

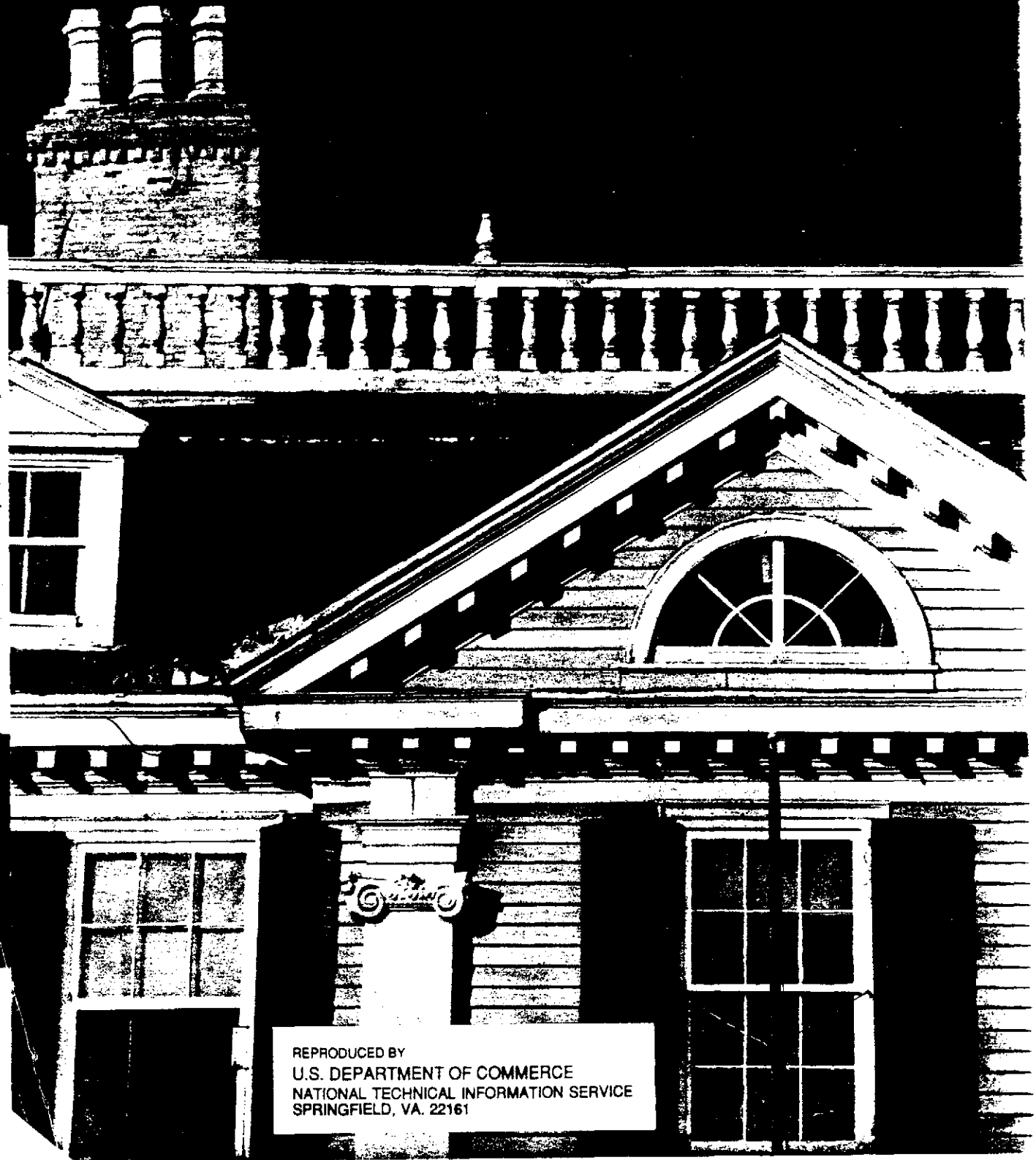
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Epoxies for Wood Repairs in Historic Buildings

Office of Archeology and
Historic Preservation

Heritage Conservation and
Recreation Service

U.S. Department of the Interior
Washington, D.C.
1978



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Morgan W. Phillips

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Technical Preservation
Services Division

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Part 1:

Part II:

