhesives that cure or harden by chemical reactions, and is more serious with liquid types than solid ones. Adhesives should be kept in tight containers to avoid loss of volatile solvents and to avoid absorption of moisture from the air. Cartridges of mastic adhesives that are once opened should be sealed tightly and then used as soon as possible to avoid further loss of solvent and introduction of oxygen or moisture.

Generally, any adhesive should be left in its original container and kept in a cool place. The oldest samples should be used first. In case of

doubt about the suitability of older, stored adhesives, mix a batch according to the prescribed directions and check to see that it is still spreadable and generally behaves like previously known fresh samples, In the case of two-part adhesives with separately supplied resin and hardener, be sure to use the hardener received with each batch of resin. Do not mix it with that from other batches. It is a good idea to date each container of adhesive when received.

Adhesives come in various forms, and most of them require some mixing or other preparation for use. Popularity of the mastic construction adhesives in disposable cartridges is due largely to their ready-to-use form. The same is true for the polyvinyl-resin emulsion systems (the so-called "white glues"). Types which require mixing include casein, urea-resin, resorcinol-resin. epoxy-resin, polyvinyl emulsions of the cross-linking type, and some polyurethane adhesives. Follow the manufacturer's instructions for mixing.

Usually the adhesive components are to be mixed by weight. For smaller quantities that are used in small shops and onsite, a dietary scale is convenient. These are readily available at low cost in most drugstores in the form of spring-type scales which are easily portable and which have an adjustment to tare the weight of the container.



M 138 389

Figure 63.–Water-jacket cooled mixer suitable for adhesives which produce moderate heat buildup when prepared. such as resorcinols. Epoxies are too reactive for mixing in such equipment and are generally prepared in small batches only.

In the case of water, the volume of this weight need be established only once by weighing in a suitable volumetric container, and can be measured thereafter by volume to an index mark. Care must be taken to avoid denting the container, which would change its volume. Volumes are not directly proportional to weight: powders should always be weighed because their density may change from batch to batch.

Most casein and urea-resin powdered adhesives require only mixing with water. Here the proportion of water to dry adhesive will control the viscosity of the mixed adhesive. The best procedure is to add the powder to the water gradually, with adequate stirring. Power mixers are best for larger batches. Small batches can be stirred by hand with suitable paddles. Resorcinol or phenol-resorcinol resins are usually sold as sirups to which a specific weight of powdered hardener is to be added. Such solid hardeners should be added gradually to the liquid resin while stirring, as for the water-base systems just described. Epoxy resins and some polyurethane resins require the addition of specific amounts of a separate hardener or curing agent, usually in liquid form. In these cases the hardener reacts chemically with the resin, and the proportions are quite critical in controlling reactivity as well as viscosity of the adhesive.

Clean containers must be used in mixing different adhesives. Containers to be reused for a different type of adhesive should be particularly clean to avoid interference of components of one type with another. Small batches can be effectively mixed by hand stirring with a wood paddle. For larger batches, simple power mixers may be more convenient. In such cases, care should be taken to avoid whipping air into the adhesive, causing frothing, which would interfere with proper spreading.

An important factor to consider is the working life of mixed adhesives. The working life is the length of time that an adhesive remains spreadable and usable after mixing. Normal working life is usually indicated in the manufacturer's literature. The working lives of resorcinol-resin adhesives or of epoxy-resin adhesives may vary from an hour or so to as much as several hours, depending on formulation and temperature of the mix. Because of the chemical reactions in such adhesives, the working life decreases as the temperature of the mix increases.

In the case of a thermosetting resin adhesive, the adhesive will set hard shortly after gelation has rendered the mix unworkable. It will then become difficult or impossible to remove from containers and spreading equipment. Solvents will not dissolve such highly reacted resins. It is important to recognize this and to mix only as much adhesive as can be used during the working life. Then, clean up equipment and spilled material before it hardens. It is impossible to thin down and continue using reactive adhesives at the end of the working life.

Some of the reactive adhesives, particularly the epoxy resins, may undergo considerable internal heating after mixing due to exothermic reactions. This heat will shorten the working life if not dissipated through external cooling. If exothermic heating is a problem, small batches should be mixed successively instead of using a single large batch. Small batches for repair work can be mixed on a sheet of aluminum or in shallow metal pans so that the heat is dissipated rapidly.

In blending large batches of adhesives other than epoxies, where heat from exothermic reaction is moderate, water-jacketed or otherwise cooled pots may be used with continual mixing (fig. 63) and the resin and hardener may be cooled to below room temperature prior to mixing.

BONDING OF ADHERENDS WITH ADHESIVES

Spreading the Adhesive

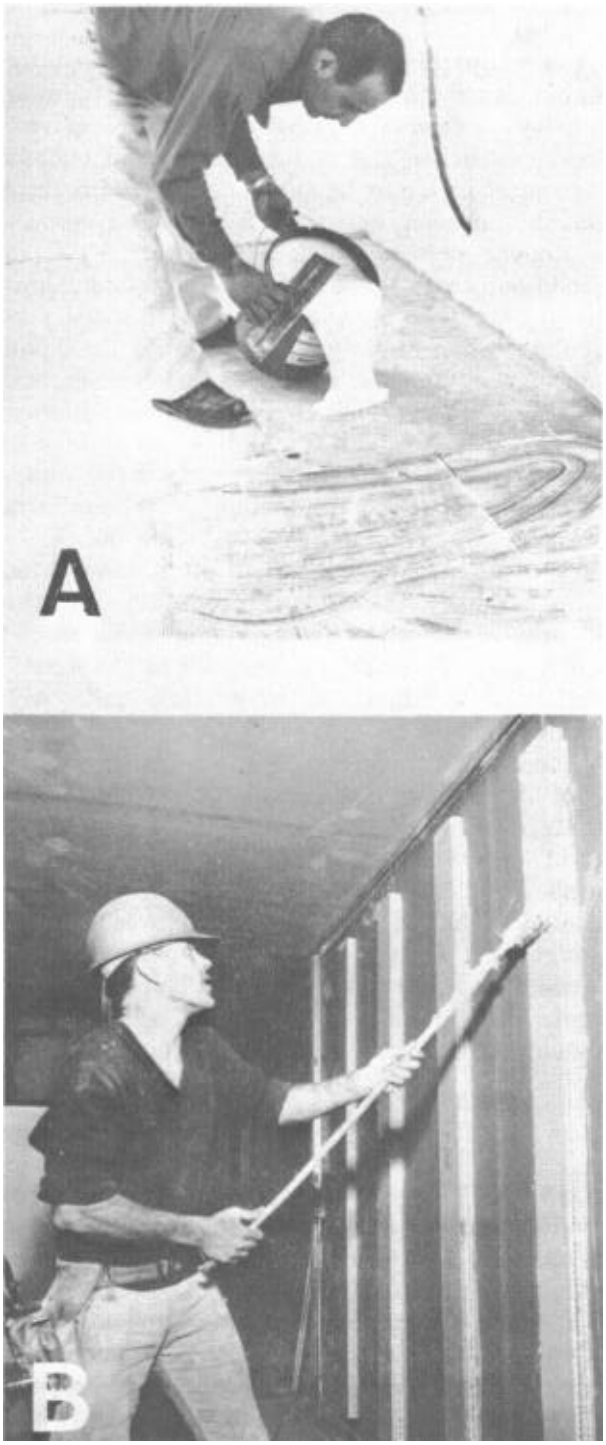
When spreading adhesive, be sure to apply enough to one or both mating surfaces within the usable working life, in a uniform pattern, and over the entire joint area. Most adhesives for thin bondlines (0.005 inch) require about the same amount of adhesive solids per square foot of joint area for good spread (approximately 30 pounds solids per 1,000 square feet). Because the amount of solids in the wet mix varies from type to type, the actual amount of wet adhesive spread varies. Here again the manufacturer's instructions should be followed closely. For highest quality results, it is best to first check the spread by weighing a scrap piece of wood of known area before and after spreading, and then to adjust the spreader accordingly.

With most conventional adhesives of interest here, the adhesive is applied only to one of the two mating surfaces (so-called single spreading). When double spreading is prescribed, adhesive is applied in a uniform layer to both substrates. Each surface receives half the amount of adhesive necessary to attain the recommended weight-of-solids spread per square foot. Double spreading is recommended in structural components since it is conducive to bond uniformity and bond strength. Double spreading is also advised where long delays are anticipated in getting large assemblies spread, assembled, and under pressure In such cases the adhesive is likely to harden partially before pressure can be applied, and will then not adequately wet and adhere to the opposite uncoated surface, although it will adhere with an opposite, coated piece. Double spreading is always done when using typical rubber-base contact adhesives, and is also usual when laminating large wood members. Double spreading is also prescribed to achieve heavy spreads of adhesive, particularly with adhesives of low solids content where insufficient adhesive will be applied by single spreading.

A good practical guide on spread is to observe the appearance and amount of squeezeout of adhesive when pressure is applied to the joint. If sufficient adhesive has been spread and pressure is then applied within permissible time limits (see "Assembly Period"). a thin line of droplets of adhesive will be visible along all exposed joint edges. Absence of such squeezeout indicates insufficient spread or too long a delay before pressure application. Excessive adhesive running down the edges of the joints indicates that an excess has been spread, that the adhesive is too dilute. or that pressure has been applied before the adhesive developed sufficient tack.

Spreading joint areas can be done effectively in some instances with stiff-bristle brushes, with paint rollers, or with a metal spatula (fig. 64). For larger areas, as in laminating large beams, mechanical roll spreaders may be desirable. The important point is to apply sufficient adhesive in a uniform layer.

Heavy-bodied mastic adhesives are conveniently spread with guns. Some guns are fed from a transportable reservoir via a flexible feed-tube, some use a reloadable reservoir integral with the



M 144 179

Figure 64.–Simple applicators may be adequate for certain adhesive applications: ***A,*** a trowel is used to spread adhesive in preparation for finish flooring; ***B,*** a long-handled brush spreads adhesive on furring strips to bond paneling.

gun, and some are simple calking guns utilizing disposable cartridges of mastic (chapter 6). Adhesive spread is controlled by replaceable nozzles in some systems, or, in the case of the disposable-cartridge type, by a plastic Lip on the cartridge that can be cut to varying diameter to yield a thickness of bead appropriate to the job. The bead thickness will also be influenced by the speed of application. Spread is usually made on a narrow wood piece by running the bead down the center of the joint area.

In factory operations, extrusion spreaders are effective for applying adhesive, and are popular in the laminated timber industry. Curtain coaters are effective in spreading the low-viscosity (runny) adhesives.

Assembly Period

The assembly period is the time interval between spreading the adhesive and applying full bonding pressure. Open assembly refers to the time during which the two mating surfaces are spread but not in contact. Closed assembly refers to the time after the two spread surfaces are joined, but before they are pressed. Sometimes both open and closed assembly may be involved in one bonding process because of the steps taken in lay ing up the complete assembly.

Generally, the maximum permissible open assembly period for a given adhesive will be considerably shorter than the permissible closed assembly period. This is because solvent evaporates when exposed to the air and so the exposed adhesive thickens more rapidly.

It should be recognized that the adhesive will be thickening during the assembly period due to loss of solvent, chemical reactions, or for both reasons. Both effects are greater at higher temperatures, so that the maximum permissible assembly periods will decrease as the temperatures of the adhesive, substrate, and the air increase. Manufacturers usually cite maximum permissible assembly periods at each of several temperatures and for both open and closed assembly, and these limitations should be observed.

Bonding performance may be diminished by assembly periods which are too short as well as by those which are too long. Many liquid adhesives are fairly low in viscosity when mixed and must thicken to some degree in the joint before pressure is applied. Adhesives intended for applications involving assembly times of as much

as an hour or more, as in timber laminating, are formulated to allow for considerable thickening before being pressed. Such adhesives would not be appropriate for situations where substrates are spread, joined, and pressed almost immediately. They would be too thin, would squeeze out of the joint excessively, and would probably yield starved joints. Any formulation of adhesive must be appropriate to the intended use.

Within certain limits, formulations of most adhesives may be varied to accommodate them to differing assembly time and other requirements. The setting rate of reactive-resin adhesives may be adjusted by choice of resin varieties, choice of hardeners, and amount of hardeners, In other adhesives, solvent content can be varied to yield differing viscosity and differing tolerance to evaporation. Viscosity can also be controlled by adding quantities of fillers like walnut shell flour or wood flour to the adhesive, usually at the point of manufacture. Also, control of adhesive and substrate temperatures, and of ambient temperature at point of assembly, can be used to affect the assembly time.

The thick mastic construction adhesives are readily adaptable to short assembly times; they are normally intended to be assembled and under nail pressure in a short time. They may be sensitive to long assemblies because they may lose solvent and then become too thick; the spread surface may skin over so that they do not wet the opposite surface properly.

Pressure

The principal purpose of pressure in bonding is to hold the two adherends in close contact until the adhesive develops sufficient strength to hold the joint together. Pressure will also distribute the liquid adhesive uniformly over the entire joint area. Pressure is thus related to effective spreading. Some adherends may not be flat and smooth when bonded, as in the case of warped thin plywood panels. Pressure is needed to hold these panels flat and in contact with lumber or other framing until the adhesive develops sufficient strength to resist stresses which might separate the adherends. The amount of pressure. as indicated in pounds per square inch, is often less critical than the uniformity of such pressure over the joint area. Hence in bonding thin adherends with mechanical clamps, it is desirable to use thicker lumber or other heavy cauls over the joints to distribute pressure evenly between the clamps. Typical pressures for bonding wood are 100 to 150 pounds per square inch. Higher pressures may compress the wood so excessively as to actually damage it and therefore should be avoided.

Generally, higher pressures are required for higher density hardwood species than for lower density softwoods. With many adhesives, pressures below the recommended 100 pounds per square inch may be quite adequate if properly distributed over the joints. Inadequate pressure or uneven pressure distribution may result in good bonds over the high spots of joints and low-quality bonds in other areas. In such cases, particularly when single spreading is used, the liquid adhesive will not wet the uncoated surface areas. The adhesive may harden without ever adhering to the wood. Low-viscosity adhesives applied in thin spreads to one surface in poorly fitted joints, then subjected to minimum or nonuniform pressure, will commonly give erratic bonds. In such cases, broken joints will often show dried joint conditions, without contact of the adherends and with the original spreader marks still visible. Thick adhesives, such as the mastic construction adhesives, may work quite well under the same conditions.

Bonding pressure can be applied with a variety of hydraulic or mechanical devices (chapter 6). Uniform adhesive squeezeout along all joints is a good guide to correct pressure. Erratic squeezeout suggests nonuniform pressing, assuming that the assembly period was properly controlled. With thick mastic adhesives, no squeezeout is normally observed. Even so, if adequate pressure has been applied, the adhesive should spread to the edges of the joint.

Temperature

Bondline temperature is particularly important for the proper curing and strength development of many adhesives. Bondline temperature will be influenced by the temperatures of the adherends, of the adhesive, and of the surrounding air during bonding. Each type of adhesive has some minimum temperature at which it can be properly used. For thermosetting-resin adhesives, which undergo chemical reaction in the joint, this minimum temperature is often cited at 21° C (70° F), but it may sometimes be lower and sometimes much higher. Here again, the manufacturer's instructions should be followed.

Wood conducts heat slowly, and absorbs considerable heat when undergoing significant surface temperature increase (because of its relatively high heat capacity). Hence, to apply a room-temperature-setting reactive adhesive on ice-cold wood, even though the air temperature may be comfortable and the adhesive at 21° C (70° F), will result in inadequate chemical curing and erratic, inferior bonds. Some reactive adhesives may dry out and harden superficially at excessively low temperatures merely by absorbing solvent into the wood, without really curing properly by chemical action. Such joints will appear to be dried and cured, but actually are not, and low-quality joints result. Some manufacturers of reactive adhesives such as resorcinols offer special formulations for use at lower working temperatures.

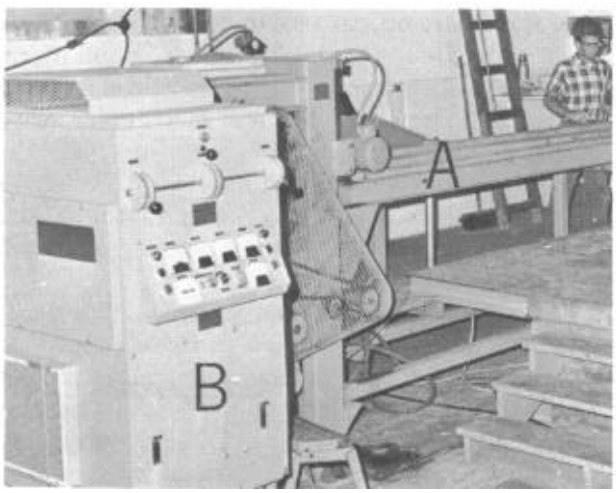


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Figure 65.–Lumber pieces with spread and assembled bondlines, ***A,*** travel on a conveyer toward radiofrequency unit, ***B,*** for curing.

Adhesives that develop strength mainly by solvent loss, such as the mastic construction adhesives, contact cements, and polyvinyl-resin emulsions, are also affected by low temperatures. This is because absorption or evaporation of solvent will be slower. Some solvent-type mastic adhesives may develop adequate strength in joints at temperatures as low as 4° C (40° F), but the time needed to develop such strength will be much longer than at higher temperatures. If joints are roughly handled before good joint strength is achieved, joints may separate and be unsatisfactory.

Higher temperatures in the bondline speed the cure of most adhesives, although there are notable exceptions. For instance, caseins show no significant acceleration of curing time with use in bondlines of elevated temperature, and certain thermoplastic adhesives, such as the hot-melts. will be inhibited in setting or in strength-development by high bondline temperatures.

A number of adhesives commonly used in factory bonding of building construction components demand elevated bondline temperatures in order to set. For instance, phenol-extended resorcinol adhesives and some of the melamine-urea-resin adhesives require intermediate temperatures, from 31° to 99° C (87° to 211° F), to cure properly. (An optimum temperature range for cure is set for each formulation by the manufacturer.)

Various heating processes may elevate bondline temperatures while joints are under pressure. The entire assembly may be pressed in a heated room such as a modified dry kiln, or may be heated by such methods as infrared heat lamps, steam coils, or heated platens in contact with the assembly. Seasoned wood is a good insulator; heat is conducted from the outside surfaces of the assembly only slowly into the bondline. Hence, it may be desirable. especially with thicker substrates, to utilize deep-penetration heating of the bondline. Techniques for accomplishing this include radiofrequency curing (figs. 65, 66) and heating by electric resistance wires placed into the bondline at assembly (fig. 67). Resistance wires may also be in a series of individual rubber pads (fig. 68).

Actual bondline temperatures may be determined with thermocouples and a potentiometer. Care should be taken to avoid excessive drying of the wood during heating of entire assemblies over long periods, as in heated rooms, by providing some humidification.

For speeding cure, an alternate process which has had limited use is heating of the actual surfaces to be bonded before adhesive is applied. This process is only applicable with thermosetting resin adhesive systems. Joint surfaces are heated with radiant heat, as from overhead heat. elements, by contact with hot platens, or by oven heating. The surfaces are then rapidly spread with adhesive. assembled, and pressed. The stored heat in the wood surfaces will quickly heat the adhesive film and thus speed the cure.

However, such preheating may excessively cure the adhesive film before the joint is assembled. This condition, known as "precure," may result in poor bonds by reducing the ability of the

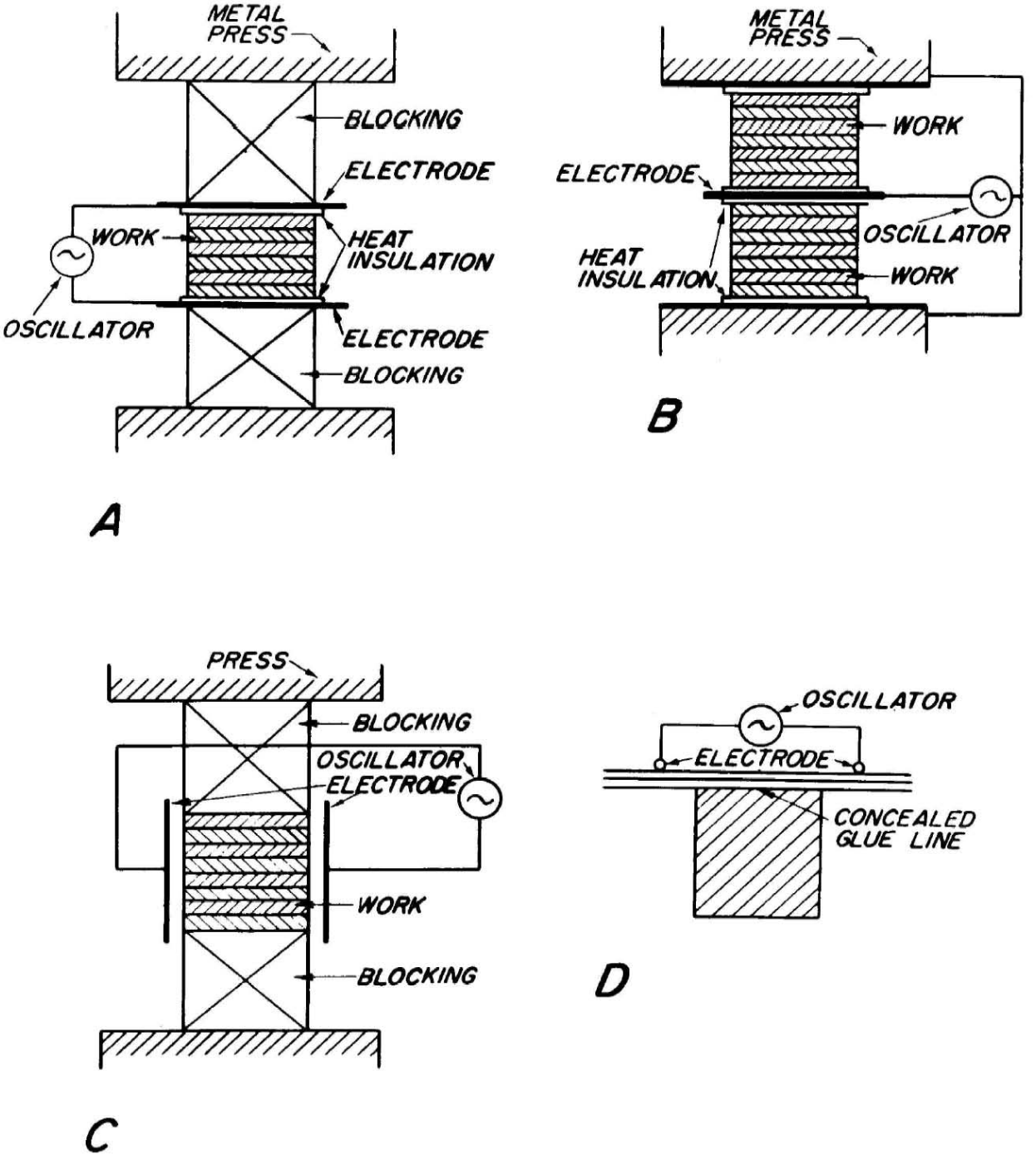

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Figure 66.–Four electrode arrangements for applying radio-frequency current to banded assemblies: ***A,*** assembly between electrodea. with electric field perpendicular to plane of joints: ***B,*** sandwich method, with high-voltage electrode between the two assemblies being bonded; ***C,*** electrodes arranged for parallel or selective beating of joints; ***D,*** stray-field heating arrangements of electrodes.

liquid adhesive to adhere completely to the opposite surface. The actual amount of heat energy absorbed at the wood surface may vary considerably from piece to piece in this type of operation and must be carefully controlled. Proper instruction of operators is essential, and the process must be subject to continuous and exacting quality control. Recommendations of the adhesive manufacturer should be obtained before using the preheating process. When properly controlled, preheating of joint surfaces has been used successfully in the manufacture of small laminated members and for other applications.

Control of temperature-time conditions is critical with preheating of joint surfaces and with deep-heating techniques such as electrical-resistance or radiofrequency heating. Therefore, such techniques are only feasible for use in well-controlled plant bonding operations.

Many thermoplastic adhesives such as hot-melts and some polyvinyl emulsions, will soften whenever heated beyond a certain point, even within joints. This property naturally limits their use to applications where excessive heating is not encountered in service. The softening point of different formulations will vary, so the user must be well informed on an adhesive's properties,

Thermoplastic adhesives may also "cold-flow" even at room temperatures, and thus are not normally used in joints under long-term stress. To avoid cold-flow problems, again the user should inform himself well on properties of the specific formulation he is using,

CONDITIONING OF JOINTS AFTER BONDING

Usually the pressure period prescribed by manufacturers for various adhesives are the minimum needed to develop sufficient joint strength for removing clamping equipment. But most adhesives continue to develop additional strength after pressure is removed. Thus, joints released after the minimum pressure periods may not yet have sufficient strength to withstand rough handling or further machining. In the case of nail-bonded pressure, where nailing is primarily for bonding pressure, the nails often supply adequate strength to permit some handling, but the joints will not be as stiff or strong as after the adhesive has had time to develop full strength. The actual level of strength required in a joint before rough handling or further processing is possible will vary considerably from one bonding operation to another. The user should obtain specific data from the manufacturer showing adhesive performance under different temperatures and other conditions, including minimum pressure periods rates of increase in joint strength, and time required to attain full cure. Wood assemblies should not be allowed to undergo significant changes in moisture content immediately after

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Figure 67.–Curing a bondline with low-voltage electric current.

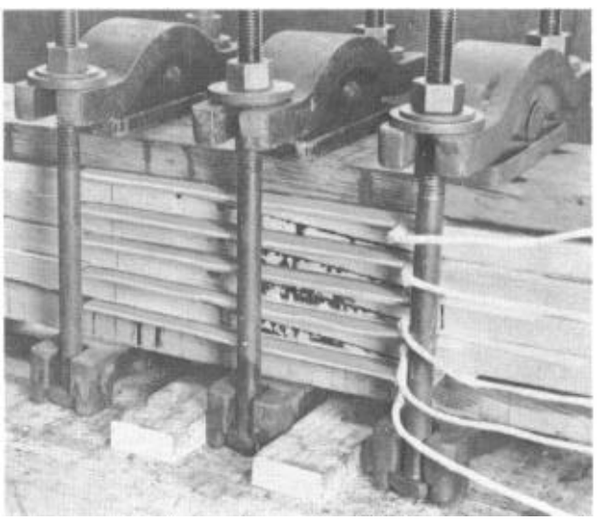

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Figure 68.–Curing bondlines with low-voltage electric elements embedded in silicone rubber pads.

pressure periods. Such changes may introduce dimensional changes and result in internal stresses which might damage the partially cured bonds.

The user must always obtain and study the instructions furnished by the manufacturer with each new adhesive. These instructions may be quite brief and general for some adhesives. and quite detailed and specific for others. There are usually sound technical reasons for the specific instructions given; they should be followed close ly to obtain high-quality joints, particularly where such joints are critical to the structural strength of the assembly.

BACKGROUND MATERIAL

Heebink, B. G.. E. W. Kuenzi, and A. K. Maki. 1964. Linear movement of plywood and flakeboard as related to the longitudinal movement of wood. USDA For. Serv. Res. Note FPL-073. For. Prod. Lab., Madison, Wis.

CHAPTER 8: TEST METHODS AND SPECIFICATIONS[11]

To select and use adhesives effectively for building construction depends on trustworthy evaluation methods and performance data for adhesives. But finding test methods and specifications can be bewildering, particularly for someone unfamiliar with adhesive technology. A search will quickly uncover many references to test methods and specifications: Industry standards; commercial standards; product standards: American Society for Testing and Materials (ASTM) standards; Federal test methods and specifications; and military specifications. Which of them apply to building construction uses? Which can be used with confidence? What are their limitations?

This chapter is intended to help make clear what test methods and specifications presently relate to adhesives in building construction, how they are developed, how they obtain acceptance, and how they can be a guide in the successful development of new adhesives and bonded products. However, test methods and specifications for building-construction adhesives are generally only in their infancy at present, and few are widely accepted. Until more adequate tests and specifications are developed specifically for building applications. recourse often must be made to those developed for other purposes. This may be done whenever the objectives of the test or specification can be construed as being relevant to the intended **use.** In general, test methods are found predominantly in ASTM standards; the other sources mentioned concentrate on specifications.

Test methods are under continual development in various laboratories, usually for specific needs of the organizations doing the work. No laboratories in the United States develop test methods for general public use in anticipation of future needs. As new needs develop, those interested in fulfilling them determine experimentally if the old methods can be applied satisfactorily, if they might be used after modification, or if entirely new tests need development. The evaluative techniques of individual laboratories, specific and limited though they may be, are points of origin for all standards and specifications.

Buyer-seller relationships, contractual arrangements, code and other regulatory requirements, and trade agreements-all suggest the need for good test methods and specifications. These needs may he only between individuals or within local communities or industries, or may widen to involve States, or regional, national, and even international interests. Each set of existing standards and specifications was devised for a specific purpose, reflecting the range of views of the interested parties. Methods and specifications of wider scope involve greater numbers of people with more divergent points of view, and have wider geographical impact. But methods and specifications, regardless of their source or purpose, are only as credible as the technology and experience that stands behind them.

[11]Written by Robert H. Gillespie, U.S. Forest Products Laboratory, Madison, Wis., and Richard F. Blomquist, Southeastern Forest Experiment Station. Athens, Ga.

SOURCES OF TEST METHODS AND SPECIFICATIONS

One of the most comprehensive efforts to list and describe specifications for adhesives in general was made by Katz in 1964. He recognized that specifications were living documents constantly being created, changed, and canceled, so he planned to publish supplements at 3-month intervals. However, only one supplement appeared in 1966. Even so, a revised edition was published under the same title and author in 1971 through the efforts of Charles V. Cagle. The publication serves as a source of information about many specifications and standards, particularly for Federal and Military procurement requirements. (For this and other references, see "Background Material," p. 128).

A similar, earlier compilation of test methods and specifications was published by Werner H. Guttmann. It includes the complete texts of a number of Federal and Military specifications available in 1961. Principal stress is on adhesives for metal bonding, military aircraft, and similar uses. However, other useful information on adhesives and bonding processes is also included.

Federal and Military Test Methods and Specifications

The Federal Government has prepared several series of specifications on adhesives for use by its own agencies in purchasing materials. These are administered by the General Services Administration. After preparation, the specifications are forwarded to other interested Government agencies for coordination and approval before release as regular Federal specifications.

Similarly, the Department of Defense prepares a large number of special adhesive specifications; however, these are mainly for applications other than building construction. These documents are also intended for the Department's own purchasing requirements in specifying adhesives for use in its own contracts. Such specifications are also prepared by the individual Armed Services for their own requirements.

Both Federal and Military specifications are often referenced in specifications intended for domestic use by the general public, because often they are the only specifications that can be found which cover specific subjects. Yet they are often not directly applicable to private needs. In addition, changes in Federal and Military specifications are controlled by these agencies for their own needs. Consumer and other domestic interests have no ready opportunity to **seek** changes in them. These deficiencies have led to the development of specific industry standards, and have more recently led to voluntary consensus standards.

Copies of Federal Specifications and Standards may be obtained for a modest fee as outlined under General Information in the Index of Federal Specifications and Standards. The Index, which includes cumulative monthly supplements as issued, is available on a subscription basis from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

Industry Standards

Many industrial firms prepare adhesive specifications for their own use, but these are not generally distributed outside the firms involved, Often a number of firms within an industry band together in a trade association to handle problems of mutual interest, including specifications. Such associations may develop standards and specifications, set up quality-control programs, and establish grademarks as a means of maintaining a respectable level of quality in the products manufactured. Although **trade** association standards are oriented mostly toward the producer's point of view, they serve a very useful purpose and provide the basis for developing commercial or product standards of wider scope.

Commercial and Product Standard

NO central consumer organization exists in the United States, and no national group is specifical-

ly charged with the responsibility to develop uniform industrial or consumer-oriented specifications. However, the U.S. Department of Commerce has means to promulgate specifications and standards for a variety of products used by industry and the public. The initiative for preparing such standards must come from some private group such as an industry association. Then the Department of Commerce supplies technical advisory services for the actual preparation of the specification. The private group must do the actual work of writing and reviewing the specification or standard. The Department of Commerce serves as a coordinating agency upon specific request, and serves as the printing and distribution agency for the resultant standards.

Until 1965, standards were adminstered by the Commodity Standards Division of the Department of Commerce, and the documents were called Commercial Standards. They were identified by a three-part code system, the first being the prefix CS as an abbreviation of Commercial Standard, the second being the serial number, and the third being the last two numbers of the year the standard was issued or last revised. For example, three commercial standards were developed in the softwood plywood industry: CS 45-60 for Douglas-fir plywood, CS 122-60 for western softwood plywood, and CS 259-63 for southern pine plywood. These were later combined into one product standard when the Department of Commerce developed new procedures and transferred the responsibility for promulgation to the Products Standard Section of the National Bureau of Standards. The softwood plywood product standard, PS 1-66, was the first issued under the revised procedures. All Commercial Standards upon revision will be converted to Product Standards with new serial numbers.

Commercial and product standards are developed to be voluntary consensus standards. Consensus standards are so-named since they are used on a nationwide basis and developed voluntarily through the cooperative efforts of all interested parties-producers, distributors, consumers, and users. They are voluntary in that a manufacturer is not required to produce according to the standard, although in most cases it is advantageous for him to do so. Compliance to such product standards is often a requirement in subsequent control documents, such as the Minimum Property Standards of the Federal Housing Administration. Department of Commerce acts as an unbiased coordinator to bring together all interested parties in developing a mutually satisfactory product standard.

At present no commercial or product standards have been prepared on adhesives for use in building construction, although there are a number for bonded wood products such as plywood and laminated timbers. These can be obtained from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC. 20402, for a small fee.

American Society for Testing and Materials Standards[12]

ASTM standards are also voluntary consensus standards. They are developed and written by committees of specialists with a carefully maintained balance of representation from producer. consumer, and general or neutral interests. ASTM Committee D-14 on Adhesives was organized in 1944 when it was felt that the unique nature of adhesives and bonded products and their rapidly expanding usage required a technical committee devoted exclusively to the development of adhesive standards. The members of this committee probably represent the broadest and most extensive technical background on adhesive technology available in the United States today. They have regular and continuous responsibilities under the ASTM charter in the development of standard test methods and specifications relating to adhesives and their use This committee is not directly concerned with methods and specifications for bonded products, but other ASTM committees are.

All ASTM standards must be reviewed and reaffirmed, revised, or canceled at least every 5 years, with opportunity to change any standard on an annual basis if the committee membership approves. ASTM standards and specifications are considerably more adaptable to modifications as needed than are various Government specifications.

A recent trend has involved the development of ASTM specifications on adhesives to replace cer-

[12]ASTM Standards. Published annually by the American Society for Testing and Materials, 1916 Race Street, Philadelphia. Pa. 19103. These standards appear as a multivolume set each year with the test methods, specifications, and recommended practices for adhesives, under the jurisdiction Of Committee D-14 on Adhesives. listed together.

tain Federal and Military specifications that continue to be referenced in standards for domestic use. For example, in the original Commercial Standard CS 253 for Structural Glued Laminated Timber, the adhesives were specified as conforming to Federal Specification MMM-A-125 for Adhesives, Casein-Type. Water and Mold Resistant, and Military Specification MIL-A-397B. February 3, 1953 (as amended) for Adhesive, Room-Temperature and Intermediate-Temperature-Setting Resin (Phenol, Resorcinol, and Melamine Base). Before CS 253 could be revised to become a useful product standard (PS 56), new adhesive specifications had to be developed by ASTM to emphasize performance properties, rather than merely to specify the types of adhesives that were suitable as in the aforementioned Government specifications. These new ASTM specifications were for adhesives used in structural laminated wood products: ASTM D 2559[13] for Use Under Exterior Exposure Conditions and ASTM D 3024 for Use Under Interior Exposure Conditions.

ASTM compilations include test methods, specifications, and recommended practices for a wide variety of adhesives. Since such documents are changing continually with new ones added, the documentation here will include those listed in the 1975 Book of Standards without reference to year of issue or revision of each particular standard. Reference should always be made to the most recent revision of the ASTM Book of Standards. Remember that test methods developed for adhesive applications not normal in building construction might be adapted to evaluate performance in construction applications.

American National Standards Institute Standards

The American National Standards Institute (ANSI) (formerly the American Standards Association, and later the United State of America Standards Institute) has sectional committees which prepare standards. Its purpose is also to serve as a coordinator and publisher on a national level of standards from other sources. All standards accepted by ANSI become available for consideration in the International Standards Organization (ISO), and can well influence international trade. ASTM, among other organizations, submits its standards to ANSI with recommendations that they be considered for inclusion in the ANSI series of standards.

Regulatory Agencies

Model building codes covering a wide range of products and practices have been developed by four building code organizations. They are the American Insurance Association: Building Officials and Code Administrators, International; International Conference of Building Officials; and Southern Building Code Congress. Their codes incorporate or reference many American National Standards as well as those of other organizations. These model codes are applied by thousands of state and local governments.

Standards are also developed to reduce loss of life and property, and to prevent fire, crime, and casualty. Organizations doing so include the National Fire Protection Association; Underwriters Laboratories, Inc.: and Factory Mutual Engineering Corporation. Many of these standards are approved by American National Standards.

The Center for Building Technology of the National Bureau of Standards encourages the development of codes and standards through its office of Building Standards and Codes Services. Among its varied activities, the office sponsors the National Conference of States on Building Codes and Standards which provides a forum for states to discuss problems identified by the Conference, to exchange information, and to develop solutions to the problems.

A national center.–The Housing and Community Development Act of 1974 authorized the establishment of a National Institute of Building Sciences. Although planned as a nongovernmental institution, the Department of Housing and Urban Development was charged with the responsibility for initiating action to organize the institute with the advice and assistance of the National Academy of Sciences, National Academy of Engineering, and the National Research Council. This institute will provide a national center for the assembly, storage, and dissemination of technical data and related information on construction; develop and promulgate nationally recognized performance criteria, standards, test methods, and other evaluative techniques; and evaluate and prequalify existing or new building technology.

[13]The full title for each ASTM standard is given in the listing of standards at the end of the chapter.