**Chemistry and
Technology**

Morgan W. Phillips

Society for the Preservation
of New England Antiquities

Case Studies

Dr. Judith E. Selwyn

Society for the Preservation
of New England Antiquities

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Foreword

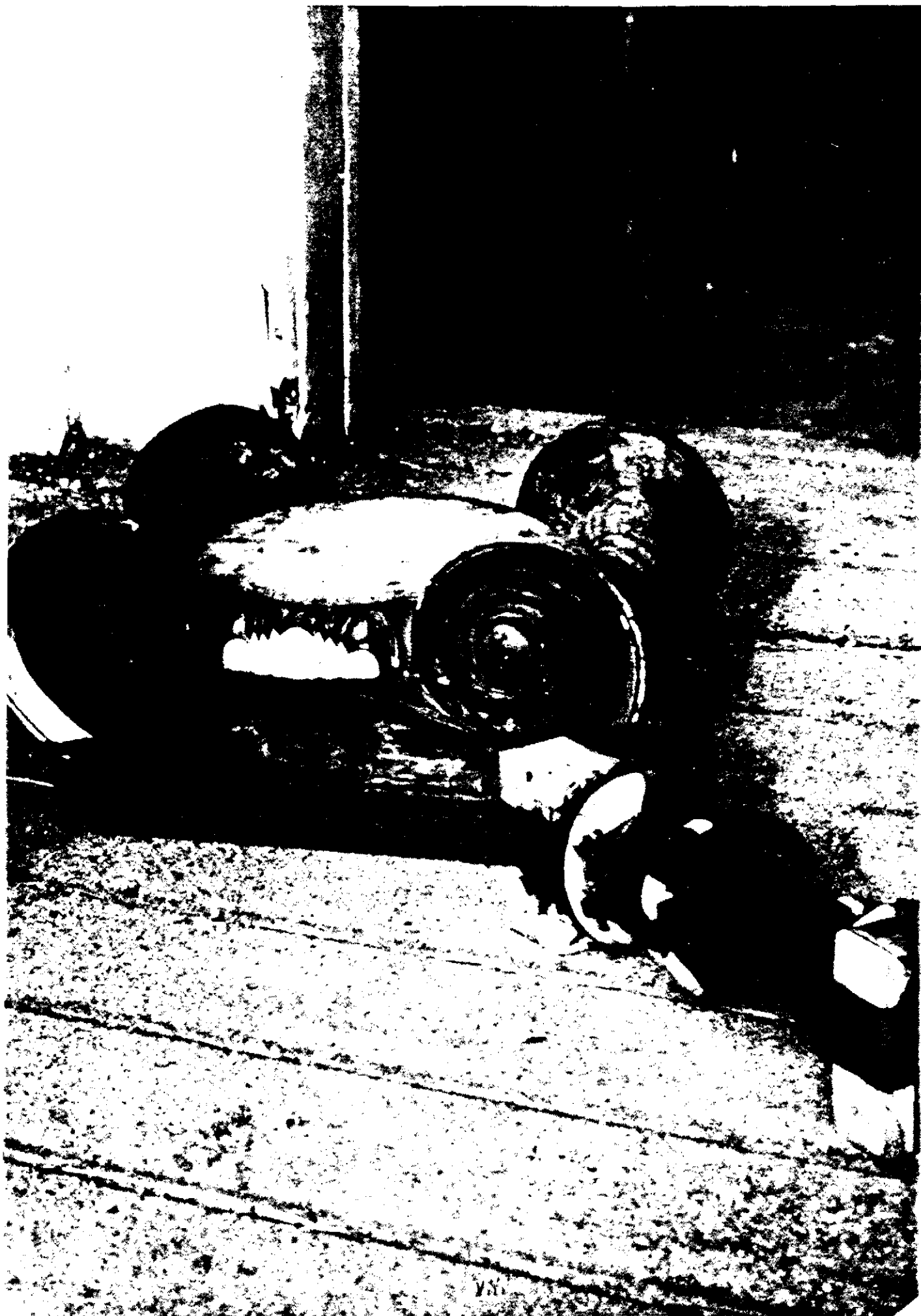
Under Executive Order 11593, signed May 13, 1971, the Secretary of the Interior was given the responsibility for developing and disseminating "to Federal agencies and State and local governments information concerning professional methods and techniques for preserving, improving, restoring and maintaining historic properties." To meet the Secretary's responsibilities, the Technical Preservation Services Division, Office of Archeology and Historic Preservation, Heritage Conservation and Recreation Service, is preparing a series of publications on the technical aspects of historic preservation for use by administrators, architects, and others at the Federal, State, and local levels involved with the preservation and maintenance of cultural resources.

This preliminary report, "Epoxies for Wood Repairs in Historic Buildings," was prepared under contract with the Consulting Services Group, Society for the Preservation of New England Antiquities (SPNEA), 141 Cambridge Street, Boston, Massachusetts 02114. "Part I: Chemistry and Technology," was written by Morgan W. Phillips, Architectural Conservator, (SPNEA); and "Part II: Case Studies," was written by Dr. Judith E. Selwyn, Conservation Scientist, (SPNEA). The research and development of Mr. Phillips' work was co-sponsored by this Division and by the North Atlantic Region, National Park Service. The early research effort was coordinated by E. Blaine Cliver, Regional Historical Architect, National Park Service, Boston.

Baird M. Smith, Historical Architect, Technical Preservation Services Division, worked with the two authors by reviewing the draft manuscripts and developing the papers into a single report for publication. The final papers were copy edited by Robert E. Haynes, National Register Division.

Comments and suggestions regarding additions or changes prior to final publication are encouraged and should be sent to Lee H. Nelson, A.I.A., Preservation Handbook Editor, Technical Preservation Services Division, Office of Archeology and Historic Preservation, Heritage Conservation and Recreation Service, U.S. Department of the Interior, Washington, D.C. 20240.

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OBJECTIVES OF THIS STUDY

This paper has two main subjects: 1) low-viscosity epoxy consolidants that can be soaked into rotted wood in order to restore its solidity, and 2) epoxy pastes (patching compounds) for filling holes and cracks in woodwork. The paper has three basic objectives: 1) to present the results of a preliminary research and testing program on epoxy consolidants and patching compounds for woodwork carried out under contract with the National Park Service; 2) to teach the reader the basic technology involved in formulating epoxy consolidants and patching compounds; and 3) to provide suggested formulations and lists of suppliers, so that the reader will be able to manufacture serviceable materials. A survey of proprietary consolidants and patching compounds might reveal some ready-made products as well suited for architectural conservation as any suggested here, but it was felt to be important to make the basic technology known to the preservation community.

Many materials besides epoxies can be used successfully as wood consolidants and as the basis for patching compounds. These include waxes and acrylic resins. Subsequent sections of this paper will explore why at the present time epoxies offer the best combination of properties for most on-site restoration of woodwork where it is to be painted.

OBJECTIVES OF CONSOLIDATION AND PATCHING PROCEDURES

Wood consolidants and patching compounds can permit deteriorated original woodwork of historical value to be reconditioned and retained in place, sometimes even serving a load-bearing function (figure 1). Efficient consolidants and patching compounds are being developed concurrently with a philosophical trend toward conserving historic architectural fabric, rather than replacing it. Such conservation *in situ* is the most important objective in using

these materials. However, some other objectives are equally well served. One is the elimination of chronic trouble spots in wooden buildings. For example, wood in chronically damp locations (such as wooden column bases) can be made to last almost indefinitely by resin impregnation. This impregnation also renders the wood effective as a dampproof course; thus, in certain applications, it protects untreated wood that rests upon it.

A further objective is that of saving money. Often small areas of deterioration in otherwise sound wood can be strengthened more inexpensively by using consolidation treatments than by replacing the whole piece or even a portion of the wood. Cracks and holes are much more quickly filled by a patching compound than by pieces of wood fitted and glued into place.