Other Agencies That Develop Standards

Many different organizations are involved to a greater or lesser extent in developing and promulgating test methods, specifications, and standards that bear on the use of adhesives in building construction. These include trade associations, federations of trade associations, technical societies, professional groups, consumer agencies, lending institutions, and regulatory agencies at the state, regional, and national level. A list of such interested organizations, which is by no means complete, is appended to this chapter.

MEASUREMENT OF ADHESIVE PROPERTIES

one must decide when reading each standard if the evaluation is of the adhesive itself or of the manufactured, adhesive-bonded product. In most cases, the basic test method and the test specimen may be essentially the same, but the means of bond preparation and specimen selection-and the interpretation of the results-may be quite different.

Test methods and specifications are designed to achieve either of two objectives: To determine the adequacy of an adhesive as a material or to determine the adequacy of a particular type of bonded product. In the first case, the adhesive is evaluated in joints prepared under laboratory conditions with adherends especially selected for high uniformity, strength, and stiffness. Bonding is performed according to manufacturer's recommended procedures for optimum strength formation. In short, variables other than adhesive bonding performance have been eliminated as far as possible. In such tests, the adhesive has the maximum opportunity to perform well and to show its full potential when properly used. Examples of such tests are ASTM D 905 with hard maple adherends in block shear tests, and ASTM D 906 with yellow birch adherends in plywood-type construction. Such test may serve to determine the selection of an adhesive for a particular end use.

When evaluating the manufactured, adhesive-bonded product, the interest is in the performance of the product as a whole. not just in the adhesive which it incorporates. To determine how well an adhesive bonds a product requires adherends and bonding procedures just as are found in manufacture. Bonding conditions, surface preparation, and exposure situations vary just as in commercial fabrication. A good example is the testing of commercially produced softwood ply wood according to U.S. Product Standard PS 1. In this case, the test specimen will be prepared from a large sheet of plywood taken directly from production-a sheet made with run-of-the-mill veneers under bonding conditions typical of the plant on that particular day.

The same procedures used to test an adhesive may be used to test a product, but the test data may be quite different. This is because a number of variables are not controlled in the second situation which are controlled in the first, such as differing qualities of woods as adherends and differing bonding conditions.

Many variables must be evaluated when considering adhesives for use in building construction. These can include a variety of strength properties, a number of working properties of the adhesives, and **the** permanence of joints in different service environments.

The procedures for strength tests may vary from rather crude approximations to complete and precise techniques. In the most precise methods, bonds are made under controlled laboratory conditions with careful selection of materials, adhesive mixing, spreading, assembly, pressing, and reconditioning of the bonded specimens. This is then followed by loading to failure under precise conditions of loading, all at controlled temperature and relative humidity. At the other extreme, joints made under any reasonable set of bonding conditions may be split open with a knife or chisel to note if sufficient strength developed to cause adherend failure rather than adhesive or interfacial failure.

Similarly, tests of working properties of adhesives-such as viscosity, working life, spreading characteristics, or rate of strength development

–can be made either under typical plant conditions with simple equipment or under carefully controlled laboratory conditions. In general, a few tests made even under rather crude conditions will generally be better than no tests at all, provided that the results of such tests are interpreted properly.

It is important to obtain a representative sample for any test. Elaborate tests on a sample of adhesive that may not be representative of the entire source can yield misleading results. Most published test methods include some instructions on selecting proper samples. It is generally batter to cut a few specimens from each of several assemblies rather than to cut a large number from only one or two assemblies. This is because actual bonding conditions will vary to indeterminate degrees from one assembly to another, no matter how precisely fabrication is controlled. The surface characteristics and strength proper ties of the adherends, particularly wood, will vary considerably from piece to piece. Such variations will affect the strength properties of joints and the types of bond failure.

Although many of the test procedures presently in use are intended for application to certain limited types of adhesive-adherend combinations, the general procedures can be modified and used for other types. For example, most of the peel, cleavage, and creep tests were developed for metal-bonding adhesive systems. These cannot be used directly for evaluating adhesives for building construction, but they can be modified to do so until specific procedures are developed.

The ASTM standards which are pertinent to performance of construction adhesives are classified below in terms of adhesives' strength properties, working properties, and permanence properties. One should always refer to the most recent revision of the standards.

Strength Properties

Shear–C 273, D 805, D 905, D 906, D 1002, D 1184, D 1759, D 2182, D 2295, D 2339, D 2557, D 2559, D 3024, and E 229.

Tension–C 297, D 987, D 1344, D 2095, D 3163, D 3164, D 3165, and D 3166.

Cleavage–D 1062 and D 143 (sections 93-97).

Peel–D 903, D 1781, D 1876, D 2918, and D 3167.

Impact–D 950, and D 143 (sections 61-76).

Creep–C 480, D 1780, D 2293, D 2294, and D 2559.

Shear modulus–E 229.

Working Properties

Filler content–D 1488 and D 1579.

Nonvolatile content–D 1489, D 1490, and D 1582.

Hydrogen-ion content (pH)–D 1583.

Applied weight–D 898 and D 899.

Consistency (viscosity)–D 1084 and D 2556,

Density–D 1875.

Storage life–D 1337.

Working life (pot life)–D 1338.

Penetration (into adherends)–D 1916.

Tack–D 2979 and D 3121.

Blocking (adherence to other materials before bonding)–D 1146.

Flow–D 2183.

Preparation of adherend surfaces (primarily metals and plastics)–D 2093, D 2094, D 2561, and D 2674.

Rate of strength development–D 1144.

Permanence Properties

Resistance of adhesive bonds to:

Atmospheric exposure–D 1828 and D 2919.

Artificial and natural light–D 904.

Continuous exposure to controlled laboratory conditions of temperature and moisture–D 1151.

Cyclic exposure to controlled laboratory conditions–C 481, D 1037, D 1101, and D 1183.

Chemical reagents–D 896.

High energy radiation–D 1879.

Mold contamination and mold conditions–D 1286 and D 1877.

Bacterial contamination–D 1174.

Rodents (rats)–D 1383.

Roaches–D 1382.

TEST DEVELOPMENT NEEDS

Many tests have been developed to determine the resistance of adhesive bonds to environmental conditions encountered in service. While each of these tests can measure some one aspect of bond permanence, they do not attempt to predict long-term performance. A major problem is the development and standardization of accelerated laboratory procedures to evaluate the long-term serviceability of new adhesives. These procedures must consider the chemical and biologically induced changes that occur in the natural process of aging. They must also consider the physical effects resulting from loads imposed on the bonds and from dimensional changes in service. The procedures must be capable of predicting performance under the different temperature and moisture conditions likely in service.

The adhesives likely to be used for building construction in the future are only now being developed. They will probably differ from those now used for large scale plywood or laminated timber production. More attention is being given to developing adhesive systems for onsite application; for prefabrication and plant construction where close-fitted joints are not typical; and where bonding conditions are less subject to control than in the production of such products as plywood. As new adhesive systems are developed, new test procedures are needed to measure their unique properties,

Another major challenge is to develop methods for evaluating creep or deformation of adhesives under load, particularly for structural applications in building construction. Although a considerable amount of work is underway to develop these test procedures, suitable standard tests are still not established.

SPECIFICATIONS

The best specifications to be imagined could not cover all applications of modem adhesives in building construction, since so many varying adhesive formulations and circumstances of use are to be found. Furthermore, new adhesives and new applications are introduced year by year. We suggest an examination of the few standard specifications for adhesives and bonded products that exist in ASTM standards and Federal specifications. For example, ASTM standards[13] currently contain specifications for adhesives used in laminated timbers (D 2559 and D 3024), for floor systems (D 3498). for acoustical materials (D 1779), for fastening gypsum board to wall framing (C 557), and for use in manufacturing nonstructural lumber products (D 3110). The use in laminated timbers and floor systems is for specific structural applications. The latter three are for nonstructural use where performance requirements are not as stringent.

In developing specifications, one must decide on performance requirements and relate performance to the pertinent adhesive properties. These properties can then be measured by recognized test procedures and realistic performance values established for each property. To do so requires a careful analysis of the end-use requirements, close attention to the variability and reliability expected in the manufacture of the assembly, and an assessment of the unplanned adversities that may occur during the service life of the product. New needed specifications are currently being developed. This should involve active participation of all interested parties. Only through the cooperative efforts of adhesive producers, users, and consumer groups will adequate new specifications be developed, become widely accepted, and be used with effectiveness.

A PARTIAL LIST OF STANDARDS AND SPECIFICATIONS

ASTM Standards for Adhesives

C 273 Standard Method of Shear Test in Flatwise Plane of Flat Sandwich Constructions or Sandwich Cores

C 297 Standard Method of Tension Test of Flat Sandwich Constructions in Flatwise Plane

C 480 Standard Method of Test for Flexure-Creep of Sandwich Constructions

C 481 Standard Method of Test for Laboratory Aging of Sandwich Constructions

C 557 Standard Specification for Adhesives for Fastening Gypsum Wallboard to Wood Framing

D 143 Standard Methods of Testing Small Clear Specimens of Timber

D 805 Standard Methods of Testing Veneer, Plywood, and Other Glued Veneer Constructions

D 896 Standard Method of Test for Resistance of Adhesive Bonds to Chemical Reagents

D 897 Standard Method of Test for Tensile Properties of Adhesive Bonds

D 898 Standard Method of Test for Applied Weight Per Unit Area of Dried Adhesive Solids

D 899 Standard Method of Test for Applied Weight Per Unit Area of Liquid Adhesive

D 903 Standard Method of Test for Peel or Stripping Strength of Adhesive Bonds

D 904 Standard Recommended Practice for Determining the Effect of Artificial (Carbon-Arc Type) and Natural Light on the Permanence of Adhesives

D 905 Standard Method of Test for Strength Properties of Adhesive Bonds in Shear by Compression Loading

D 906 Standard Method of Test for Strength Properties of Adhesives in Plywood Type Construction in Shear by Tension Loading

D 907 Standard Definitions of Terms Relating to Adhesives

D 950 Standard Method of Test for Impact Strength of Adhesive Bonds

D 1002 Standard Method of Test for Strength Properties of Adhesives in Shear by Tension Loading (Metal-to-Metal)

D 1037 Standard Methods of Evaluating the Properties of Wood-Base Fiber and Particle Panel Materials

D 1062 Standard Method of Test for Cleavage Strength of Metal-to-Metal Adhesive Bonds

D 1084 Standard Methods of Test for Viscosity of Adhesives

D 1101 Standard Method of Test for Integrity of Glue Joints in Structural Laminated Wood Products for Exterior Use

D 1144 Standard Recommended Practice for Determining Strength Development of Adhesive Bonds

D 1146 Standard Method of Test for Blocking Point of Potentially Adhesive Layers

D 1151 Standard Method of Test for Effect of Moisture and Temperature on Adhesive Bonds

D 1174 Standard Method of Test for Effect of Bacterial Contamination on Permanence of Adhesive Pereparations and Adhesive Bonds

D 1183 Standard Methods of Test for Resistance of Adhesives to Cyclic Laboratory Aging Conditions

D 1184 Standard Method of Test for Flexural Strength of Adhesive Bonded Laminated Assemblies

D 1286 Standard Method of Test for Effect of Mold Contamination on Permanence of Adhesive Preparations and Adhesive Bonds

D 1337 Standard Method of Test for Storage Life of Adhesives by Consistency and Bond Strength

D 1338 Standard Method of Test for Working Life of Liquid or Paste Adhesives by Consistency and Bond Strength

D 1344 Standard Method of Testing Cross-Lap Specimens for Tensile Properties of Adhesives

D 1382 Standard Method of Test for Susceptibility of Dry Adhesive Films to Attack by Roaches

D 1383 Standard Method of Test for Susceptibility of Dry Adhesive Films to Attack by Laboratory Rats

D 1488 Standard Method of Test for Amylaceous Matter in Adhesives

D 1489 Standard Method of Test for Nonvolatie Content of Aqueous Adhesives

D 1490 Standard Method of Test for Nonvolatile Content of Urea-Formaldehyde Resin Solutions

D 1579 Standard Method of Test for Filler Content of Phenol, Resorcinol, and Melamine Adhesives

D 1582 Standard Method of Test for Nonvolatile Content of Phenol, Resorcinol, and Melamine Adhesives

D 1583 Standard Method of Test for Hydrogen Ion Concentration of Dry Adhesive Films

D 1759 Standard Method of Conducting Shear-Block Test for Quality Control of Glue Bonds in Scarf Joints

D 1779 Standard Specification for Adhesive for Acoustical Materials

D 1780 Standard Recommended Practice for Conducting Creep Tests of Metal-to-Metal Adhesives

D 1781 Standard Method for Climbing Drum Peel Test for Adhesives

D 1828 Standard Recommended Practice for Atmospheric Exposure of Adhesive-Bonded Joints and Structures

D 1875 Standard Method of Test for Density of Adhesives in Fluid Form

D 1876 Standard Method of Test for Peel Resistance of Adhesives (T-Peel Test)

D 1877 Standard Method of Test for Permanence of Adhesive-Bonded Joints in Plywood Under Mold Conditions

D 1879 Standard Recommended Practice for Exposure of Adhesive Specimens to High-Energy Radiation

D 1916 Standard Method of Test for Penetration of Adhesives

D 2093 Standard Recommended Practice for Preparation of Surfaces of Plastics Prior to Adhesive Bonding

D 2094 Standard Recommended Practice for Preparation of Bar and Rod Specimens for Adhesion Tests

D 2095 Standard method of Test for Tensile Strength of Adhesives by Means of Bar and Rod Specimens

D 2182 Standard Method of Test for Strength Properties of Metal-to-Metal Adhesives by Compression Loading (Disk Shear)

D 2183 Standard Method of Test for Flow Properties of Adhesives

D 2293 Standard Method of Test for Creep Properties of Adhesives in Shear by Compression Loading (Metal-to-Metal)

D 2294 Standard Method of Test for Creep Properties of Adhesives in Shear by Tension Loading (Metal-to-Metal)

D 2295 Standard Method of Test for Strength Properties of Adhesives in Shear by Tension Loading at Elevated Temperatures (Metal-to-Metal)

D 2339 Standard Method of Test for Strength Properties of Adhesives in Two-Ply Wood Construction in Shear by Tension Loading

D 2556 Standard Method of Test for Apparent Viscosity of Adhesives Having Shear-Rate-Dependent Flow Properties

D 2557 Standard Method of Test for Strength Properties of Adhesives in Shear by Tension Loading in the Temperature Range From -267.8 to -55 C (-450 to -67 F)

D 2559 Standard Specification for Adhesives for Structural Laminated Wood Products for Use Under Exterior (Wet Use) Exposure Conditions

D 2651 Standard Recommended Practice for Preparation of Metal Surfaces for Adhesive Bonding

D 2674 Standard Methods of Analysis of Sulfochromate Etch Solution Used in Surface Preparation of Aluminum

D 2918 Standard Recommended Practice for Determining Durability of Adhesive Joints Stressed in Peel

D 2919 Standard Recommended Practice for Determining Durability of Adhesive Joints Stressed in Shear by Tension Loading

D 2979 Standard Method of Test for Pressure-Sensitive Tack of Adhesives Using an Inverted Probe Machine

D 3024 Standard Specification for Protein-Base Adhesives for Structural Laminated Wood Products for Use Under Interior (Dry Use) Exposure Conditions

D 3110 Specification for Adhesives Used in Nonstructural Glued Lumber Products

D 3111 Tentative Recommended Practice for Flexibility Determination of Hot-Melt Adhesives by Mandrel Bend Test Method

D 3121 Standard Method of Test for Tack of Pressure Sensitive Adhesives by Rolling Ball

D 3163 Standard Recommended Practice for Determining the Strength of Adhesively Bonded Rigid Plastic Lap Shear Joints in Shear by Tension Loading

D 3164 Standard Recommended Practice for Determining the Strength of Adhesively Bonded Plastic Lap Shear Sandwich Joints in Shear by Tension Loading

D 3165 Standard Method of Test for Strength Properties of Adhesives in Shear by Tension Loading of Laminated Assemblies

D 3166 Standard Method of Test for Fatigue Properties of Adhesives in Shear by Tension Loading (Metal/Metal)

D 3167 Tentative Method of Test for Floating Roller Peel Resistance of Adhesives

D 3310 Standard Recommended Practice for Determining Corrosivity of Adhesive Materials

E 229 Standard Method of Test for Shear Strength and Shear Modulus of Structural Adhesives

D 3433 Standard Recommended Practice For Fracture Strength in Cleavage of Adhesives in Bonded Joints

D 3434 Standard Recommended Practice for Multiple-Cycle Accelerated Aging Test (Automatic Boil Test) for Exterior Wet Use Wood Adhesives

D 3498 Specification for Adhesives for Field-Gluing Plywood to Lumber Framing for Floor Systems

Examples of Federal Specifications and Standards

MMM-A-100 Adhesive, animal glue, 25 July 1967.

MMM-A-110 Adhesive, asphalt, cut-back type (for asphalt and vinyl asbestos tiles). 16 March 1966.

MMM-A-115 Adhesive, asphalt, water emulsion type (for asphalt and vinyl asbestos tile), 3 January 1964.

MMM-A-125 Adhesive, casein type, water and mold resistant, 18 March 1969.

MMM-A-130 Adhesive, contact, 15 June 1964.

MMM-A-137 Adhesive, linoleum, 2 July 1965.

MMM-A-138 Adhesive, metal to wood, structural, 2 March 1967.

MMM-A-00150 Adhesive for acoustical materials, 3 October 1962.

MMM-A-180 Adhesive, polyvinyl acetate resin emulsion (alkali dispersible). 2 September 1964.

MMM-A-181 Adhesive, room temperature curing and intermediate temperature curing resin (phenol, resorcinol, and melamine resin). 5 October 1967.

MMM-A-188 Adhesive, urea-resin-type (liq uid and powder), 8 November 1960.

MMM-A-193 Adhesive, vinyl acetate resin emulsion, 26 October 1967.

Federal Test Method Standard No. 175, Adhesives: Methods of Testing, Latest revision.

Examples of Military Specifications and Standards

MIL-A-5092 Adhesive, rubber base, general purpose. 23 May 1969.

MIL-A-5433 Adhesive, application of room-temperature and intermediate-temperature-setting resin (phenol, resorcinol, and melamine base), 22 August 1966.

MIL-A-5535 Adhesive, application of high-temperature-setting resin (phenol, melamine, and resorcinol base), 12 March 1951.

MIL-G-6803 Gluing, application of cold-setting resin (urea type), 25 July 1961.

MIL-A-8623 Adhesive, epoxy resin, metal to metal structural bonding, 23 September 1960.

MIL-A-9067 Adhesive bonding, process and inspection requirements for, 16 March 1961.

MIL-A-14042 Adhesive, epoxy. 17 August 1964.

MIL-A-18065 Adhesive, high initial bond, 23 June 1966.

MIL-A-21016 Adhesive, resilient deck covering, 26 January 1967.

MIL-A-21366 Adhesive. for bonding plastic table top material to aluminum, 16 February 1966.

MIL-A-22397 Adhesive, phenol and resorcinol resin base (for marine use), 8 September 1960.

MIL-A-45059 Adhesive for bonding chipboard to terneplate, tinplate and zinc-plate, 3 February 1964.

MIL-A-46050 Adhesive, special; rapid room temperature curing, solventless, 10 August 1964.

MIL-STD-401 Sandwich Constructions and Core Materials: General Test Methods, 15 June 1956.