Returning to the question of the conservation of historic fabric, consolidation and patching procedures probably are more often and more urgently needed in architectural conservation than in other kinds of conservation. It must be remembered that, unlike museum objects, buildings cannot normally be put in storage under controlled conditions. Their exteriors are under constant attack by the weather, and, in order to maintain the building's security against the weather, defective portions must either be replaced or reconditioned. In the case of woodwork that is rotting or admitting rain, the choice is forced: either replace the element or consolidate and patch. If the woodwork has historical value as part of the building's early fabric, replacement is usually the least desirable of all alternatives, because it diminishes the amount of surviving historic fabric. Admittedly, replacement with a reproduction may be the best choice for a wooden element of great delicacy and exceptional value, if the original can realistically be expected to be given proper and permanent storage as a museum object after it is removed. For example, an antique wooden weathervane would be such an element. However, the record in architectural conservation clearly



Figure 1. Section of structural oak post consolidated with epoxies. Insect damage had converted this post to a hollow, powdery shell. Wax and clay were used to stop up cracks and holes in the exterior surface while the post was filled with penetrating epoxies. (Photo: Author)

shows that more ordinary wooden elements, such as column capitals or window heads, are likely to be discarded, lost, or destroyed once they are removed from a building, or the record of their original location on the building is lost. Once the policy of removing and replacing wooden elements has been adopted in a restoration project, the number of pieces removed usually becomes too large for proper accessioning and storage, and some future maintenance person is apt to throw the whole collection away. Consequently, original architectural fabric is lost and the building's value as a historical artifact is diminished.

NEED FOR FURTHER TESTING

The tests performed in the course of this project were preliminary. Only a few samples of each formulation were tested—sometimes only one sample. The types of tests were limited, and the duration of the tests was short. Thus, the tests were not statistically adequate to determine which are the best formulations. They certainly do not reveal which are the best raw materials used in the formulations, because all the materials could have been recombined differently into better formulations. The tests do not provide proof of the long-term durability of any of the formulations. Clearly, more extensive and systematic laboratory testing is needed, combined with a program to refine formulations according to information gained from testing.

In addition, the performance of various formulations in actual service must be observed and evaluated, and adjustments made to improve such performance. This will be possible only if those who use the materials keep an accurate record of what formulations were used, in what buildings and specific locations, and under what conditions. When failure occurs, its nature should be ascertained. For example, did a patching compound break at the

bond line with the wood (adhesive failure) or did it break within the compound itself (cohesive failure)?

RESULT OF RESEARCH AND TESTING

If research and testing to date have been preliminary and tentative, what has been accomplished? The tests to date have given an approximate indication of the range of properties that can be achieved by various combinations of certain raw materials. Additionally, the project has resulted in the choice of several formulations that are probably good enough to use in building conservation and that are being used by the National Park Service, the National Trust for Historic Preservation, and the Society for the Preservation of New England Antiquities.

How good is good enough? The architectural conservator and the conservator of museum objects might answer this question differently. In architectural conservation, certain practical problems may require the use of materials meeting different criteria from those applied to materials for museum conservation. In selecting materials to restore a building's exterior, a conservator faces the practical problems of choosing materials that can withstand the weather, and that have some strength. He must realize also that such materials are likely to be applied by workmen not trained in conservation, and must be purchased and applied in large quantity at reasonable cost. In order to meet such requirements, an architectural conservator may have to use materials that would not satisfy a museum conservator's standards of reversibility and proven long-term chemical stability.

Perhaps more significantly, in museum conservation if no well-tested materials are available for treating an object, the object can often be put aside for a period of years in a controlled environment until such materials have been developed. By contrast, the architectural conservator is often forced to proceed immediately with radical treatments, even at some risk, in order

to maintain the exterior watertightness of a building. The best available materials must be used. When confronted with rot, cracks, or holes in wood, the architectural conservator surveying the range of practical treatments now available for exterior woodwork finds that none are perfectly tested and proven in service. There are some proprietary epoxy consolidants for rotted wood, but none have been thoroughly tested as materials for conservation. As for patching compounds to fill holes and cracks, even the simplest tests make it abundantly clear that the better formulations suggested here—and a few related proprietary products—are much more suitable for building conservation than the materials now in common use. Thus, in this case, "good enough to use" simply means material as good as, or better than, that which is already in use.

It must be emphasized that there is a significant risk in using materials of which the long-term durability is not established; but when the only practical alternative is completely replacing a valuable piece of woodwork, some risk in trying to save the original becomes acceptable. Clearly, there is no reason to take this risk in the case of woodwork in serviceable condition.

Thus formulations are offered here in hopes that some of them will serve well, and that they will be refined through further research and testing, and through critical observation of their performance in actual service.

BASIC APPROACH

The basic approach used in consolidating fragile architectural woodwork is to impregnate the wood with a material in liquid form, that is able to solidify in the wood. A wide variety of materials can be used. For most architectural woodwork, synthetic resins are generally the most useful.

RESINS AND POLYMERS DEFINED

All materials may be classified according to both chemical composition and physical properties. "Alcohol" and "ester" are examples of chemical classifications. "Rubber" and "wax" are examples of terms that are somewhat ambiguous chemically but quite specific in regard to physical properties. The term "resin" likewise describes physical properties more than chemical properties: resins generally have no significant crystalline structure or distinct X-ray diffraction pattern; they tend to break in a glass-like, conchoidal manner; and they have no sharp melting point. There are gradations between most of the physical categories of materials used in conservation; some of the materials that will be described in this report exhibit rubbery properties almost to the same extent as they exhibit resinous ones. The elasticity of rubbers is familiar to all of us.

Waxes of various chemical types, such as paraffins and esters, are extensively used to consolidate museum objects in situations where little strength is required in the end product. The greater strength potentially attainable in resins makes them generally the most useful materials for consolidating woodwork that is to remain in service as part of a building.

"Polymer" is another term that requires clarification. Robert Feller defines a polymer as "a compound in which a large number (poly) of identical or similar atoms or groups of atoms (representing the monomer) are united by primary chemical bonds" (figure 2).¹

Most resins are polymers—as are most rubbers, waxes, and many other materials used in conservation. About resins, Feller writes,

the word 'polymer' . . . refers specifically to the chemical structure of the resin. . . . Perhaps it might be said that, the less that is known about the chemical structure of a resin-like material, the more likely it will be called a resin. Cellulose, vegetable polysaccharides, lignin, and many proteins are properly called natural polymers, while other substances, natural and synthetic, are still designated simply as resins.²

REQUIREMENTS FOR WOOD CONSOLIDANTS; CHARACTERIZATION OF EPOXIES

In designing a product for a specific purpose, it is useful to list desired properties and to evaluate different possible materials in relation to each property. This was the approach used during the present project. The following discussions are organized according to the desired properties.

Low shrinkage; chemical-setting systems

Polymers must be in a fluid state in order to be absorbed into a porous material such as wood or stone. Their usefulness will depend upon their ability to solidify. There are three basic mechanisms of solidification, and thus three basic types of systems in which polymers can be applied: hot-melt, solvent-loss, and chemical-setting systems.

An example of the first group is molten wax, which solidifies on cooling. Hot-melt systems are impractical for most on-site architectural carpentry, although hot-wax impregnation is used for portable wooden objects by laboratories having the appropriate equipment.

In solvent-loss systems, the polymer is dissolved (solvent-type systems) or emulsified (emulsion systems) in a volatile liquid. As this liquid evaporates, the polymeric material solidifies (or more properly in the case of emulsion

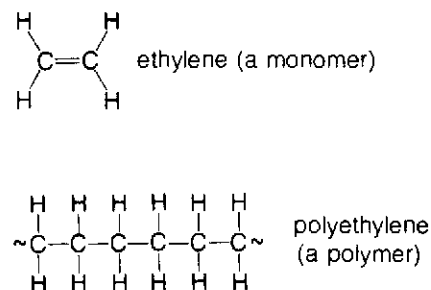


Figure 2. Monomer and Polymer.

¹Robert L. Feller, Nathan Stolow, and Elizabeth H. Jones, *On Picture Varnishes and Their Solvents*, rev. ed. (Cleveland and London: Press of Case Western Reserve University, 1971), p. 119.

²*Ibid.*

systems, coalesces). Although solvent-loss systems are used in wood consolidation, they have several disadvantages. One is the shrinkage that generally accompanies the loss of the solvent. In a fragile piece of wood, this shrinkage can lead to contractile stresses. A second disadvantage is that a fluid material in a solvent, having been impregnated into wood, can to some extent migrate back toward the surface of the wood along with the evaporating solvent. A third problem arises when the evaporation of the solvent produces a porous structure. The result may be weaker and more susceptible to moisture than it would be if it were not porous. However, as we shall see later, there may be cases in which weakness and permeability are desirable.

Chemical-setting systems are distinguished from hot-melt and solvent-loss systems in that conversion to solid occurs by a chemical reaction. Because there is no solvent to evaporate, solidification entails little shrinkage—only that which is associated with the reorganization of molecules. In some chemical-setting systems, a solvent may be present to lower viscosity or for other reasons, but a chemical reaction brings about ultimate solidification after the solvent evaporates.

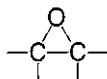
Thus, using chemical-setting systems, the conservator can choose whether or not to use solvents, and in what proportion, in order to control application properties and the final properties of the consolidated material. The chemical reaction involved in solidification may take the form of linear polymerization: the formation of chainlike linear polymers from monomers (figure 2). For example, the acrylic monomer, methylmethacrylate, is a liquid, and, having been introduced into wood, can be caused to form the polymer polymethylmethacrylate. Other materials in uncured, liquid form may be polymers of low molecular weight: that is, relatively short chains built up of relatively simple units. These materials generally solidify by forming networks through *cross links* between the chains. The concept of cross-linking is illustrated in

figure 3. Such cross-linking may be induced in several ways: in the case of epoxies, the uncured (that is, incompletely reacted) liquid resin is mixed with another substance—the curing agent—with which it reacts chemically to form a cross-linked structure. The uncured epoxy resin and the curing agent are mixed just prior to use and can be soaked into a wooden object before chemical solidification has had time to occur.

Most solvent-loss systems are convenient to package and easy to apply, since the entire formulation can be packaged in one container and will dry only when the solvent is permitted to evaporate. The use of a chemical-setting system is slightly less convenient, as most require separate packaging for the resin and the curing agent. Alternatively, heating or irradiation may be required to produce a cure.

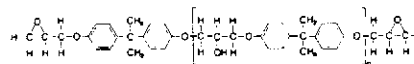
Controllable curing mechanism; epoxy chemistry summarized

If a consolidant is intended to harden principally by a chemical reaction rather than by solvent loss, the reaction must permit convenient and reliable use under poorly controlled conditions, such as those usually found on building sites. Reliability of cure is a major reason why this study concentrates on epoxies rather than acrylics or unsaturated polyester resins. These latter two cure by a chain reaction involving "free radicals." Free radical curing mechanisms are easily affected by such factors as the presence of oxygen or moisture and thus may be hard to control. Epoxy curing does not depend on free radicals. By definition, an epoxy compound is one that contains the triangular structure



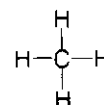
which is known as the epoxide group. The lines projected from the two carbons indicate bonds to other atoms in the molecule. Thus the term "epoxy" (more properly "epoxide") is a chemical

term indicating a particular functional group. The most common epoxy resin is based on the diglycidyl ether of bisphenol-A, commonly abbreviated DGEBA. It has the following idealized structure, where the value of "n" can vary:



Higher n values indicate materials of higher molecular weight and therefore greater viscosity. Uncured DGEBA resins are usually mixtures of epoxies of different n values, and, depending on the degree of chemical purity, are either colorless or a transparent brownish-yellow. Since DGEBA has two epoxy functional groups per molecule, it is known as a diepoxide. Its molecular structure can be visualized as a chain of atoms with an epoxy group at each end, which can serve as a linkage point with other molecules. DGEBA resins contribute high strength, adhesion, and insolubility to epoxy formulations.

Throughout this report, as in most chemical literature, hydrogen atoms in chemical formulas may be indicated in three ways. The formula for methane, for example, may be drawn as:



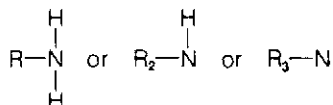
or an abbreviated form may be written as:



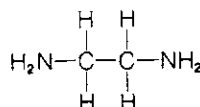
or, hydrogens not of importance in a given reaction may be ignored, and only the chemical bonds shown. For convenience, in some cases these three graphic forms may be mixed.

Epoxy groups in the epoxy molecule react readily with a wide variety of functional groups in other molecules. In epoxy formulations most useful for room temperature curing, the molecules with which the epoxy reacts are commonly amines. Amines are a class of relatively simple nitrogen-containing compounds, derivatives of ammonia (NH₃).