PARTIAL LIST OF ORGANIZATIONS INVOLVED WITH STANDARDS

Acoustical and Board Products Association
Adhesive and Sealant Council
American Institute of Timber Construction
American Insurance Association, Division of Codes and Standards
American National Metric Council
American Plywood Association
American Society of Civil Engineers
American Wood Preservers' Institute
American Wood-Preservers' Association
Architectural Woodwork Institute
Building Officials and Code Administrators International
Building Research Institute, National Research Council
California Redwood Association
Construction Specifications Institute
Council of American Building Officials
Factory Mutual Engineering Corporation
Federal Housing Administration, Department of Housing and Urban Development
Hardwood Plywood Manufacturers Association
International Conference of Building Officials
Model Code Standardization Council
Mobile Home Institute
National Association of Building Manufacturers
National Association of Home Builders of the United States
National Conference of States on Building Codes and Standards
National Fire Protection Association
National Forest Products Association
National Institute of Building Sciences
National Particleboard Association
National Woodwork Manufacturers Association
Product Fabrication Service
Society of the Plastic Industry
Society of Automotive Engineers
Southern Building Code Congress International
Southern Forest Products Association
Timber Engineering Company
Underwriters Laboratories, Incorporated
United States Savings and Loan League, Architectural and Construction Research
Western Wood Moulding and Millwork Producers
Western Wood Preservers Institute
Western Wood Products Association

BACKGROUND MATERIAL

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1964. Adhesive materials-Their properties and usage. Foster Publishing Co., Long Beach, Calif.

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1971. Adhesive materials-Their properties and usage. Rev. Charles V. Cagle. Foster Publishing Co., Long Beach, Calif.

CHAPTER 9:

INSPECTION AND CONTROL[14]

The wood and building construction industries have perhaps been slower than others to recognize the importance of quality control as a separate and distinct function. However, with present trends toward industrializing aspects of building construction, it becomes imperative that production lines be subject to an effective quality-control system.

With adhesive bonding, more so than other fabrication methods, control of production variables will determine bond quality and thus the performance of the finished product. Therefore, driven by necessity, industries using adhesives for fabrication have developed efficient quality control systems.

THE QUALITY CONTROL DEPARTMENT

In each manufacturing operation, quality control should be established as a recognized function along with engineering, production, sales, and purchasing. Manpower responsible for this function should be assigned, and the quality control department should be clearly shown on the firm's organizational chart.

Organization

In setting up lines of authority it is imperative that quality-control personnel not be under the supervision of the production department. Ideally, they should answer directly to the general manager or other top management. The production department normally should set up certain production line checks, but this is not synonymous with, nor a substitute for, an effective quality-control department.

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Interrelation with Production

A healthy relationship between the production and quality-control departments can be aided by good management. Quality of production is more related to the attitude of top management than it is to the attitude of the worker on the machine. If management is bringing undue pressure on the production department to reach production and profit goals, inspectors will have problems and quality will suffer. Management should reflect a consistent attitude toward quality to all personnel.

The production superintendent can offer valuable support to any quality-control program imposed by management in his area of responsibility. He knows most thoroughly the various factors which affect quality: Tools, fixtures, equipment, processes, materials. and personnel.

When good cooperation between production and quality control does not exist, a breakdown in communication is usually at fault. It is most important that the people involved in production

supervision recognize quality control as important and that they make maximum use of its personnel's specialized expertise. The production supervisor should gladly cooperate with the quality-control department because:

1. He will ultimately be held responsible for the cost, schedule, and quality of the finished product.

2. If design, processes, equipment, method, operator, training, or other control factors are faulty, he will fail to reach assigned goals of cost, schedule, and quality.

3. He may make some improvements on his own, but quality-control personnel have the skill, time, and budget to help him reach solutions.

Quality-control personnel should never forget that they are to be a part of the solution, not a part of the problem. They are to spot potential problems so that, wherever possible, rejection or reworking of a faulty product is prevented. They should realize the importance of accomplishing their **task** so that production is not hampered more than is necessary.

Quality-control personnel are sometimes in a unique position to spot potential production improvements. They should be free to recommend changes.

Personnel

Personnel for quality control should have experience, training, and integrity. Experience should include a good background in the use of adhesives, preferably in the kinds and applications immediately concerned. Quality-control training in inspection and testing procedures is an important part of an effective department. Written examinations should be employed to assure that the training has adequately prepared the individuals for what is expected of them.

Integrity and character are necessary in inspection personnel. The ability to say "no," tact, and sound judgment should all be sought in choosing inspectors.

Equipment

The quality-control department should have all of the gages, instruments, tools, and other equipment necessary to make quick and accurate checks of all factors having a substantial effect on the quality of the finished product,

Following is a list of equipment normally needed to do effective inspection of a wood-adhesive fabrication operation:

1. Moisture meter-to measure moisture content of lumber.

2. Small oven capable of a temperature of 100° C (220° F)–to measure moisture content of plywood and treated lumber.

3. Set of calipers accurate to 0.001 inch–to check dimensional variation in lumber and plywood.

4. Balance scales accurate to 0.1 gram–used as a part of measuring moisture content of ply wood and calculating adhesive spread.

5. Pyrometer with thermocouple wire attachment with a minimum range of -18° to 149° C (0° to 300° F)–to measure temperature of materials, platens, bondlines under cure, and so forth.

6. Torque wrench with a range of at least 0 to 300 foot-pounds-to accurately set required pressure when assemblies are being clamped by tightening bolts. In some laminating operations, a range of 0-600 foot-pounds is necessary.

7. Compressometer or other device which will accurately measure total pressure in pounds-to calibrate bolts with torque wrenches when bolted assemblies are used to apply pressure.

8. Psychrometer or hygrometer-to aid in the control of temperature and humidity in the plant.

9. Watch or clock-to monitor open and closed assembly time, presstime, and other operations where time is critical.

10. One-half-inch heavy-duty drill with 2-inch diameter corecutting saw and template- to take samples from finished members for bondline tests.

11. Straight edge and set of feeler gages-to measure dimensional variations in surfaces to be bonded, beds of planers or other surfacing equipment, and so forth.

12. Measuring devices capable of checking finished product for dimensional tolerance, squareness, surfacing, and so forth.

13. Electric hand saw equipped to take scarf samples.

For bonded laminated timber, the following additional laboratory equipment is desirable:

14. A block shear testing device or equipment to cut and test 1-inch-diameter cylindrical core specimens.

15. Equipment for performing the vacuum pressure (cyclic delamination) test, including autoclave and drying oven.

16. Equipment for testing end joints in bending or tension.

If regular laboratory tests to demonstrate the strength and durability of bonds being achieved are not being carried out by an independent agency, the manufacturer should have testing machines to accomplish such tests in-plant.

All gages, instruments, and tools should be kept clean and maintained in proper working order. They should be recalibrated periodically to insure accuracy of measurement. Instructions for proper maintenance and recalibration are usually supplied by the manufacturer of each measuring device.

ROLE OF THE INDEPENDENT TESTING AGENCY

The concept of third-party inspection, testing, and certification is now widespread with construction products and systems, particularly when adhesives are being used structurally in the manufacturing process. This principle is employed in the industry-wide, quality-control pro grams, referred to earlier, which are operated by American Plywood Association, American Institute of Timber Construction, and Product Fabrication Service.

In the early 1930's in one of the earliest formal efforts toward quality control with adhesives, leaders of the then-young softwood plywood industry determined that quality control was a key element in the effective marketing of plywood. The Douglas-fir Plywood Association (now called American Plywood Association) was charged by its members with the marketing of a product with known performance based on a sound, industry wide, quality-control program. This was one of the first, and remains as one of the outstanding, examples of a wood industry policing itself and delivering to the customer a product in which he can have confidence. Subsequently, similar programs were evolved for laminated wood beams through the American Institute of Timber Construction, and for plywood structural components through Plywood Fabricator Service (now called Product Fabrication Service).

Each of these organizations, in its own industry, serves as an unbiased, independent third party, supplementing in-plant quality control. Agency personnel perform random unannounced inspections on a continuing basis.

These organizations offer the manufacturer and consumer several advantages. First of all, agency personnel are chosen for their high degree of expertise in the production of particular bonded products. They are valued for the know-how that they bring to a plant. Because they move about the industry, they are in a position to recommend many good ideas for improving production, and to warn against ideas that have been unsuccessful. They can be trusted never to give away trade secrets.

Undoubtedly the most tangible value of third-party certification is the increased product acceptance when certified by an approved independent agency as being in conformance with an established standard. Indeed, many regulatory bodies will not accept bonded structural elements unless they are so certified, and the trend is to more and more requirements of this kind.

Furthermore, third-party certification within an industry tends to stabilize quality, making it difficult for the manufacturer not willing to produce to industry standards to gain acceptance in the marketplace. Self-certification, increasingly under attack, tends to cause wide nonuniformity in interpretation of industry standards with a resulting wide range in quality among products supposedly manufactured to the same standard.

The independent testing agency has five main roles to play in the plants of its clients:

1. Establishing procedures. The first responsibility of the agency is the preparation of a quality-control manual which establishes inspection and testing procedures that are tailored to the particular production of that plant, These specifics will normally he based on established general procedures by which the agency operates in all similar plants.

2. The manufacturer is responsible for assigning manpower to the function of in-plant quality control, hut the agency will need to examine these people for qualifications and in most cases institute an on-the-job training program to make them fully qualified for the job they are to do. Some agencies require in-plant inspectors to take written examinations at the conclusion of training. Upon the successful completion of the examinations, these people are designated "Certified Inspectors."

3. The third role of the agency is that of supervising the in-plant, qualitycontrol program. Records are examined, such as those of inspection and sampling, and the in-plant inspector is observed as he carries out his function in the plant.

4. Agency personnel also carry out their own inspections during their regular visits to the plant. Of course, the findings during their inspections must generally agree with those reported in their absence or they will want to determine why.

5. The major role of the agency is that of administering product certification. The goal of all its effort is to provide the user of the product with a label which gives him assurance that the prod. uct he has purchased does in fact meet specification. It is imperative that the agency not only police the inspection and testing so that product quality can be determined, but that it also maintain strict control of its quality label so that only those products which are in full conformance can have it applied. The agency cannot tell the manufacturer what he is going to make or how he is go. ing to make it, but it can tell him on which products he can apply the agency's "quality in spected" label.

ROLE OF THE REGULATORY BODY

Although the independent agency is providing a paid service to the manufacturer under contract, in a real sense the agency also becomes the instrument of the regulatory bodies in whose jurisdiction the product will be installed. Two basic services are performed by the regulatory body: (1) Approving the plans and specifications for the product, and approving the agency as authorized to police the production for compliance; (2) monitoring the performance of both the manufacturer and the approved agency. Monitoring involves checking on product quality in the field as well as making infrequent visits to both the plant and the agency.

IN-PLANT QUALITY CONTROL

The in-plant, quality-control program must be a continuing operation. It should combine production, supervision, and workmanship with plant inspection and laboratory testing, and it must be directed at all production. The quality-control system starts with the materials that are to be used and continues through the manufacturing operation until the finished product leaves the plant. The inspector must have his own set of approved drawings and specifications for the job and be able to read and understand them. He must know how to make the inspections and how to use the equipment.

Inspection of a bonding operation will include: (1) Materials: (2) workmanship; (3) in-process checks, tests, and calculations; and (4) equipment and how to use it.

The inspection details which follow will generally correspond to those actually performed by one industry association when inspecting the fabrication of wood and wood-base components. Inspection of any bonding operation will normally include the same or similar steps.

Materials

The quality-control inspector starts by inspecting all of the materials to be used in the production run. This includes lumber, plywood, adhesive, and in some cases allied materials such as paper honeycomb, urethane, or polystyrene foam.

Lumber

The lumber must be inspected for proper species, grade, moisture content, surfacing, dimensions, and warp. It should bear a grademark of a grading agency approved by the American Lumber Standards Committee. This grademark will show the lumber's species and grade. If the lumber has been resawn, a qualified inspector must regrade the material. (For laminating timbers, the lumber must be regraded at the laminating plant, with particular attention paid to slope of grain for tension laminations.)

The moisture content must be checked to be sure it is within the limits called for in the specifications. A typical requirement would be that the moisture content at the time of bonding be between 7 and 16 percent, and that the variation between pieces bonded together not exceed 5 percent.

All bonding surfaces of lumber, including face, end, and edge, must be smooth and free of raised or torn grain, skips, burns, glazing, or other deviations from the plane of the surface that might interfere with joint contact. Lumber should also be free from dust, foreign matter, or exudation that might be detrimental to satisfactory bonding. The lumber should be free of warp, twist, cup, or other characteristics which would prevent intimate contact of adjacent bonded surfaces.

Lumber with thickness or width variations greater than specifications should he rejected unless it can be scheduled for use where exact dimensions are not requisite. Thickness is critical for multiple laminations and width is critical for multiple framing members in stressed skin panels. In these cases, excess variation in dimensions of lumber will prevent bonding surfaces from making intimate contact. Oversized dimensions can be corrected by resurfacing to precise sizes just prior to bonding.

Plywood

Plywood is inspected according to specifications for species group number, type, grade, thickness, moisture content, and trademark of a qualified inspection and testing agency,

The grade-trademark on the plywood certifies that it meets applicable requirements, such as those in Product Standard PS-1. The trademark also includes information as to the species group number, the type (exterior or interior), and the grade.

The inspector must check the plywood for thickness and moisture content. Moisture meters will give accurate readings on many plywoods, but some plywoods contain adhesives more conductive than wood which will elevate the readings. With plywoods containing conductive adhesives, it is necessary to use the ovendrying method to reliably determine moisture content.

The surface of the plywood to be bonded must be clean and free of oil, dust, paper tape, and other materials which would be detrimental to satisfactory bonding.

Adhesive

The inspector checks to make sure the correct type of adhesive is used. A typical fabrication specification permits an interior-type adhesive to be used when the equilibrium moisture content of the member in use does not exceed 18 percent (16 percent for laminated lumber).

The only purely interior-type adhesive for construction bonding much used at the present time is casein containing a mold inhibitor, which must conform with ASTM D 3024.

Exterior-type adhesives must be used for construction bonding when the equilibrium moisture content of the member in use exceeds 18 percent (16 percent for laminated timber) or when directly exposed to the weather. These adhesives must meet ASTM Specification D 2559. They include synthetic resins of phenol, resorcinol, and melamine. A moisture content of 18 percent in wood will normally be reached with an average relative humidity of 85 percent at temperatures from 0° to 38° C (32° to 100° F) maintained for over a week. The inspector must make certain that the adhesive has been stored according to the manufacturer's suggestions and that shelf life has not been exceeded.

In general, phenol-resorcinol resin adhesives have poor gap-filling properties, casein has fair gap-filling properties, and elastomeric construction adhesives are especially formulated for good gap-filling performance.

Allied Materials

When allied materials such as paper honeycomb or foam cores of urethane or polystyrene are to be bonded to wood. the inspector must make sure that the materials are in full compliance with specifications and that manufacturers' recommendations are followed in their handling and use.

Workmanship

Workmanship is considered in all of the steps of a bonding operation. It starts with raw material preparation and does not end until the finished product is loaded for shipment.

Material Preparation

Stressed-skin components, including plywood scarfed to lengths longer than 8 feet, must be checked for squareness and correct length. Specifications require that the plywood be square within 1/8 inch for panels 4 feet wide and proportionally to this for other widths. Cutouts made in the plywood before bonding must be located and cut accurately. The lumber must be surfaced to the correct dimension and cut to the proper lengths.

Stringers and headers for a stressed-skin panel are frequently assembled into a frame. Stringers must be properly located and alined. The various pieces of lumber in any one frame must be equal in depth to within 1/32 inch to prevent areas of low or no pressure during bonding.

The inspector should measure the ambient temperature and relative humidity in the work space and determine the temperature of the material to be bonded. With this information he can specify assembly times as recommended by the adhesive manufacturer.

Fabrication

The inspector should check for proper mixing of the adhesive, including the weighing of the ingredients, to see that the proportions are as required by the adhesive manufacturer. He should see that they are mixed in the proper order, with correct mixer speed. Comments on bonding techniques and their limitations in the following sections are based mainly on conventional casein and phenol-resorcinol resin woodworking adhesives.

As the panels are laid up, the inspector watches all phases of the layup. Spreading of the adhesive must be as recommended by its manufacturer. It must be spread over the entire bonding area with no skips, and at the proper rate. As the operation proceeds, the inspector watches to see that the working life of the adhesive is never exceeded and that new batches of adhesive are mixed when necessary. He determines the shop temperature because it affects assembly times. He verifies that open and closed assembly times are within the specified limits.

As the pieces of the component are assembled, the inspector watches to see that the end joints in the lumber and plywood are in the locations shown in the specifications. The correct location and placement of any stiffeners or blocking is noted. Edges of components are examined to see that they conform to the drawings.

After the component is assembled, the inspector observes its placement in the press. In a cold-press operation, the panels must be stacked up evenly to insure that all bondlines receive equal pressure. If it is a hot-press operation, panels must be centered in the press to avoid uneven pressure or damage to the press. Pressure application is observed to assure correct amount and duration. (A minimum of 100 pounds per square inch over all joint areas is recommended for wood-to-wood bonding.)

Some components are nail bonded. Here the inspector makes certain that the size of the nails or staples and their spacing is as specified. He needs to be doubly alert to be sure that they are properly driven into the wood if an adequate adhesive bond is to be achieved.

When the adhesive cures, and especially when heat is applied, the inspector checks the bondline temperature and makes sure it is maintained for the specified time. (Failure to cure the adhesive properly can result in delamination or failure under stress.)

Finishing

After the adhesive has cured, the components are ready to be cleaned up for final grading and shipping. It is at this time that the inspector removes required test samples from noncritical areas. Any holes that result must be patched.

For example, a typical specification for ply wood components provides for two appearance grades. The first requires that the exposed skin surface be of a sanded grade of plywood; that all adhesive and other foreign matter be removed from the surface and any area where it might interfere with fitting panels together; that nailheads be countersunk and filled; and that all holes and butt joints in the skins be filled with wood shims or plugs and be neatly sanded.

The second appearance grade permits unsanded plywood and open spaces up to 1/8 inch in butt joints in the skin. Excess adhesive and foreign matter need not be removed except where it would interfere with fit of the panels, and nailheads need not be countersunk and filled.

The inspector checks the components for final dimensions-thickness, width, length, and squareness-and makes sure they are free of twist and bow.

In-Process Checks, Tests, and Calculations

As the quality-control inspector performs his duties, he may make several checks and tests.

Moisture Content

The first is to check the moisture content in **the** lumber and plywood. The amount of moisture in wood is ordinarily expressed as a percentage of the weight of the wood when ovendried. Two methods of determining moisture content are: (1) The ovendry method, which is probably the most exact but is slow and necessitates heating of wood, and (2) a moisture meter, which is the most rapid method.

In the ovendrying method, a cross section about 1 inch long in the direction of the grain is cut from representative boards of a lot of plywood or lumber. These sections should be cut at least 1 foot from the ends of the boards to avoid the effect of end drying and should be free from knots and other irregularities.

Each section is immediately weighed on a scale capable of weighing to the nearest 0.1 gram before any drying or absorption of moisture has taken place, and is then placed in an oven heated to 101° to 105° C (214° to 221° F) and kept there until it reaches constant weight. If the section

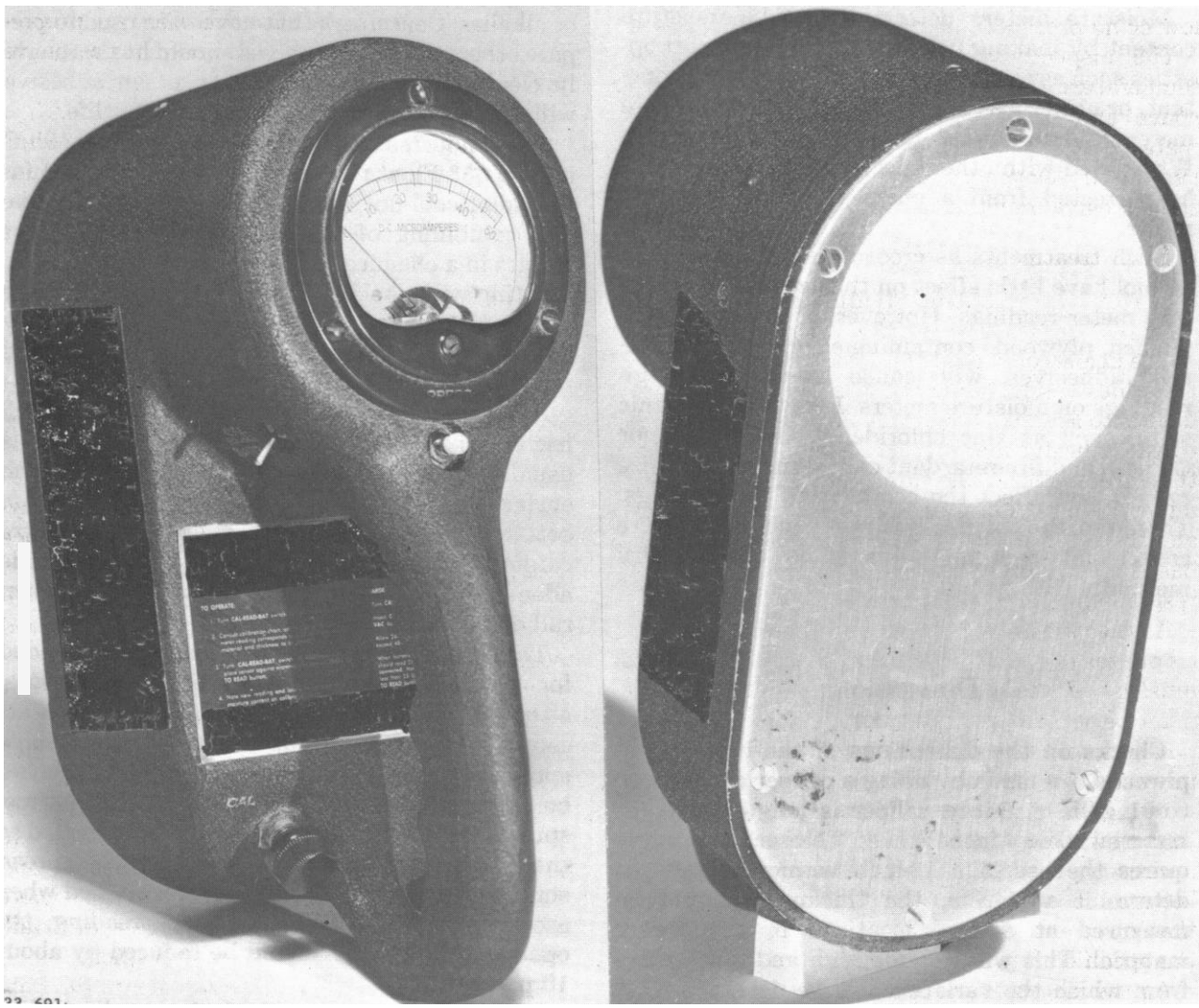

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Figure 69.–A moisture meter for indicating percent moisture content of wood. The model shown is of the dielectric type.

cannot be weighed immediately after it is cut, it should be wrapped in metal foil until it can be weighed. In the oven, a section will reach a constant weight in 12 to 48 hours.

The formula to determine the percentage of moisture content is:

$$\text{Percent moisture content} = \frac{\text{Weight when cut - ovendry weight} \times 100}{\text{Ovendry weight}}$$

For an example, a piece of wood weighs 1,245 grams before drying and 990 grams after drying. Using the above formula, the moisture content is:

$$\frac{1{,}245 \text{ grams} - 990 \text{ grams}}{990 \text{ grams}} \times 100 = 25.7 \text{ percent moisture content.}$$

Moisture meters determine wood's moisture content by making use of wood's electrical properties such as electrical resistance, dielectric constant, or power-loss factor (fig. 69). Most moisture meters are calibrated for use with Douglas-fir. When used with other species, the reading must be corrected from a chart provided with the meter.

Such treatments as creosote and pentachlorophenol have little effect on the accuracy of moisture meter readings. However, as previously explained, plywoods containing electrically conductive adhesives will cause inaccurate, high readings on moisture meters. Likewise, inorganic salts, such as zinc chloride, Wolman salts, or Osmose and fire-retardant compounds, electrolize readily and affect the accuracy of the readings. Therefore, the only reliable way to check moisture content of such materials is by the ovendry method.

Dimensions

Checks on the dimensions of the lumber and plywood are made by using a caliper accurate to 0.001 inch. A 6-inch caliper is long enough for material up to 4 inches thick. Thicker material requires the use of a 12-inch vernier caliper. To determine variation, the thickness should be measured at several locations in a piece of material. This will provide high and low figures from which the variation can be determined. A straight edge and a set of feeler gages are used to measure variations in long or large surfaces to be bonded.

Temperature and Relative Humidity

The temperature and relative humidity of the bonding area are measured with a psychrometer. This should be done before bonding starts to determine recommended open and closed assembly times.

Adhesive Mixing and Spreading

Ingredients should be accurately measured and added in proper sequence. The use of a mechanical mixer is recommended. All mixing and spreading equipment should be clean and free from acids or alkalies. Containers that have been used to prepare other types of adhesives should be thoroughly cleaned, since contamination of an adhesive will affect its performance and working life.

The liquid resins should be cool, 16° to 19° C (60° to 65° F), at the time of mixing and the mixture kept cool until the adhesive spread is made. The combining of the resin with the hardener results in a chemical reaction that produces heat. Starting with cool resin, maintaining the mixture at or near 21° C (70° F) and stirring occasionally reduces the heat build-up in the adhesive mix, and increases working life.

An adhesive spread of 70 to 100 pounds of adhesive mix per 1,000 square feet of bondline is usually recommended, one-half applied to each surface in order to wet both surfaces and provide better bonding. Where bonding conditions are carefully controlled, a lower adhesive spread is adequate for some operations, such as when radiofrequency curing is used.

The spreading of both surfaces is recommended for the production of structural components, although spreading adhesive on one surface is acceptable in some applications when a double spread is not possible. In this case, control should be established to insure that the assembly time, spread, and application of pressure are selected so that good transfer of adhesive from the spread surface to the opposing surface is obtained when assembly is made. When single spreading, the open assembly time should be reduced by about 10 percent.

The most common method of spreading adhesive for bonded-laminated timber is by the extruder which applies the adhesive in closely

spaced narrow strips on only one face of the member. This method of spreading permits handling the individual laminates without removing the adhesive. Also the allowable assembly time may be somewhat longer than is obtained with roller spreading. Assembly time is usually based on a partial open condition where individual laminates are not in contact during the entire assembly period. This frequently occurs in large assemblies of laminated timbers.

Heavier spreads should be employed when long assembly times are required, or when wood or room temperature is above 27° C (80° F). The **amount** of adhesive spread in pounds per thousand square feet of single bondline is determined by using the following formula:

$$\frac{\text{Weight of the adhesive in grams} \times 319}{\text{Area of sample in square inches}}$$

= pounds per thousand square feet of single bondline

For an example, a piece of plywood 10 by 20 inches (200 square inches) weighs 100 grams. After it is spread with adhesive, it weighs 150 grams. Using the above formula, the adhesive spread is:

$$\frac{[150 \text{ grams} - 100 \text{ grams}] \times 319}{10 \times 20}$$

= 79.7 pounds per thousand square feet of single bondline

Working Life, Assembly Time, and Squeezeout

An inspector cannot control an adhesive's working life, but he should be aware of errors on the part of workmen which may unduly shorten it. With reactive adhesives, the higher the temperature the shorter the usable life of the adhesive. Therefore, the mixed adhesive should be kept cool, using cooled glue pots during warm weather. Also, the working life of many adhesives is extremely sensitive to even traces of acids, so all equipment should be kept clean.

The open and closed assembly times will vary depending **on** the wood temperatures, the relative humidity, the weight of adhesive spread, and the number of laminates to be put under pressure as one package. A clock or other timing device is used to keep track of total assembly time. The clock is started when the first piece has adhesive spread on it, and is stopped when the pressure is applied. The inspector must be alert to distinguish the open time from the closed time.

A slight squeezeout of adhesive uniformly along the edge of all joints when the pressure is applied is a good indication that the spread is adequate and that the total assembly time has not been exceeded. On the other hand, excessive squeezeout may indicate that the assembly time was too short, the spread was too heavy, the pressure was too high, or combinations of these three factors.

Pressure

A minimum pressure of 100 pounds per square inch and a maximum of 150 pounds per square inch is recommended for lumber to lumber, ply wood to plywood, and plywood to lumber applications. A caul placed over the assembly and under the clamps will provide a better distribution of pressure, especially where thin plywood or other sheet material is applied. Clamps should be spaced close enough to give a uniform pressure and bolts should be checked with a calibrated torque wrench to be sure that sufficient and uniform pressure is applied. If a large assembly is placed in a heated chamber for cure, the pressure should be checked several times during the first hour of heat-up and adjusted if necessary. A bondline thickness of between 0.002 to 0.007 inch is recommended.

To determine the amount of pressure on a bondline. the following formula is used:

$$\frac{\text{Total force applied in pounds}}{\text{Bondline area in square inches}}$$

= pressure in pounds per square inch

To calculate the total force applied for a press with hydraulic cylinders, the area of the cylinder, line pressure, and number of cylinders must be known.

As an example, to calculate the pressure on a stressed-skin panel that has two headers 1-1/2 inches wide and 48 inches long, and four stringers 1-1/2 inches wide and 100 inches long, assume a hot press that has eight cylinders, 12 inches in diameter (113 square inches), and with a line pressure of 100 pounds per square inch.

First calculate the bondline area:

2 headers x 1-1/2 x 48 inches + 4 stringers x 1-1/2 x 100 inches = 144 + 600 = 744 square inches

Next determine the force applied by the press:

8 cylinders x 113-square-inch area of 1 cylinder x 100 pounds per square inch line pressure = 90,400 pounds

Then determine pounds per square inch on the bondline:

$$\frac{\text{90,400 pounds}}{\text{744 square inches}} = \text{121 pounds per square inch}$$

Many fabricators use presses that have fire hoses filled with air to apply the pressure. With this type of press, the length of the fire hose, the contact area with the caul, and the air pressure in the hose must be known.

For an example, assume the length of the fire hose is 100 inches, there are four fire hoses (one over each stringer), and the contact area of each inflated hose is 3 inches. The total force is:

4 hoses x 3 x 100 inches x 80 pounds per square inch (hose pressure)
= 96,000 pounds

If this force is applied to the panel above (744 square inches). the pressure is:

$$\frac{\text{96,000 pounds}}{\text{744 square inches}} = \text{128 pounds per square inch}$$

In some cold-press operations, the pressure is applied with clamps held in place by two chains or rods, one on each side. If the press is 100 inches long and has eight clamps (located 12 inches on center), and each clamp applies a force of 12,000 pounds (6,000 pounds at each end), then the total force on the press is 96,000 pounds. This force applied to the same stressed-skin panel (744 square inches) will give 128 pounds per square inch on the bondline.

In a press such as this, the rods or chains are tightened with impact wrenches to approximately the force required (fig. 70). They then are tightened to the final desired force with a torque wrench. The torque wrench must be calibrated to the rods or chains used. Calibrating the torque wrench will be discussed later.

Pressure Period and Curing Temperatures

The time that components should be kept under pressure depends on the bondline temperature. For a resorcinol resin adhesive, the rate of chemical reaction between the liquid resin and the powdered hardener is increased at higher temperatures. Speeding up the reaction after the adhesive is applied by heating the bondline will shorten the pressure period.

The pressure period interval is measured from the time the innermost bondline reaches the indicated curing temperature until clamp removal. This pressure period is independent of the initial temperature of the wood. The wood temperature, of course, will affect the heat-up period before the desired bondline temperature is reached.

The bondline temperature is measured by using thermocouples embedded in the bondline and connected to a pyrometer. Enough thermocouples must be used. scattered throughout the bondline, to locate any area or areas that might be cold. The temperature of the platen in a hot press must be checked frequently with a surface-reading thermocouple attached to the pyrometer to be certain the press is heating evenly. Cold spots can be caused by trapped condensate in a steam. heated press, or by failure of a heater in an electrically heated press.

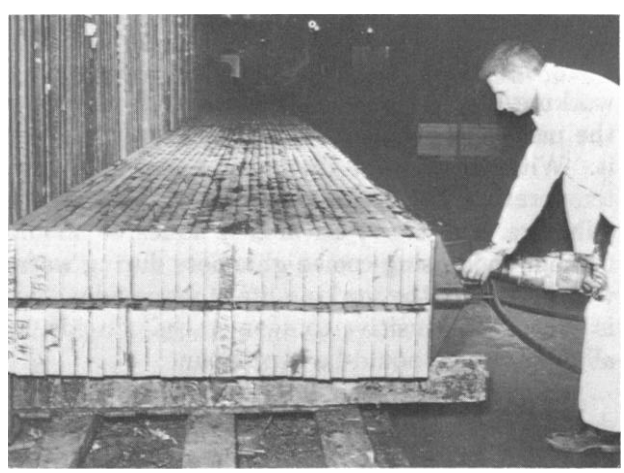

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Figure 70.–Tightening clamps on bonded assemblies with impact wrench operated by compressed air.

Equipment and How to Use It

Moisture Meter

To operate the resistance-type moisture meter, connect the electrode to the moisture detector and make sure that the meter is in adjustment. The pins on the electrode should be driven into the wood a distance recommended by the meter manufacturer (usually about 5/16 inch) in such a manner that the current will flow parallel to the grain. Some electrodes use a sliding hammer to drive the pins into the wood. Another type of electrode is the hammer type which is satisfactory for use in softwoods. Care must be taken to keep the pins perpendicular to the grain of the wood.

Some resin adhesives used to make plywood affect the operation of the moisture meter. To determine whether or not the accuracy is affected, drive the contact pins through not more than one-half the thickness of the first ply and read the meter. Then drive the pins so that they just pass through the first bondline. If there is no appreciable increase in moisture reading as the pins make contact with the bondline. then the adhesive may be considered to have no effect and the reading will be correct. Some pins have an insulating coating on the shank with only the tips bare so that surface moisture will not give abnormally high readings in relation to the bulk moisture content.

Some types of moisture meters operate on either power-loss or capacitance principles which do not require the wood to be penetrated by electrodes. The hand-held meter can generally be operated faster than the resistance type, but is influenced more by variations in density. Another type of meter may be installed in the production line to measure the moisture content of every piece of lumber used.

Caliper

On most calipers accurate to 0.001 inch, the bar of the tool is graduated in fortieths of an inch (0.025 inch). Every fourth division represents a tenth of an inch, and is numbered. On the vernier is a space divided into 25 parts with every fifth mark numbered. Read the tool to inches, tenths (0.1). and fortieths (0.025). The zero mark on the vernier is from the zero mark on the bar; add to the reading the number of divisions on the vernier from the zero line to a line that exactly coincides with a line on the bar. Dial calipers are also used. They are easier to read than vernier calipers, and some have maximum and minimum pointers which can be preset.

Balance Scale

The most frequently used balance scale, accurate to 0.1 gram, is of the triple-beam type. The scale should be placed level and balanced with the sliding poises located at their zero marks. The item to be weighed should be placed on the scale and each of the sliding poises moved, starting with the one for the 100 grams, then the 10 grams, and finally the 1 and 0.1 gram. until the scale is balanced. The marks on each of three scales are then added together. If the scale is moved, it must be zeroed again before using.

Pyrometer

The pyrometer is used to measure bondline temperatures. The correct type of thermocouple wire must be used with the instrument for accurate readings. A thermocouple is two wires of dissimilar metals, a plus and a minus wire, joined together. The wires may be purchased as bare wires or with insulation between them. The point at which the two wires touch each other is the point at which the temperature is recorded.

The wires, joined together by twisting, are placed in the bondline at the location where the temperature is to be measured. Temperature measurements must be made throughout a press load so as to find any places where the temperature may be low. A thermocouple usually is placed at the midpoint of the bondline farthest from the heat source.

Compressometer

The compressometer or other pressure-measuring device is used to calibrate torque wrenches with clamping rods or chains so that accurate pressure readings can be made (see "Torque Wrench" below). The instrument must be equipped with an accurate gage. It is essential that the compressometer be centered in the clamp setup used so that even pressure will be applied by the bolts being tested. A more convenient compressometer is the hollow-ram type, which has a hole through the piston. This allows calibration on one bolt at a time.

Torque Wrench

Since the pressure applied to the package of laminations varies not only with the torque applied to the nuts, but also with the size of bolts, number of threads per inch, and the condition of the threads and washers used, it is necessary to calibrate the torque wrench with each set of bolts used on the job. The following or other methods which give comparable results may be used in the calibration of the torque wrench when a solid-ram type of compressometer is used:

1. Select a number of bolts which will be used for application of pressure on the job at hand.

2. Select two clamp blocks with a bolt hole in each end of each block. Also have available miscellaneous short blocking for extending compressometer setup to full length of bolts.

3. Set up compressometer and assemble bolts and blocking

4. Place nuts on bolts and turn evenly with hand wrench until compressometer gage reads a certain amount, such as 5,000 pounds or so.

5. Secure a torque wrench reading in foot-pounds on each bolt. Reading should be taken at the instant that the nut starts to turn.

6. Repeat this operation several times using different bolts from the preselected representative stock, but hold to the 5,000-pound compressometer reading on each setup.

7. Compute an average torque wrench reading from the various readings obtained. Torque wrench readings for various bolts on the project will usually vary somewhat, but no substantial variation should occur if bolts are uniform and in good condition.

8. This average torque reading corresponds to a certain load in pounds on one bolt, which is equal to one-half of the compressometer gags reading because two bolts are used. In the example used, this amount will be 2,500 pounds per bolt. The equipment is now calibrated and the inspector knows the torque wrench dial reading in foot-pounds which will indicate a certain total force on the assembly.

Since torque wrench readings are, within workable limits, proportional to the pull on a bolt, the actual pull on any bolt can readily be determined by means of the torque wrench and the use of simple proportion computations.