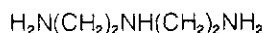
Most are colorless or brownish-yellow liquids having the general formula



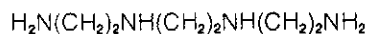
R, above, is a generalized symbol for other portions ("radicals") of the molecule, usually carbon and hydrogen chains (alkyl radicals) or rings. A compound with two amine groups per molecule is called a *diamine*, with three a *triamine*, and so on. A simple amine is ethylene diamine:



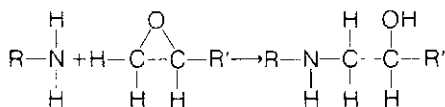
Amines of the structure RNH_2 are called primary amines; R_2NH amines are called secondary amines; and R_3N tertiary amines. A widely used curing agent containing both primary and secondary amine groups is diethylene triamine:



The name of this compound indicates that it has three amine groups (a "*tri*-amine") and two ethylene groups ("*di*-ethylene"); the ethylene groups are the $(\text{CH}_2)_2$ groups). Thus triethylene tetraamine, another common curing agent has three ethylene groups and four amine groups:



In epoxy curing reactions with primary and secondary amines, the nitrogen of the amine group forms a bond with one of the carbons of the epoxy group. In that process, the three-membered epoxy ring is opened and the nitrogen of the amine group loses one of its protons (H^+ ions), so that, in the end, the nitrogen still has the correct number of bonds. The oxygen of the epoxy ring quickly picks up any available proton to form a hydroxyl (OH) group. In graphic form:

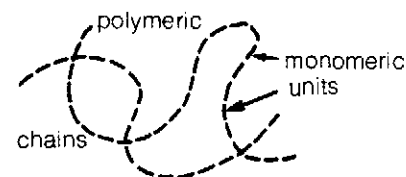


The number of hydrogen atoms that an amine group has available to lose is the number of new bonds that can be made in place of nitrogen-hydrogen bonds. Such hydrogen atoms are called "active" hydrogens. Figure 4 is a schematic representation of a diepoxide cross-linked with a primary diamine ($\text{H}_2\text{N}-\text{R}-\text{NH}_2$). Note that since each primary amine group has two "active" hydrogens, and since each amine molecule has two amine groups, each of the primary diamine molecules is bonded to four epoxy molecules. One can readily understand that in order to act as a link with primary or secondary amines, an epoxy molecule has to have at least two epoxy groups to link at both ends rather than just at one end. Thus it must be at least a diepoxide. If it has only one epoxy group, it can be tied at only one end and thus is useless as a connecting link (figure 5). In the same way, amines must be able to form at least two bonds to serve as connecting links.

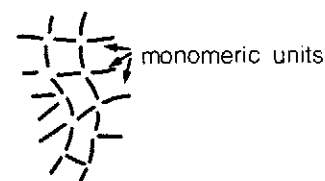
In figures 3 and 4 it is easy to see that a cross-linked (as opposed to linear) structure can only be formed if either the epoxy or the curing agent can form more than two linkages. In figure 4, the amine has four "active" hydrogens, and can form four linkages. The number of potential links that a molecule can form in a given system is described as the functionality of the molecule; a molecule that can form four links, such as an ethylene diamine, is said to have a functionality of four.

When tertiary amines (R_3N) are used as curing agents, the curing mechanism is quite different from that already described. Different theories exist concerning the details of tertiary amine curing.³ In general, it is felt that the tertiary amine molecules do not act principally as links themselves but rather cause epoxy molecules to cross link with each other through their epoxy groups. This process is called *homopolymerization*. A two-stage description of tertiary-amine-initiated homopolymerization has

³W. G. Potter, *Epoxide Resins* (New York: Springer-Verlag, 1973), pp. 48, 49.



a. Linear polymer (polymeric chains not interconnected).



b. Cross-linked polymer (polymeric chains linked together).

Figure 3. Linear and cross-linked polymers.

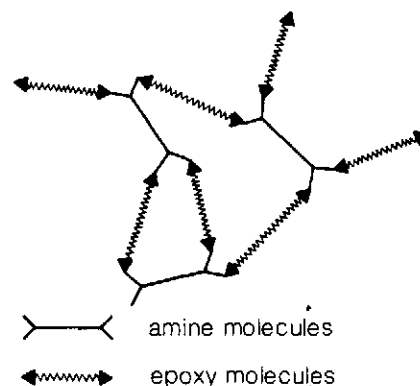


Figure 4. Diepoxide cross linked with a primary diamine.

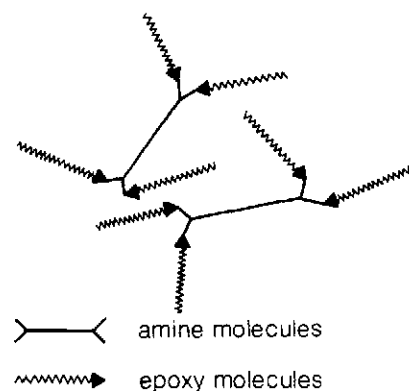
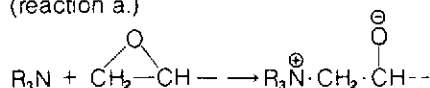


Figure 5. Monofunctional epoxide reacted with a primary diamine. No cross links are formed.

been proposed as shown below.⁴

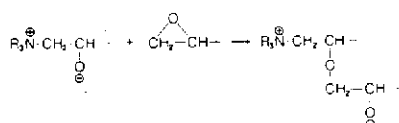
First the tertiary amine opens the epoxy ring:

(reaction a.)



Then the negatively charged oxygen atom of the opened epoxy ring opens another epoxy ring and links to it. This can continue as a chain reaction.

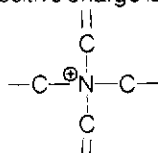
(reaction b.)



It can be seen from the above reaction that in homopolymerization each epoxy group has a functionality of two. Homopolymerization is not thought to be of major importance when epoxies are reacted with primary and secondary amines, even though tertiary amine groups are formed when primary and secondary amines lose their active hydrogens.⁵ Thus epoxy groups are considered to have a functionality of one when reacted with primary and secondary amines.

One might raise—only speculatively—two possible concerns about the stability of some tertiary-amine-cured epoxy systems. One is that in some systems if the epoxy groups are reacted mostly with other epoxy groups, not enough of them may react with the tertiary amine to insure that all the amine is bonded into the cured system. This would be particularly true if the amine functions as a true catalyst and is not consumed in the reactions. Under such conditions some of the amine may remain as a free liquid that could migrate out of the material and react with paint layers or cause other damage. The second possible concern is that to the extent a tertiary amine does become bonded into the molecular structure of the cured material, the polymer at that point is ionic (has localized centers of positive and negative charge) and may therefore be less stable under some conditions than if it were non-ionic. This

ionic character is due to the fact that a tertiary amine has no active hydrogen that it can lose to compensate for a new covalent bond on the nitrogen. Having formed a covalent bond with an epoxy molecule, for example, the tertiary amine becomes a quaternary nitrogen ion bonded four ways and thus carrying a positive charge, as shown below in the above reaction. The ionic character of the molecule at this point is maintained even if the positive charge is neutralized.



These possible concerns are purely speculative and may be of little significance, since tertiary-amine-cured epoxy systems are widely used with successful results.

Epoxy/amine curing reactions are greatly accelerated by heat and retarded by low temperatures. Fortunately, the formulator has a wide variety of fast- and slow-curing epoxies and amines to choose from, and can adjust cure rates to field conditions. Accelerators can also be used, some of which are tertiary amines. A slow curing rate is generally advantageous in wood impregnation, since it allows plenty of time for the impregnant to penetrate the wood before curing has advanced to the state where the material becomes highly viscous. The larger the piece of wood, generally, the more desirable it will be to have a slow curing rate to allow the deepest possible penetration. Typical commercial epoxy consolidants tend to cure too fast for most architectural uses; the formulations offered here cure much more slowly.

A major advantage of epoxies is the degree of control that can be exerted over curing rates through selection of different resins, curing agents, and accelerators.

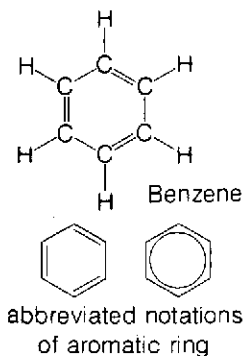
Durability

The architectural conservator and the museum conservator may define durability in different ways, placing em-

phasis on different aspects of durability. For example, water resistance is a primary consideration for the architectural conservator using materials in outdoor applications. Typical cured epoxies excel in water resistance. The museum conservator is apt to place more emphasis on other aspects of durability such as resistance to photochemical degradation since he is principally concerned with objects that are kept dry. Most epoxy formulations are subject to deterioration principally by yellowing, under the influence of ultraviolet light. In treating woodwork that is to be kept painted, the architectural conservator would have little concern about this.

Speaking broadly, epoxies have given indication of good long-term durability since they were introduced in the late 1940's. Admittedly, the manufacturers of epoxies usually do not have in mind for their products the extremely long life spans that conservators of museum objects expect from the materials they use. Little work has been done in attempting to predict the behavior of epoxies after a century's aging or more. Certain acrylics, by contrast, have been subjected to the most careful scrutiny for use as varnishes for valuable paintings.⁶


Chemically the most common epoxies are of the *aromatic* type incorporating a particular type of ring structure that, in its simplest form, is represented by benzene:



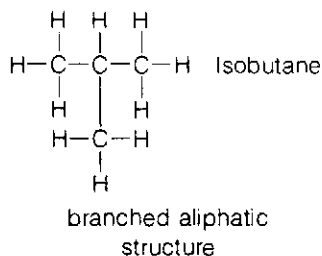
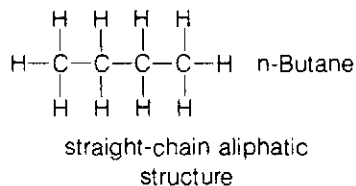
⁴*ibid.*

⁵*ibid.*, p. 39.

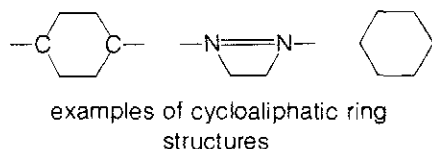
⁶Feller, et al., *On Picture Varnishes*, pp. 117-218.

(In industrial literature the aromatic ring is sometimes improperly denoted by a plain hexagon )

Some epoxies lack this particular ring structure and are therefore, by definition, classed as *aliphatic* compounds.



Cycloaliphatic resins and curing agents have ring structures not related to benzene. The formulas for cycloaliphatic compounds contain ring formations that lack either of the specific notations shown above for the aromatic ring. In the examples below, CH_2 groups are assumed to be present at the corners of the polygons where no other indication is given.



(In literature where the aromatic ring is improperly shown as a plain hexagon, a saturated six-membered cycloaliphatic ring may be denoted, also improperly, by an S in the middle of the ring to distinguish it from an aromatic ring.)

It is commonly considered that an aliphatic structure gives improved resistance to photochemical deterioration. Accordingly, this writer attempted to produce good epoxy consolidants and patching compounds using only currently available and well-known aliphatic resins and curing agents. Practical observations support the feeling

in the industry that, at present, some amount of aromatic resin is needed to give a good product in most room-temperature-cured systems (judged by strength and resistance to water). More searching would undoubtedly produce many highly satisfactory aliphatic systems. Ciba-Geigy will soon be ready to market a new aliphatic epoxy that is claimed to exhibit photochemical stability almost equal to that of acrylics. Munnikendam has investigated some straight chain aliphatic and cycloaliphatic systems as consolidants.

Since acrylics are singularly resistant to yellowing and other forms of photochemical deterioration, certain acrylics may be preferable to commonly used epoxies when dealing with wooden objects of great aesthetic value. Unpainted woodwork might also offer many occasions to use acrylics, since color retention would be of importance. When consolidating such objects, special measures should be taken to prevent surface gloss and translucency. The use of acrylic monomers as consolidants for wood is described in various works by Munnikendam and by Schaffer (see bibliography). A commercial U.S. firm offering custom impregnation with acrylic monomers is ARCO (see appendix). Where strength is not important, pre-polymerized acrylic resins dissolved in solvents can be skillfully applied as consolidants in such ways as to minimize the problems of shrinkage and migration noted under "Low Shrinkage; chemical-setting Systems" above. These problems may be less significant when only the surface zone of an object needs consolidation. Acryloid® B67 in mineral thinner and Acryloid® B72 in aromatic hydrocarbon solvent, both Rohm and Haas products, are two acrylic solutions of great color stability, which can be thinned with additional solvent and then brush applied as penetrating surface consolidants.