9. The inspector may for his own convenience make up a calibration chart or table for the shop

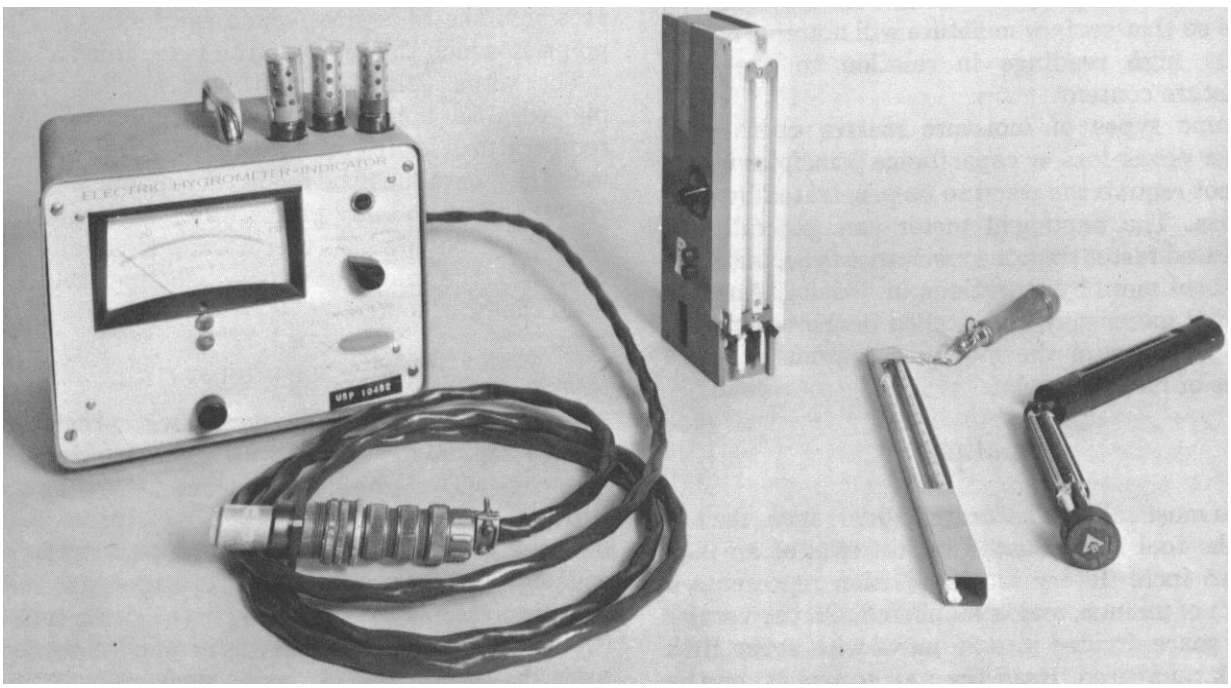

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Figure 71.–Instruments for measuring relative humidity. Left to right: electric hygrometer, with three sensors utilizing conductive salts; blower-type psychrometer, battery powered and portable; two sling psychrometers.

torque wrenches. The corresponding bolt loads and torque readings form a straight line when plotted on cross-section paper. When the hollow-ram compressometer is used, only one bolt is used, and the torque corresponding to various force readings is easily determined without the necessity for averaging.

Some torque wrenches do not have a dial but can be preset to a desired torque. When the desired torque is reached, the torque wrench emits a clicking sound. In this case, the torque wrench and bolts are calibrated by setting the torque on the wrench and reading the compressometer gage when the wrench clicks.

Psychrometer or Hygrometer

Several types of instruments are available to measure relative humidity (fig. 71). Psychrometers measure relative humidity by showing the temperature on two matched thermometers, one with a dry-bulb and the other a wet-bulb. A stream of moving air is required to depress the wet-bulb temperature by evaporation. Then, the two temperatures yield relative humidity by reference to a chart supplied with the instrument.

The sling psychrometer is the simplest type. Moving air is supplied to the wet-bulb by whirling the entire instrument on a cord for 15 or 20 seconds. Many psychrometers today use battery powered blowers to provide an air stream. Both types are compact and easily portable. The blower type is simpler to use.

Psychrometers can be highly accurate but are susceptible to contamination of the wet-bulb wick, and the sling type to operator error. Accuracy of psychrometers is greatest at high, and poorest at low, relative humidities. This can be a difficulty because plant bonding is often under conditions of comparatively low relative humidity.

Modern electric hygrometers provide an alternative to psychrometers. although they are more expensive. Portable types are available. Many operate on the principles of capacitance or electrical resistance. using adsorbent salts like lithium chloride or aluminum oxide in their sensors. They are capable of high accuracy and near instantaneous readings. Some have a computer function so relative humidity can be read directly, without charts or calculations.

One-Half Inch Drill and Hole Saws

For cutting test samples from plywood-to-lumber joints it is convenient. to use a 1/2-inch drill equipped with a hole saw about 2-1/2 inches in diameter. The pilot drill is removed from the hole saw so as to avoid holes in the center of the test specimens. To guide the hole saw, a plywood template is used.

Confirming Laboratory Tests

Adhesive Strength

The standard shear test specimen for determining adhesive strength of wood-to-wood bonds is described in ASTM Standard D 905. This test specimen is 2 by 2 inches with a 1/4-inch step at each end which results in a test area 1-1/2 by 2 inches, or 3 square inches. Stress is applied along the grain.

For quality-control purposes, testing laboratories have found it convenient to reduce the size of ASTM standard specimens or to devise specimens for testing specific types of joints. The following describes test specimens used by one reputable testing laboratory, not necessarily by all.

For quality control strength tests, a smaller block shear test specimen may be used. such as 1 by 1-1/2 inches with 1/4-inch steps at each end. This specimen provides a test area of 1 square inch.

Such specimens should be tested in a block shear tool with the load applied along the grain through a self-alining seat to insure uniform lateral distribution of the load (fig. 72). Rate of load application is 0.2 inch per minute. Ultimate load is read to the nearest 5 pounds, and wood failure is estimated to the nearest 5 percent. This procedure is similar to the one specified in ASTM D 905.

One testing agency requires a dry strength of 650 pounds per square inch for Douglas-fir, southern pine, and western larch, and 520 pounds per square inch for other western softwoods. The American Insitute of Timber Construction (AITC) has similar but somewhat different requirements depending on the species and the moisture content at the end of bonding.

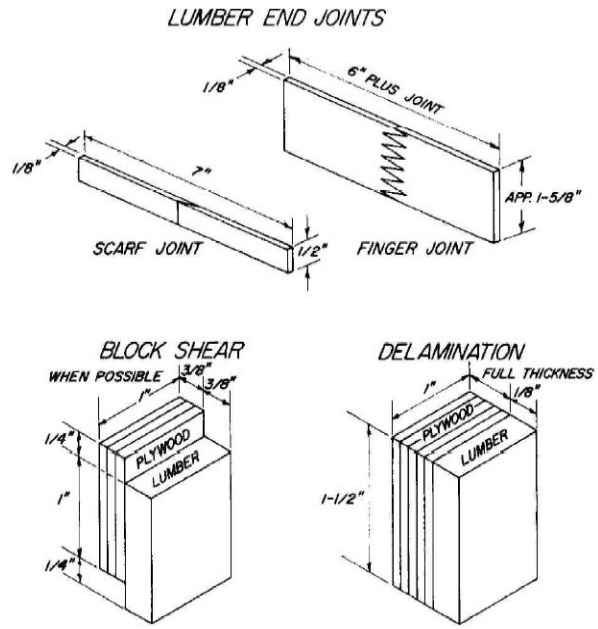
Other test specimens are used for determining the dry strength of adhesive bonds in lumber and

plywood scarf joints and honeycomb sandwich panels (figs. 73 and 74). At least eight test specimens are cut for each full-sized lumber scarf joint. The test specimens are 1/8 ± 0.005 by 1/2 ± 0.005 by 7 inches long with the joint in the center of the specimen running diagonally across the 1/8-inch face. Half the specimens are tested dry for tension in a testing machine capable of loading them at the rate of 0.4 inch per minute. The remaining half of the specimens are tested for delamination.

The Douglas-fir, western larch, and southern yellow pine specimens are required to carry an average of 7,000 pounds per square inch, with at least 80 percent of the specimens carrying 6,000 pounds per square inch. Other western softwood must carry an average of 6,000 pounds per square inch with at least 80 percent of the specimens carrying 5,000 pounds per square inch. Wood failure requirements, regardless of species, must average 80 percent but with a minimum requirement that 90 percent of the individual specimens have not less than 40 percent wood failure.

M 141 912

Figure 12.–Testing specimens for shear strength.



M 141 774

Figure 73. Suitable test specimens for lumber and lumber-plywood combinations for shear. tension, and delamination.

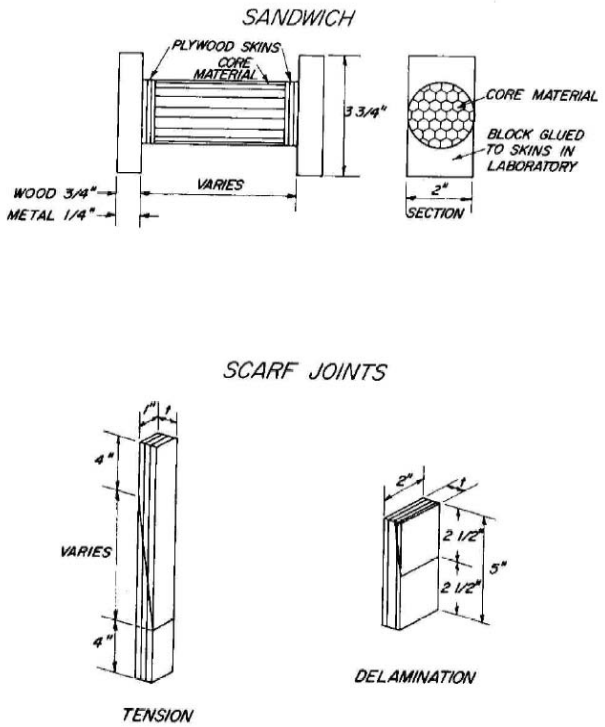
Full-sized plywood scarf samples are cut into 20 test specimens, 1 inch wide and 7 inches longer than the scarf joint. For example, specimens from 1/2-inch plywood with a scarf cut 4 inches long would he 11 inches. One-half the test specimens are tested dry for tension, the other half are tested wet after exposure to standard cyclic treatments described in U.S. Product Standard PS 1.

Plywood scarf specimens are required to meet the dry strength requirement of U.S. Product Standard PS 1: Three test specimens from any one panel must average:

Group 1	4,000 pounds per square inch
Groups 2 and 3	2,800 pounds per square inch
Group 4	2,400 pounds per square inch

The stress requirements are computed on the plies parallel to the direction of the applied load. In addition to the stress requirement, and regardless of species, the wood failure must average 80 percent, but with a minimum requirement that 90 percent of the specimens have not less than 50 percent wood failure.

For testing honeycomb sandwich panels, test specimens 2 inches in diameter are cut through the panel (fig. 75). To each side of the specimen are bonded wood blocks 2 by 3-1/4 by 3/4 inches which fit a fixture in the testing machine. The specimens are loaded in tension at the rate of 0.4



M 141 769

Figure 74.–Suitable test specimens for sandwich materials and scarf joints in plywood for tension and delamination.

of an inch per minute. The specimens are required to carry 90 percent of the ultimate shear stress as listed in the core manufacturer's specifications.

Adhesive Durability

Several tests are used to determine if a joint, manufactured with an adhesive of known durability, can be expected to perform satisfactorily in the anticipated end-use environment-usually either in exterior or interior applications, The following test procedures are intended to assure that the bonding process has produced bonds as durable as the adhesive is capable of attaining. These tests **induce** typical swelling and shrinkage stresses on joints under wet and dry cyclic conditions. Such stresses may be more severe than external stresses involved in typical mechanical tests on dry specimens initially. Adequate qualification tests must also include resistance to the influences of long-term aging, such as heat, chemicals. and micro-organisms,

Exterior-Type Bonds (Cold Soak)

Test specimens are submerged in water at room temperature for 48 hours and then dried for 8 hours at a temperature of 63° ± 3° C (145° ± 5° F), followed by two cycles of soaking for 16 hours and again drying for 8 hours. The specimens are soaked again for a period of 16 hours and tested wet. Specimens are then sheared while wet and percent wood failure estimated.

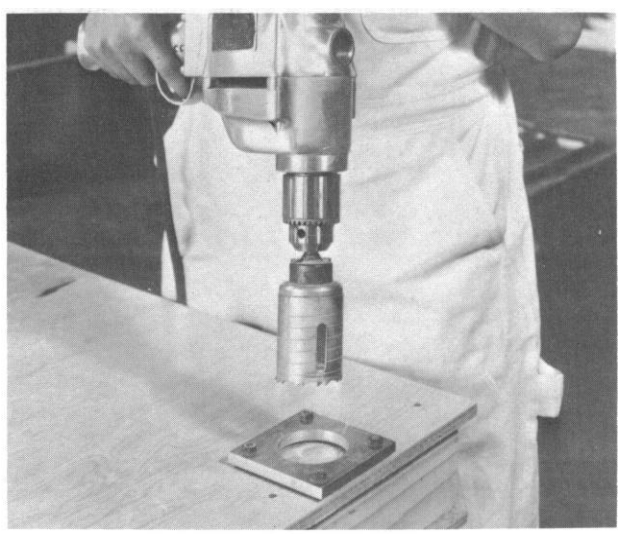
ExteriorType Bonds (Vacuum Pressure)

The specimens are placed in the pressure vessel and weighted down. Water, at a temperature of 18° to 27° C (65° to 80° F) is admitted so that the specimens are completely submerged. The specimens are separated by stickers, wire screens, or other means in such a manner that all end-grain surfaces are freely exposed to the water. A vacuum of 20 to 25 inches of mercury (at sea level) is drawn and held for 30 minutes. The vacuum is released and a pressure of 40 ± 5 pounds per square inch is applied for 2 hours. Specimens are removed from the vessel and tested as specified.

Specimens are sheared while still wet, dried, and the wood failure estimated. The exterior durability requirement is that wood failure must average 85 percent or more. but 90 percent of all specimens tested must show 60 percent or more wood failure. and 80 percent of all specimens tested must show 80 percent or more wood failure.

Interior-Type Bonds (Cold Soak)

This test requires that the specimens be submerged in water at room temperature for a



M 141 924

Figure 75.–Cutting specimen from sandwich panels.

period of 4 hours and then dried at a temperature between 38° and 41° C (100° and 105° F) for a period of 19 hours. Air circulation in the drying cabinet should be sufficient to lower moisture content of the specimen to a maximum of 8 percent based on ovendry weight. This test procedure must be conducted through three cycles unless all specimens have failed. A specimen is said to have failed when the adherends delaminate for a continuous length of 1 inch along the edge of the specimen for a depth of 1/4 inch.

To pass the test, 95 percent of all specimens must pass the first cycle, and 85 percent must pass three cycles.

Interior-Type Bonds (Vacuum-Pressure)

This test requires placing the specimens in a pressure vessel and weighting them down. Water, at a temperature of 43.3° C (110° F) is admitted in sufficient quantity so that the specimens are completely submerged.

The specimens are separated by stickers, wire screen, or other means in such a manner that all end-grain surfaces are freely exposed to the water. A vacuum of 15 inches of mercury (at sea level) is drawn and held for 30 minutes. The vacuum is released and the specimens are allowed to soak for 4-1/2 hours with no additional heating. The specimens are removed from the vessel and dried in an oven at 66° C (150° F) for 15 hours. To pass this test, 85 percent of all specimens must pass one cycle.

Other Cyclic Delamination Tests

AITC 201 requires joints prepared with a wet use (exterior) adhesive to pass one of three cyclic delamination tests. All of these tests are variations of ASTM D 1101. At the completion of the tests, the amount of open bondline is measured and must not exceed 5 percent.

Exterior lumber and plywood scarf specimens are given the same durability tests as listed earlier for the block shear specimens, and then tested in tension while still wet. Exterior lumber scarfs are required to average 85 percent wood failure, but 90 percent of the specimens must average not less than 50 percent wood failure.

Exterior plywood scarf joints must average not less than 85 percent wood failure. The requirements for interior plywood scarfs are the same as for the block shear specimens: For the first test, 35 percent of the specimens must pass one cycle, and 85 percent of the specimens must pass three cycles. In the second interior durability test (vacuum soak), 65 percent of the specimens must pass one cycle.

Honeycomb interior durability test specimens are tested in either of the interior tests, and then tested in tension. The exterior honeycomb specimens are tested in the exterior durability (cold soak) method as listed for the block shear test with an additional 8-hour drying period at 63° C (145° F). The specimens are then **tested** in tension.

Both exterior and interior honeycomb specimens are required to carry 90 percent of the ultimate shear stress as listed in the core manufacturer's specifications.

ONSITE BONDING AND QUALITY CONTROL

Until recent years durable adhesives capable of performing structurally were limited to a few types, all of which had such restricted use requirements that in-plant use under controlled conditions was all that could be recommended. Recent developments in adhesive technology, particularly with elastomeric type adhesives, have made available products suitable for use in the field.

For example, onsite bonding of plywood to wood framing in floor construction is now a proven method of achieving superior floor construction that virtually eliminates the age-old problems of squeaky floors and nail-pop. At the same time, increased spans for floor joists are possible, and the plywood can be applied with considerably fewer nails (chapter 2).

Quality control under this kind of field situation must obviously be less sophisticated and formal. However, for good performance, personnel applying the adhesive should be trained in proper procedures, and supervisors should set up checks to make sure these are followed and that proper bonding is evident.

Adhesive manufacturers' recommendations should be followed without deviation. Any limitations noted on the containers should be strictly observed.

It is particularly important that the surfaces to be bonded be free of ice, snow, free water, mud. sawdust, and any other foreign materials. The adhesive should be spread at the rate recommended and, in any case, there should be a sufficient quantity to produce a uniform bead of squeezeout. The adhesive should be applied to all contact areas between the two surfaces, normally to the framing members. Thick mastic adhesives, commonly applied as a bead down the center of the joint, will not normally squeeze out, but there should be evidence that the mastic has spread to the edges of the joint.

Unless the manufacturer's recommendations specifically permit otherwise, the adhesive should be spread for only one or two panels at a time. In any case, manufacturer's recommended assembly time should be observed, and the proper number, spacing, and size of mechanical fasteners should be installed.

The adhesive should be carefully chosen as one specified for construction purposes, and it should be certified by an approved independent testing agency as being in compliance with industry standards. In addition to an initial certification, the agency must carry out continuing field sampling and followup testing to assure sustained quality.

GLOSSARY

(Source of most definitions is indicated at the end of each. See Identification at end of Glossary.)

Acoustical board.–A low-density, sound-absorbing structural insulating board having a factory applied finish and a fissured, felted-fiber, slotted or perforated surface pattern provided to reduce sound reflection. Usually supplied for use in the form of tiles. ASTM

Adhere.–To cause two surfaces to be held together by adhesion. ASTM

Adherend.–A body which is held to another body by an adhesive. ASTM

Adhesion.–The state in which two surfaces are held together by interfacial forces which may consist of valence forces or interlocking action or both. ASTM

Adhesion, mechanical.-Adhesion between surfaces in which the adhesive holds the parts together by interlocking action. ASTM

Adhesion, specific.-Adhesion between surfaces which are held together by valence forces of the same type as those which give rise to cohesion. ASTM

Adhesive.– A substance capable of holding materials together by surface attachment. ASTM ASTM

Adhesive, assembly.–An adhesive which can be used for bonding parts together, such as in the manufacture of a boat, airplane. furniture, and the like. ASTM

NOTE: The term "assembly adhesive" is commonly used in the wood industry to distinguish such adhesives (formerly called "joint glues") from those used in making plywood (sometimes called "veneer glues"). It is applied to adhesives used in fabricating finished structures or goods, or subassemblies thereof, as differentiated from adhesives used in the production of sheet materials for sale as such, for example, plywood or laminates.