Reversibility; thermoplastic and thermosetting resins

In the conservation of museum objects, a high premium is placed on the reversibility of all treatments, since it is assumed that any material used in repair is subject to failure or degradation and may require eventual replacement. In the case of a resin that has been used to impregnate the fibers of a wooden object, the only conceivable way of removing the resin would be by dissolving the cured resin in a solvent and then washing it out of the object or possibly volatilizing it. Cured epoxies are not redissoluble to any practical extent.

Related to the problem of reversibility is the distinction between thermoplastic and thermosetting resins. Thermoplastic resins are linear polymers without cross links between molecular chains. In general they can be melted or dissolved. Thermosetting resins are generally of the network or cross-linked type and once cured, cannot be melted or dissolved. Epoxies are thermosetting resins. Most acrylics are thermoplastic; certain ones such as Acryloid® B72 are particularly valued as removable protective varnishes for paintings.

Removal of a thermoplastic resin by dissolution becomes much more difficult when, rather than serving only as a surface coating, the resin is diffused through a three-dimensional object, such as a piece of wood. Moreover, the practicality of such removal decreases rapidly with the size of the treated object. Thus in the conservation of stone and wooden architectural objects, the theoretical reversibility of thermoplastic resins has limited practical significance. Certain thermosetting resins have advantages of practical importance for some purposes in architectural conservation. Greater strength and increased resistance to some aspects of weathering are among these advantages.

Adjustable strength

In structural applications or if subjected to abrasion or any hard service, consolidated wood requires a fair propor-

tion of its original strength. Epoxy consolidants can be formulated to provide high strength to thoroughly rotted wood. (The term strength is used loosely here to include various concepts such as elastic modulus and hardness.)

There are many cases in which an extreme value of strength is not desirable. Where consolidated wood must be nailed, planed, sanded, or otherwise worked, excessive strength can cause inconvenience. Furthermore, where only a portion of a wooden member is unsound and requires impregnation, excessive strength in the consolidated portion may induce stresses in nearby unconsolidated wood. It must be remembered that an impregnant almost invariably alters the mechanical properties of wood, such as its characteristics of expansion and contraction with changes in humidity and temperature. If one portion of a wooden item is made extremely strong by impregnation, and then responds differently from the untreated portion to changing loads or environmental conditions, the relationship between the treated and untreated portions may be a stressful one, in which the untreated portion may suffer by cracking, developing "compression set," or in other ways. Thus, when only a portion of a piece of wood is to be impregnated, it is probably a good general policy to keep the strength of that portion below that of the untreated, sound portion. This theory is subject to debate, and perhaps some testing should be done to prove or disprove it.

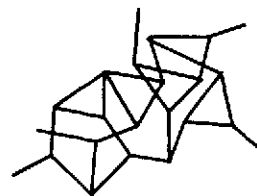
Epoxy resin systems can be formulated to have low elastic moduli, which, together with other properties, are collectively understood as "flexibility." One way of making cured epoxies flexible is to choose epoxies or amines of which the molecules have inherent flexibility. These are apt to be aliphatic materials. Another way is to select epoxies or amines having long chains of atoms between the epoxy or amine groups so

that there is a long interval between epoxy/amine cross-linking points. It is easy to understand how closely spaced cross-link points produce a higher "cross-link density" and thus a more rigid structure. The term cross-link density refers to the number of cross links per unit volume of material. The reason a densely cross-linked structure is more rigid can be understood by a simple architectural analogy: a wooden frame with short timbers bracing each other at frequent intervals is stronger than a frame with long timbers less frequently interconnected.

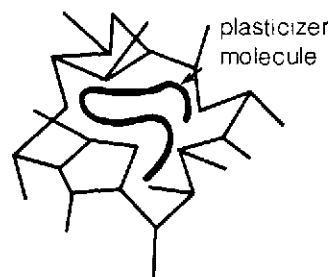
A high order of flexibility, even at low temperatures, can be achieved by reacting an epoxy with a rubber that has amine groups (or other groups reactive with epoxies), at the ends of the rubber molecule. Rubbers are flexible because their molecular chains are not only very long but also highly "kinked" or crooked. This crookedness allows for lengthening as the rubber stretches. Two types of rubbers used in this way are discussed later.

When flexibility is achieved in the ways we have been discussing—through modification of the structure of the molecules—a resin is said to be "internally plasticized." The term "flexibilize" is used in the epoxy industry to denote internal plasticization. By contrast, a less expensive way to introduce flexibility into a resinous system is to add certain non-reactive materials that do not enter into the molecular structure of the cured resin; these are in a sense separate from or external to the molecular structure. The substances are simply called "plasticizers" and are usually viscous liquids. Instead of producing long chains between cross-linking points, they simply take up space and thus distend any pattern of linkages regardless of the length of the chain segments. In figure 6, the lengths of chain segments between cross links are the same in both 6a and 6b, but in 6b a plasticizer molecule is taking up space in the middle of the epoxy and amine network, thus extending the network in volume and effectively reducing the cross-link density. Besides saving cost,

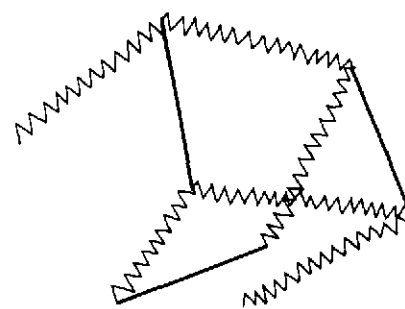
Figure 6. Internal and external plasticization.



6a. Rigid structure: short chain segments frequently cross linked. High cross-link density.



6b. "External" flexibilization: plasticizer molecule distends pattern of short chain segment reducing cross-link density.



6c. "Internal" flexibilization: low cross link density results from greater length of chain segments between cross-link points.

other reasons for using plasticizers are to control viscosity, cure rate, and other properties.

The problem with non-reactive plasticizers is that they are not tied into the cured solid resin because they do not react with the link-forming materials. Although intimately dispersed through the cured resin, they remain as free liquids and might eventually evaporate from the resin, or migrate out in the liquid form. This can lead to embrittlement of the resin and other problems, such as staining of paints.

Many "proprietary" (that is, secret) formulations contain non-reactive plasticizers. Although some perform well, the purchaser does not know the precise composition of such products and can evaluate their comparative performance only by long-term testing of each product.