Adhesive, cold-setting.–An adhesive which sets at temperatures below 20° C (68° F). ASTM

Adhesive, contact.–An adhesive which is apparently dry to the touch and which will adhere to itself instantaneously upon contact: also called contact bond adhesive or dry bond adhesive. ASTM

Adhesive, gap-filling.–Adhesive suitable for use where the surfaces to be joined may not be in close or continuous contact owing either to the impossibility of applying adequate pressure or to slight inaccuracies in matching mating surfaces. ASTM

Adhesive, heat-activated.–A dry adhesive film which is rendered tacky or fluid by application of heat or heat and pressure to the assembly. ASTM

Adhesive, hot-melt.–An adhesive that is applied in a molten state and forms a bond on cooling to a solid state. ASTM

Adhesive, hot-setting.–An adhesive which requires a temperature at or above 100° C (212° F) to set it. ASTM

Adhesive, intermediate-setting.–An adhesive which sets in the temperature range 31° to 99° C (87° to 211° F). ASTM

Adhesive, room-temperature-setting.–An adhesive which sets in the temperature range of 20° to 30° C (68° to 86° F), in accordance with the limits for Standard Room Temperature specified in the Standard Methods of Conditioning Plastics and Electrical Insulating Materials for Testing (ASTM Designation: D 618). ASTM

Adhesive, separate application.–A term used to describe an adhesive consisting of two parts; one part being applied to one adherend and the other part to the other adherend and the two brought together to form a joint. ASTM

Adhesive, solvent. –An adhesive having a volatile organic liquid as a vehicle. ASTM

NOTE: This term excludes water-based adhesives.

Adhesive, solvent-activated.–A dry adhesive film which is rendered tacky just prior to use by application of a solvent. ASTM

Anisotropic.–Material exhibits differing values for physical properties when measured along differing axes. Wood is an anisotropic material. AUTH

Axial.–In the direction of, or along an axis. AUTH

Balanced construction.–A construction such that the forces induced by uniformly distributed changes in moisture content will not cause warping. Symmetrical constructions in which the grain direction of the plies is either parallel or perpendicular to each other are balanced constructions, ASTM

Beam.–A structural member transversely supporting a load. AH73

Bond, n.–The union of materials by adhesives. ASTM

Bond, v.–To unite materials by means of adhesive. ASTM

Bondline.–The layer of adhesive which attaches two adherends. AUTH

Bond strength.–The unit load applied in tension, compression, flexure, peel, impact, cleavage, or shear. required to break an adhesive assembly with failure occurring in or near the plane of the bond. ASTM

Casehardening.– (1) A condition of stress and set in dry lumber characterized by compressive stress in the outer layers and tensile stress in the center or core. AH72

(2) Surface condition of a substrate that renders it difficult to wet with adhesives. AUTH

Catalyst.–A substance which markedly speeds up the cure of an adhesive when added in minor quantity as compared to the amounts of the primary reactants. ASTM

Gaul.–A sheet of material employed singly or in pairs in hot or cold pressing of assemblies being bonded. Cauls are employed usually to protect either the faces or the press platen or both against marring and staining, to prevent sticking, and to facilitate press loading. ASTM

NOTE: Cauls may be made of aluminium, stainless steel, hardboard, or fiberboard with the length and width generally equal to the platen size of the press in which they are employed.

Centroid.–That point in a system of parallel forces having fixed points of application, through which their resultant will always pass, regardless of how the forces may be turned. SAF

Check.–In the case of wood, a separation along the grain, the greater part of which occurs across the rings of annual growth. ASTM

Chemical bond.–A chemical bond exists between two atoms or groups of atoms where the forces acting between them are such as to lead to the formation of an aggregate with sufficient stability to make it convenient for the chemist to consider it as an independent molecular species. AUTH

Chord.–Either of the two outside members of a truss connected and braced by the web members. AUTH

Closed assembly.–See Assembly time.

Cobwebbing.–A phenomenon observed during the spray application of an adhesive characterized by the formation of weblike threads along with the usual droplets as the adhesive leaves the nozzle of a spray gun. AUTH

Coefficient of thermal expansion.–The change in unit volume per degree temperature increase over a specified initial temperature. It is commonly stated as the average coefficient over a given temperature range. ASTM

Cohesion.–The state in which the particles of a single substance are held together by primary or secondary valence forces. As used in the adhesive field, the state in which the particles of the adhesive (or the adherend) are held together. ASTM

Cold pressing. – A bonding operation in which an assembly is subjected to pressure without the application of heat. ASTM

Composite.–A structural element consisting of wood and combination of other materials in which all pieces are attached together to act as a single unit. AITC

Compression wood.–Abnormal wood formed on the lower side of branches and inclined trunks of softwood trees. Compression wood is identified by its relatively wide annual rings, usually eccentric; its relatively large amount of summerwood. sometimes more than 50 percent of the width of annual rings in which it occurs; and a lack of demarcation between springwood and summerwood in the same annual ring. Compression wood shrinks excessively lengthwise as compared with normal wood. ASTM

Compressometer.–A device for measuring force or pressure. AITC

Condensation.–A chemical reaction in which two or more molecules combine with the separation of water or some other simple substance. If a polymer is formed, the process is called polycondensation. ASTM

Conditioning (pre and post).–The exposure of a material to the influence of a prescribed atmosphere for a stipulated period of time or until a stipulated relation is reached between material and atmosphere. ASTM

Consistency.–That property of a liquid adhesive by virtue of which it tends to resist deformation. ASTM

NOTE: Consistency is not a fundamental property but is comprised of viscosity. plasticity, and other phenomena.

Construction adhesive.–Any adhesive used to assemble primary building materials into components during building construction-most commonly applied to elastomer mastic-type adhesives. AUTH

Contact cement,–See Adhesive, contact.

Core.–A generally centrally located layer or composite component of a sandwich construction, usually low density, which separates and stabilizes the facings and transmits shear between them and provides most of the shear rigidity of the construction. ASTM

Crazing.–Fine cracks which may extend in a network on or under the surface of or through a layer of adhesive. ASTM

Creep.–The dimensional change with time of a material under load, following the initial instantaneous elastic or rapid deformation. Creep at room temperature is sometimes called cold flow. ASTM

Cross grain.–A pattern in which the fibers and other longitudinal elements deviate from a line parallel to the sides of the piece. Applies to either diagonal or spiral grain or a combination of the two. ASTM

Crossband.–To place the grain of layers of wood at right angles in order to minimize shrinking and swelling: also, in plywood of three or more plies, a layer of veneer whose grain direction is at right angles to that of the face plies. AH72

Cup.–A distortion of a hoard in which there is a deviation flatwise from a straight line across the width of the hoard. AH72

Cure.–TO change the physical properties of an adhesive by chemical reaction, which may be condensation, polymerization, or vulcanization; usually accomplished by the action of heat and catalyst, alone or in combination, with or without pressure. ASTM

Curtain coating.–Applying adhesive to wood by passing the wood under a thin falling curtain of liquid. ABW

Decorative laminate.–A multilayered panel made by compressing sheets of resin-impregnated paper together into a coherent solid mass. AH72

Defect.–In the case of wood, any irregularity occurring in or on the wood that may lower its strength. ASTM

Delamination.–The separation of layers in a laminate because of failure of the adhesive, either in the adhesive itself or at the interface between the adhesive and the adherend, or because of cohesive failure of the adherend. ASTM

Density.–As usually applied to wood of normal cellular form, density is the mass of wood substance enclosed within the boundary surfaces of a wood-plus-voids complex having unit volume. It is variously expressed as pounds per cubic foot, kilograms per cubic meter, or grams per cubic centimeter at a specified moisture content. AH72

Diaphragm.–A relatively thin, usually rectangular element of a structure that is capable of withstanding shear in its plane. By its rigidity, it. limits the deflection or deformation of other parts of the structure. Diaphragms may have a planed or curved surface. AITC

Dielectric constant.–The ratio of the capacitance of a given configuration of electrodes with the material as the dielectric, to the capacitance of the same electrode configuration with a vacuum as the dielectric. ASTM

Diluent.–An ingredient, usually added to an adhesive to reduce the concentration of bonding materials. ASTM

Dimensional stability.–Ability of a material to resist changes in dimensions due to changing environments that affect their size or volumes, i.e., metals in changing temperatures, wood in changing moisture conditions. AUTH

Doctor bar or blade.–A scraper mechanism that regulates the amount of adhesive on the spreader rolls or on the surface being coated. ASTM

Doctor roll.–A roller mechanism that is revolving at a different surface speed, or in an opposite direction, resulting in a wiping action for regulating the adhesive supplied to the spreader roll. ASTM

Double spreading.–Application of adhesive to both adherends of a joint. ASTM

Dressed sire.–The dimensions of lumber after being surfaced with a planning machine. The dressed Size is usually 1/2 to 3/4 inch less than the nominal or rough size. A 2- by 4-inch stud, for example, actually measures about 1-1/2 by 3-1/2 inches. AH72

Dry.–To change the physical state of an adhesive on an adherend by the loss of solvent constituents by evaporation or absorption, or both. ASTM

Dry kiln.–A chamber having controlled airflow, temperature, and relative humidity for drying lumber, veneer, and other wood products. AH72

Durability.–As applied to gluelines, the life expectancy of the structural qualities of the adhesive under the anticipated service conditions of the structure. AITC

Earlywood.–The portion of the annual growth ring that is formed during the early part of the growing season. It is usually less dense and weaker mechanically than latewood. AH72

Edge banding.–A thin. Bat strip of material bonded to edges of panels as a decorative and protective finish. AUTH

Elastic limit.–The greatest stress which a material is capable of sustaining without any permanent strain remaining upon complete release of the stress. ASTM

NOTE: Due to practical considerations in determining the elastic limit, measurements of strain, using a small load rather than the zero load, are usually taken as the initial and final reference.

Elastomer.– A macromolecular material which, at room temperature, is capable of recovering substantially in size and shape after removal of a deforming force. ASTM

Equilibrium moisture content.–The moisture content at which wood neither gains nor loses moisture when surrounded by air at a given relative humidity and temperature. AH72

Exothermic.–Characterized by or formed with evolution of heat. AUTH

Extender.–A substance. generally having some adhesive action, added to an adhesive to reduce the amount of the primary binder required per unit area. ASTM

Extractives.– Substances in wood, not an integral part of the cellular structure, that can be removed by solution in hot or cold water, ether. benzene, or other solvents that do not react chemically with wood components. AH72

Extrusion spreading.–Adhesive forced through small openings in spreader head (see also Ribbon spreading). ABW

Face.–The better side of a panel in any grade of plywood calling for a face and back: also either side of a panel where the grading rules draw no distinction between faces. ASTM

Facing.–The outermost layer or composite component of a sandwich construction, generally thin and of high density, which resists most of the edgewise loads and flatwise bending moments; synonymous with face and skin. ASTM

Failure, adherend.–Rupture of an adhesive bond, such that the seperation appears to be within the adherend. ASTM

Failure, adhesive.–Rupture of an adhesive bond, such that the plane of separation appears to he at the adhesive-adherend interface. ASTM

Failure, cohesive.–Rupture of an adhesive bond, such that the separation appears to be within the adhesive. ASTM

Fiber saturation point.–The stage in the drying or wetting of wood at which the cell walls are saturated and the cell cavities free from water. It applies to an individual cell or group of cells, not to whole boards. It is usually taken as approximately 30 percent moisture content, based on ovendry weight. AH72

Fiberboard.–A broad generic term inclusive of sheet materials of widely varying densities manufactured of refined or partially refined wood (or other vegetable) fibers, Bonding agents and other materials may he added to increase strength. resistance to moisture, fire, or decay, or to improve some other property. AH72

Filler.–A relatively nonadhesive substance added to an adhesive to improve its working properties, permanence, strength, or other qualities. ASTM

Fillet.–That portion of an adhesive which fills the corner or angle formed where two adherends are joined. ASTM

Finger joint.–An end joint made up of several meshing wedges or fingers of wood bonded together with an adhesive. Fingers are sloped and may be cut parallel to either the wide or edge faces of the piece. AH72

Fire endurance.–A measure of the time during which a material or assembly continues to exhibit fire resistance under specified conditions of test and performance. AH72

Fire retardant.–A chemical or preparation of chemicals used to reduce flammability to retard spread of a fire over the surface. AH72

Flakeboard.–A particleboard composed of flakes. AH72

Flow.–Movement of an adhesive during the bonding process, before the adhesive is set. ASTM

Furring.– Strips of wood or metal applied to a wall or other surface to even it and normally to serve as a fastening base for finish material. AH73

Gap-filling adhesive.–See Adhesive, gap-filling.

Gel.–A semisolid system consisting of a network of solid aggregates in which liquid is held. ASTM

Glue.–Originally, a hard gelatin obtained from hides, tendons. cartilage. bones, etc., of animals. Also. an adhesive prepared from this substance by heating with water. Through general use the term is now synonymous with the term "Adhesive." ASTM

Glulam.–A term used in North America for parallel-laminated wood structural members bonded with adhesives into large sections and slopes. See Wood, glued laminated. AUTH

Green strength.–The strength of a bondline shortly after assembly and before full cure. AUTH

Growth rings, annual.–The layer of wood growth put on a tree during a single growing season. In the temperate zone the annual growth rings of many species (e.g., oaks and pines) are readily distinguished because of differences in the cells formed during the early and late parts of the season. In some temperate zone species (black gum and sweetgum) and many tropical species, annual growth rings are not easily recognized. AH72

Gusset.–A flat wood, plywood, or similar type member wed to provide a connection at intersection of wood members. Most commonly used at joints of wood trusses. They are fastened by nails, screws, bolts, or adhesives. AH73

Hardboard.– A generic term for a panel manufactured primarly from interfelted lignocellulosic fibers (usually wood). consolidated under heat and pressure in a hot press to a density of 31 pounds per cubic foot or greater, and to which other materials may have been added during manufacture to improve certain properties. AH72

Hardener.–A substance or mixture of substances added to an adhesive to promote or control the curing reaction by taking part in it. The term is also used to designate a substance added to control the degree of hardness of the cured film. ASTM

Heartwood.–The wood extending from the pith to the sapwood, the cells of which no longer participate in the life processes of the tree. Heartwood may contain phenolic compounds, gums, resins. and other materials that usually make it darker and more decay resistant than sapwood. AH72

Honeycomb core.–A sandwich core material constructed of thin sheet materials or ribbons formed to honeycomblike configurations. AH72

Humidify.– To increase, by any process, the quantity of water vapor within a given space. ASTM

Hygroscopic.– Term used to describe a substance, such as wood, that absorbs and loses moisture readily. ABW

Insulation board, rigid.–A structural building board made of coarse wood or cane fiber in 1/2. and 25/32-inch thicknesses. It can be obtained in various size sheets, in various densities, and with several treatments, AH73

Joint.–The junction of two pieces of wood or veneer.

Butt joint.–An end joint formed by abutting the squared ends of two pieces.

Edge joint.–The place where two pieces of wood are joined together edge to edge, commonly by gluing. The joints may be made by gluing two squared edges as in a plain edge joint or by using machined joints of various kinds, such as tongued-and-grooved joints.

End joint.–The place where two pieces of wood are joined together end to end, commonly by scarf or finger jointing. AH72

Joint, lag.–A joint made by placing one member partly over another and bonding the overlapped portions. AH72

Joint, scarf.–An end joint formed by joining with glue the ends of two pieces that have been tapered or beveled to form sloping plane surfaces, usually to a feather edge, and with the same slope of the plane with respect to the length in both pieces. In some cases. a step or hook may be machined into the scarf to facilitate alinement of the two ends. in which case the plane is discontinuous and the joint is known as a stepped or hooked scarf joint. AH72

Joint, starved.–A glue joint that is poorly bonded because an insufficient quantity of glue remained in the joint. AH72

Joist.–One of a series of parallel beams used to support floor and ceiling loads and supported in turn by larger beams, girders, or bearing walls. AH72

Laminate, n.–A product made by bonding together two or more layers of material or materials. ASTM

Laminate, v.–To unite layers of material with adhesive. ASTM

Laminated, cross.–A laminate in which some of the layers of material are oriented at right angles to the remaining layers with respect to the grain or strongest direction in tension. ASTM

NOTE: Balanced construction of the laminations about the centerline of the thickness of the laminate is normally assumed.

Laminated, parallel.–A laminate in which all the layers of material are oriented approximately parallel with respect to the grain or strongest direction in tension. ASTM

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

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

Vertically laminated wood.–Laminated wood in which the laminations are so arranged that the wider dimension of each lamination is approximately parallel to the direction of load. AH72

Lamination.–The process of preparing a laminate. Also, any layer in a laminate. ASTM

Latewood.–The portion of the annual growth ring that is formed after the earlywood formation has ceased. It is usually denser and stronger mechanically than earlywood. AH72

Lignin.–The second most abundant constituent of wood. located principally in the secondary wall and the middle lamella, which is the thin cementing layer between wood cells. Chemically it is an irregular polymer of substituted propylphenol groups, and thus no simple chemical formula can be written for it. AH72

Longitudinal.–Generally, parallel to the direction of the wood fibers. AH72

Lumber.–The product of the saw and planing mill not further manufactured than by sawing, resawing, passing lengthwise through a standard planing machine, crosscutting to length, and matching. AH72

Lumber, stress-graded.–Lumber separated by nondestructive testing into categories or grades for which allowable design properties are assigned. AUTH

Manufactured unit.–A quantity of finished adhesive or finished adhesive component, processed at one time. ASTM

NOTE: The manufactured unit may be a batch or a part thereof.

Mastic.–A material with adhesive properties, usually used in relatively thick sections, that can be readily formed by application with trowel or spatula. ASTM

Mat-formed particleboard.–A particleboard in which the coated particles are formed first into a mat having substantially the same length and width as the finished hoard before being flat-platen pressed. ASTM

Mechanical fastener.–Nails, screws, bolts. and similar items. ABW

Modifier.–Any chemically inert ingredient added to an adhesive formulation that changes its properties. ASTM

Modulus of elasticity.–The ratio of stress to corresponding strain below the proportional limit.

Tension or compression.–Young's modulus (modulus in tension or modulus in compression).

Shear or torsion.–Commonly designated as modulus of rigidity, shear modulus, or torsional modulus. ASTM

Modulus of rupture in bending.–The value of maximum tensile or compressive stress (whichever causes failure) in the extreme fiber of a beam loaded to failure in bending computed from the flexure equation:

$$S_b = Mc/I$$

where

M is maximum bending moment, computed from the maximum load and the original moment arm,

c is initial distance from the neutral axis to the extreme fiber where failure occurs, and

I is initial moment of inertia of the cross section about the neutral axis. ASTM

Moisture content.–The amount of water contained in the wood, usually expressed as a percentage of the weight of the ovendry wood. AH72

Nail bonding.–Obtaining bonding pressure by nailing together the pieces spread with adhesive. AUTH

Nail popping.–Protrusion of nailheads because of shrinking and swelling of wood. AUTH

Neutral plane.–Of a beam, the longitudinal section, perpendicular to the plane of loading, in which no strain develops. SAF

Nominal size.–As applied to timber or lumber, the size by which it is known and sold on the market; often differs from the actual size. AH72

Onsite bonding.–Bonding of assemblies, often under outdoor conditions, at the building construction site. AUTH

Open assembly.– See Assembly time.

Orthotropic.–Having unique and independent properties in three mutually orthogonal (perpendicular) planes of symmetry. A special case of anisotropy. AH72

Ovendry wood.– Wood dried to a relatively constant weight in a ventilated oven at 101° to 105° C. AH72

Overlay.–A thin layer of paper, plastic film, metal foil, or other material bonded to one or both faces of panel products or to lumber so as to provide a protective or decorative face or a base for painting. AH72

Paper, building.–A general term for papers, felts, and similar sheet materials used in buildings without reference lo their properties or uses. AH73

Paper laminates.–See Decorative laminate.

Particleboard– A generic term for a panel manufactured from lignocellulosic materials-commonly wood -essentially in the form of particles (as distinct from fibers) which are bonded together with synthetic resin-or other suitable binder, under heat and pressure, by a process wherein the interparticle bonds are created wholly by the added binder. AH72

Penetration.–The entering of an adhesive into an adherend. ASTM

NOTE: This property of a system is measured by the depth of penetration of the adhesive into the adherend.

Permanence.–See Durability.

Pith.–The small. soft core occurring near the center of a tree trunk, branch, twig, or log. AH72

Plank.–A broad board, usually more than 1 inch thick, laid with its wide dimension horizontal and used as a bearing surface. AH72

Plant bonding.–Bonding of assemblies indoors at a central location, from which they are trans. ported to the building construction site. AUTH

Plastic laminate.–See Decorative laminate.

Plasticizer.– A material incorporated in an adhesive to increase its flexibility, or distensibility. The addition of the plasticizer may cause a reduction in melt viscosity, lower the temperature of the second-order transition, or lower the elastic modulus of the solidified adhesive. ASTM

Platen.–A plate of metal, especially one that exerts or receives pressure. as in a press used for gluing plywood. ASTM

Plywood.– A panel composed of an assembly of layers or plies of veneer (or veneers in combination with lumber core, particleboard core, hardboard core, or of special core material) joined with an adhesive. Except for special constructions, the grain of alternate plies is always approximately at right angles. AUTH

Polymer.–A compound formed by the reaction of simple molecules having functional groups which permit their combination to proceed to high molecular weights under suitable conditions. Polymers may be formed by polymerization (addition polymer) or polycondensation (condensation polymer). When two or more monomers are involved. the product is called a copolymer. ASTM

Polymerization.– A chemical reaction in which the molecules of a monomer are linked together to form large molecules whose molecular weight is a multiple of that of the original substance. When two or more monomers are involved, the process is called copolymerization or heteropolymerization. ASTM

Porosity.– The ratio of the volume of a material's pores to that of its solid content. ABW

Post.–A length of timber generally round or square-cut used as a pillar or other upright support in building, fencing, etc. SAF

Pot life.–See. Working life.

Power-loss factor.–Also known as the dielectric loss factor, is a measure of the power per unit volume that will be dissipated as heat by a nonconducting material from an external electric field that is oscillating with a given amplitude and frequency. ASTM

Precure.–Condition of too much w-e or set of the glue before pressure is applied, resulting in inadequate flow and glue bond. ASTM

Preproduction test.–A test or series of tests conducted by (1) an adhesive manufacturer to determine conformity of an adhesive batch to established production standards, (2) a fabricator to determine the quality of an adhesive before parts are produced, or (3) an adhesive specification custodian to determine conformance of an adhesive to the requirements of a specification not requiring qualification tests. ASTM

Preservative.–Any substance that. for a reasonable length of time, is effective in preventing the development and action of wood-rotting fungi, borers of various kinds, and harmful insects that deteriorate wood. AH72

Psychrometer.–An instrument for measuring the amount of water vapor in the atmosphere. It has both a dry-bulb and wet-bulb thermometer. The bulb of the wet-bulb thermometer is kept moistened and is, therefore, cooled by evaporation to a temperature lower than that shown by the dry-bulb thermometer. Because evaporation is greater in dry air, the difference between the two thermometer readings will be greater when the air is dry than when it is moist. AH72

Pyrometer.–An instrument for measuring temperatures. ASTM

Qualification procedure.–A test or series of tests conducted by a qualified testing agency, or an agent thereof, to determine the conformance of either materials or materials systems to the requirements of a specification. If products are shown by the testing to meet the specification, they are usually awarded recognition, either by being added to a products list published under the specification or by other means. AUTH

NOTE: Qualification under a specification may require conformance to all tests in the specification, or it may be limited to conformance to a specific type or class, or both.

Racking.–Application of pressure to the end of a wall anchored at the base but free to move at top. ABW

Radiofrequency (RF) curing.– Curing of bondlines by the application of radiofrequency energy. AUTH

Radiofrequency energy.– Electrical energy produced by electric fields alternating at radiofrequencies. ABW

Relative humidity.–Ratio of the amount of water vapor present in the air to that which the air would hold at saturation at the same temperature. It is usually considered on the basis of the weight of the vapor but, for accuracy, should be considered on the basis of vapor pressures. AH72

Resin.–A solid, semisolid, or pseudosolid organic material which has an indefinite and often high molecular weight, exhibits a tendency to flow when subjected to stress, usually has a softening or melting range, and usually fractures conchoidally.

Liquid resin.–An organic polymeric liquid which when converted to its final state for use becomes a resin. ASTM

Rheology.–The science of treating the deformation and flow of matter. AUTH

Ribbon spreading.– Spreading a glue in parallel ribbons instead of a uniform film. ASTM

Roll spreading.– Application of a film of a liquid material (liquid resin) on a surface with rolls. ABW

Sandwich panels.– See Structural sandwich construction.

Sapwood.–The wood of pale color near the outside of the log. Under most conditions the sapwood is more susceptible to decay than heartwood. AH72

Scarf joints.–Sloping joint between ends of two wood members. ABW

Set.–To convert an adhesive into a fixed or hardened state by chemical or physical action, such as condensation, polymerization, oxidation, vulcanization. gelation, hydration, or evaporation of volatile constituents. ASTM

Shear.–A condition of stress or strain where parallel planes slide relative to one another. AH72

Shear block test (also called block shear test).- A means of testing a bond joint in shear. ASTM

Sheathing.–The structural covering, usually of boards, building fiberboards, or plywood, placed over exterior studding or rafters of a structure. AH72

Showthrough.–Term used when effects of defects within a panel can be seen on the face. ABW

Siding.–The finish covering of the outside wall of a frame building, whether made of horizontal weatherboards, vertical hoards with battens. shingles, or other material. AH72

Softwoods.–Generally, one of the botanical groups of trees that in most cases have needlelike or scalelike leaves; the conifers, also the wood produced by such trees. The term has no reference to the actual hardness of the wood. AH72

Solids content.–The percentage by weight of the nonvolatile matter in an adhesive. ASTM

NOTE: The actual percentage of the nonvolatile matter in an adhesive will vary considerably according to the analytical procedure that is used. A standard test method must be used to obtain consistent results.

Specific gravity.–As applied to wood, the ratio of the ovendry weight of a sample to the weight of a volume of water equal to the volume of the sample at a specified moisture content (e.g., green, airdry, or ovendry). AH72

Spread.–The quantity of adhesive per unit joint area applied to an adherend, usually expressed in pounds of adhesive per thousand square feet of joint area.

Single spread.–refers to application of adhesive to only one adherend of a joint.

Double spread.–refers to application of adhesive to both adherends of a joint. ASTM

Springwood.–See Earlywood.

Squeezeout.– Bead of glue squeezed out of a joint when gluing pressure is applied. ABW

Starved joint.–See Joint, starved.

Static bending.–Bending under a constant or slowly applied load; flexure. AH72

Stickering.–The use of wooden strips (stickers) between courses of boards in a lumber pile; the stickers are placed at a right angle to the long axis of the lumber. Stickering permits air circulation and facilitates rapid and even drying of lumber. AUTH

Storage life.–The period of time during which a packaged adhesive can be stored under specific temperature conditions and remain suitable for use. Sometimes called shelf life. ASTM

Strain.–The unit change. due to force, in the size or shape of a body referred to its original size or shape. Strain is a nondimensional quantity, but it is frequently expressed in inches per inch, centimeters per centimeter, etc. ASTM

Strength.–(1) The ability of a member to sustain stress without failure. (2) In a specific mode of test, the maximum stress sustained by a member loaded to failure. AH72

Strength. wet.–The strength of an adhesive joint determined immediately after removal from a liquid in which it has been immersed under specified conditions of time, temperature, and pressure. ASTM

NOTE: The term is commonly used alone to designate strength after immersion in water. In the latex adhesives the term is also used to describe the joint strength when the adherends are brought together with the adhesive still in the wet state.

Stress.–The force (per unit area) developed in resistance to loading or. under certain conditions, self-generated in the piece by internal variations of moisture content, temperature, or both. ABW

Stressed-skin construction.–A construction in which panels are separated from one another by a central partition of spaced strips with the whole assembly bonded so that when loaded it acts as a unit. AH72

Stringer.–A timber or other support for crossmembers in floors or ceilings. In stairs, the support on which the stair treads rest. AH72

Structural adhesive.–A bonding agent used for transferring required loads between adherends exposed to service environments typical for the structure involved. ASTM

Structural sandwich construction.–A layered construction comprising a combination of relatively high-strength facing materials intimately bonded to and acting integrally with a low-density core material. AH72

Structural timber.–Pieces of wood of relatively large size. the strength of which is the controlling element in their selection and use. Trestle timbers (stringers, caps, posts, sills, bracing, bridge ties, guardrails); car timbers (car framing, including upper framing, car sills); framing for buildings (posts, sills. girders); ship timbers (ship timbers, decking); and crossarms for poles are examples of structural timbers. AH72

Stud.–One of a series of slender wood structural members used as supporting elements in walls and partitions. AH72

Subfloors.–Boards or plywood laid on joists over which a finish floor is to be laid. AH73

Substrate.–A material upon the surface of which an adhesive-containing substance is spread for any purpose, such as bonding or coating. A broader term than adherend. (See also Adherend.) ASTM

Summerwood.– See Latewood.

Surfaced lumber.–Lumber that is dressed by running it through a planer. AH72

Synthetic rubber.–Any of various products (as GR-S, neoprene, butyl rubber, or nitrile rubber) that resemble natural rubber more or less closely in their properties. AUTH

Tack.–The property of an adhesive that enables it to form a bond of measurable strength immediately after adhesive and adherend are brought into contact under low pressure. ASTM

Tack, dry.–The property of certain adhesives, particularly nonvulcanizing rubber adhesives, to adhere on contact to themselves at a stage in the evaporation of volatile constituents, even though they seem dry to the touch. Sometimes called "aggressive tack." ASTM

Tacky-dry.– Pertaining to the condition of an adhesive when the volatile constituents have evaporated or been absorbed sufficiently to leave it in a desired tacky state. ASTM

Tangential.–Strictly, coincident with a tangent at the circumference of a tree or log, or parallel to such a tangent. In practice, however, it often means roughly coincident with a growth ring. A tangential section is a longitudinal section through a tree or limb perpendicular to a radius. Flat-grained lumber is sawed tangentially. AH72

Telegraphing.– A condition in a laminate or other type of composite construction in which irregularities, imperfections, or patterns of an inner layer are visibly transmitted to the surface. ASTM

NOTE: Telegraphing is occasionally referred to as photographing. See Showthrough.

Temperature, curing.-The temperature to which an adhesive or an assembly is subjected to cure the adhesive. ASTM

NOTE: The temperature attained by the adhesive in the process of curing it (adhesive curing temperature) may differ from the temperature of the atmosphere surrounding the assembly (assembly curing temperature).

Temperature, dry-bulb.–The temperature of the air as indicated by an accurate thermometer, corrected for radiation if significant. ASTM

Temperature, drying.–The temperature to which an adhesive on an adherend or in an assembly or the assembly itself is subjected to dry the adhesive. ASTM

NOTE: The temperature attained by the adhesive in the process of drying it (adhesive drying temperature) may differ from the temperature of the atmosphere surrounding the assembly (assembly curing temperature).

Temperature, maturing.–The temperature, as a function of time and bonding condition, which produces desired characteristics in bonded components. ASTM

NOTE: The term is specific for ceramic adhesives.

Temperature, setting.–The temperature to which an adhesive or an assembly is subjected to set the adhesive. ASTM

NOTE: The temperature attained by the adhesive in the process of setting it (adhesive setting temperature) may differ from the temperature of the atmosphere surrounding the assembly (assembly setting temperature).

Temperature, wet-bulb.–Wet-bulb temperature (without qualification) is the temperature indicated by a wet-bulb psychrometer constructed and used according to specifications. ASTM

Tempered hardboard.–A hardboard subjected to tempering as previously defined or specially manufactured with other variation in usual process so that the resulting product has special properties of stiffness, strength, and water resistance associated with boards meeting specifications for that quality product. ASTM

Tension, parallel to grain.–Stress on a material (wood) in the long direction of its fibers. ABW

Tension wood.–A form of wood found in leaning trees of some hardwood species and characterized by the presence of gelatinous fibers and excessive longitudinal shrinkage. Tension wood fibers hold together tenaciously, so that sawed surfaces usually have projecting fibers and planed surfaces often are torn or have raised grain. Tension wood may cause warping. AH72

Thermal expansion.–An increase in length or volume caused by an increase in temperature. AUTH

Themocouple.–Two dissimilar thermoelements so joined as to produce a thermal electromotive force when the junctions are a different temperature. ASTM

Thermoplastic.– A material which will repeatedly soften when heated and harden when cooled. ASTM

Thermoset.–A material which will undergo or has undergone a chemical reaction by the action of heat. catalysts, ultraviolet light, etc., leading to a relatively infusible state. ASTM

Thermosetting.–Having the property of undergoing a chemical reaction by the action of heat, catalysts, ultraviolet light, etc., leading to a relatively infusible state. ASTM

Thinner.–A volatile liquid added to an adhesive to modify the consistency or other properties. ASTM

Thixotropy.– A property of adhesive systems to thin upon isothermal agitation and to thicken upon subsequent rest. ASTM

Timbers.– Wood in forms suitable for heavy construction, e.g., lumber 5 or more inches in width and thickness. SAF

Time, assembly.–The time interval between the spreading of the adhesive on the adherend and the application of pressure or heat, or both, to the assembly. ASTM

NOTE: For assemblies involving multiple layers or parts, the assembly time begins with the spreading of the adhesive on the first adherend.

Open assembly time.–The time interval between the spreading of the adhesive on the adherend and the completion of assembly of the parts for bonding.

Closed assembly time.–The time interval between completion of assembly of the parts for bonding and the application of pressure or heat, or both, to the assembly.

Time, curing.–The period of time during which an assembly is subjected to heat or pressure. or both, to cure the adhesive. ASTM

NOTE: Further cure may take place after removal of the assembly from the conditions of heat or pressure, or both.

Time, drying.–The period of time during which an adhesive on an adherend or an assembly is allowed to dry with or without the application of heat or pressure, or both. ASTM

Time, setting.–The period of time during which an assembly is subjected to heat or pressure, or both, to set the adhesive. ASTM

Torque.– The product of a force and a lever arm which tends to twist or rotate a body, for example, the action of a wrench turning a nut on a bolt. Torque is commonly expressed in foot-pounds, i.e.. the product of the applied force measured in pounds and the lever arm measured in feet. This action is called a "moment." AITC

Torque wrench.–Wrench equipped with indicating device for measuring torque. ABW

Torsion.– Act of turning or twisting, or state of being twisted; the twisting or wrenching of a body by the exertion of a lateral force tending to turn one end or part of it about a longitudinal axis, while the other is held fast or turned in the opposite direction. AUTH

Truss.–An assembly of members, such as beams, bars, rods, and the like. so combined as to form a rigid framework. All members are interconnected to form triangles. AH72

Twist.–A distortion caused by the turning or winding of the edges of a board so that the four corners of any face are no longer in the same plane. AH72

Underlayment.–A material placed under finish coverings. such as flooring, or shingles, to provide a smooth, even surface for applying the finish. AH73

Vapor barrier.–A material with a high resistance to vapor movement, such as foil, plastic film, or specially coated paper, that is used in combination with insulation to control condensation. AH72

Vehicle.– The liquid portion of an adhesive or a finishing material; it consists of the binder (nonvolatile) and volatile thinners. AUTH

Veneer.–A thin layer or sheet of wood.

Rotary-cut veneer.–Veneer cut in a lathe which rotates a log or bolt, chucked in the center, against a knife.

Sawed veneer.–Veneer produced by sawing.

Sliced veneer.–Veneer that is sliced off a log, bolt, or flitch with a knife. AH72

Viscosity.– The ratio of the shear stress existing between laminae of moving fluid and the rate of shear between these laminae. ASTM

Volatile solvent.–Any nonaqueous liquid that has the distinctive property of evaporating readily at room temperature and atmospheric pressure. ASTM

Warp.–A significant variation from the original, or plane surface. ASTM

Waterproof.– As applied to plywood, the term is synonymous with exterior; that is. plywood, bonded with highly resistant adhesives, which is capable of withstanding prolonged exposure to severe service conditions without failure in the glue bonds. ASTM

Water-repellent preservative.–A liquid designed to penetrate into wood and impart water repellency and a moderate preservative protection. It is used for millwork, such as sash **and** frames, and is usually applied by dipping. AH73

Water resistant.–A term frequently applied to plywood, bonded with moderately resistant adhesives, which is capable of withstanding limited exposure to water or to severe conditions without failure in the glue bonds. ASTM

Webbing.–Filaments or threads that may form when adhesive transfer surfaces are separated. ASTM

NOTE: Transfer surfaces may be rolls, picker plates, stencils, etc.

Wettability.–A condition of a surface that determines how fast a liquid will wet and spread on the surface or if it will be repelled and not spread on the surface. AUTH

Wood failure.–The rupturing of wood fibers in strength tests on bonded specimens, usually expressed as the percentage of the total area involved which shows such failure. ASTM

Wood flour.– Wood reduced to finely divided particles approximately those of cereal flours in size, appearance. and texture, and passing a 40 to 100 mesh screen. AH72

Wood, glued–laminated.– An assembly made by bonding layers of veneer or lumber with an adhesive so that the grain of all laminations is essentially parallel. ASTM

Wood substance.–The solid material of which wood is composed. It usually refers to the extraetive-free solid substance of which the cell walls are composed, but this is not always true. There is no wide variation in chemical composition or specific gravity between the wood substance of various species, the characteristic differences of species being largely due to differences in extractives and variations in relative amounts of cell walls and cell cavities. AH72

Working life.–The period of time during which an adhesive, after mixing with catalyst, solvent, or other compounding ingredients, remains suitable for use. Also called pot life. ASTM

Working properties.–The properties of an adhesive that affect or dictate the manner of application to the adherends to be bonded and the assembly of the joint before pressure application, i.e., viscosity, pot life. assembly time, setting time, etc. AUTH

Yield value.–The stress (either normal or shear) at which a marked increase in deformation occurs without an increase in load. ASTM

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