All the formulations given in this paper are internally plasticized, in the interest of insuring a long-term retention of flexibility. Many slow-curing epoxies become more rigid with time, since that which is considered the curing period is not long enough for all possible cross links to be formed. The process of cross linking or curing goes on for a long time, at a slower and slower rate, until the full network of cross links is established. It is hard to judge accurately after a short time what the properties of an epoxy resin will be after many years, although heating of the cured resin to speed up the final cure sometimes gives a fairly good indication. Thus, epoxy formulations should be made flexible enough so that even after many years the chance of their exerting undue stress on surrounding wood is minimal.

Highly volatile solvents can also be incorporated into epoxy consolidants to provide a porous structure in the finished product. This may help to bring many mechanical properties of treated wood more into line with those of adjacent untreated wood.

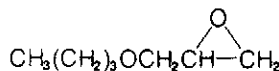
Low viscosity

If little or no solvent is to be used to "thin down" a liquid resin used as an

impregnant, the resin itself must have low enough inherent viscosity to permit easy penetration of deteriorated wood. For example, the acrylic monomer methyl methacrylate has an extremely low viscosity, approaching that of water. The viscosity of epoxies varies over a wide range; in the course of this study epoxy consolidants have been made "thin" enough to penetrate deteriorated wood easily.

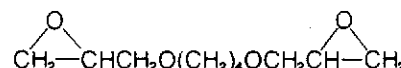
In formulating for low viscosity, the approach has been to start with a DGEBA epoxy resin of lower molecular weight (and therefore lower viscosity) than the most common grade of DGEBA. To further reduce viscosity a large proportion of an aliphatic reactive diluent, an epoxy of extremely low viscosity, is added. They are called diluents, rather than resins, since they do not generally produce good final products when used as the sole epoxy component, although more experiments along this line would be worthwhile. The fact that they are epoxies, and thus reactive, is their great advantage over other low-viscosity materials, such as solvents and plasticizers, which can be used to thin down a resin. By reacting with amine curing agents, they become locked into the final molecular structure of the cured solid resin and thus cannot evaporate or migrate out as free liquid.

Some reactive diluents are monofunctional, which means that there is an epoxy group at only one end of the molecule. Thus the molecule is tied in at only one end; this is perfectly adequate for locking the material into the structure. The use of monofunctional epoxies is one way of reducing cross-link density, since some of the reactive points on amine molecules are taken up by epoxy molecules that connect to nothing else. Butyl glycidyl ether is a common monofunctional diluent:



Other reactive diluents are difunctional. These are able to react at both

ends and thus participate in the formation of a cross-linked system. For this reason they do not weaken a cured product as much as monofunctional diluents and can be used in much higher proportions without danger of rendering the final product overly weak, cheesy, or water soluble. A typical difunctional reactive diluent is 1,4-butanediol diglycidyl ether (Ciba Araldite® RD2):



Low toxicity

Uncured epoxies and amines must not be ingested. They are, generally speaking, skin irritants and, in liquid or vapor form, can irritate the eyes and respiratory tract. Skin contact with epoxy formulations must be carefully avoided, since skin sensitivity is increased with each exposure. Gloves must be worn at all times, and spillage carefully cleaned up. A user can easily become overconfident during early exposures to epoxy formulations, since the skin has not yet been sensitized. Work spaces must be ventilated.

However, if handled correctly, the materials suggested in this report are not dangerous. To keep noxious fumes to a minimum, materials of relatively low vapor pressure have been chosen as consolidants.

Good retention of paints

Fully cured epoxies form a good substrate for paints. Residues of non-reactive plasticizers, or of uncured epoxies or amines, could interfere with paint adhesion. As described later in this report, no tests were made to evaluate the paint-holding ability or completeness of cure of the suggested consolidants, but the two formulations now in actual service appear to be holding paint satisfactorily.

PROCEDURES

Formulation

The foregoing sections have discussed

the ways epoxies, amines, and accelerators can be chosen and combined to achieve desired properties, both during application and when finally cured. A principal aspect of correct formulation is the achievement of a certain chemical balance between amines and epoxies. In curing reactions using primary or secondary amines, one active hydrogen must be lost from an amine for each epoxy/amine bond. Thus, if every potential bond is to be formed, epoxies and amines must be mixed together in such proportions that there will be one active amine hydrogen for every epoxy group. This ideal proportion of each component is called the "stoichiometric ratio," and the condition of chemical balance is called "stoichiometry." It is not important to achieve perfect stoichiometry, since a modest imbalance in favor of either the epoxies or amines will merely result in some epoxy molecules or amine molecules being tied into the structure by fewer than the maximum number of bonds. In some cases, a non-stoichiometric ratio results in a more complete reaction than a stoichiometric ratio; many factors affect the extent to which reactions are driven to completion. A non-stoichiometric ratio in which some molecules remain only partially reacted is sometimes deliberately used as a way of reducing the cross-link density and thus the stiffness or rigidity of the cured resin. Most of the formulations given in this paper are stoichiometric because the purpose of the project was to compare the physical properties of different cured resins, and such comparison would be less meaningful if some formulations were more nearly stoichiometric than others.

Stoichiometry is less significant in the case of tertiary amines than with primary or secondary amines, because the former do not have active hydrogens and serve mainly as catalysts or initiators.

The calculations used to achieve stoichiometry are simple. Epoxies all have a certain "epoxide equivalent weight" (EEW), or "weight per epoxide" (WPE), which is the molecular weight of the

resin divided by the number of epoxy groups. Thus if the total molecular weight of a certain epoxy molecule is 380, and if it contains two epoxy groups, the weight per epoxy group is $380 \div 2$ or 190.

The same measure is applied to amines. The "amine equivalent weight" (AEW) is the molecular weight divided by the number of active hydrogens. Thus, if an amine molecule has a total molecular weight of 230, and if it has four active hydrogens, the molecular weight per active hydrogen is $230 \div 4$ or approximately 57.

To achieve stoichiometry, one uses the weight of epoxy that contains one epoxy group with the weight of amine which contains one active hydrogen. This means that one uses the materials in the ratios, by weight, of their EEW's or AEW's. Grams, ounces, or any other units of weight can be associated with the EEW's or AEW's as long as the same unit is chosen for both epoxy and amine. Thus if an epoxy has an EEW of 190 and an amine has an AEW of 57, one uses 57 grams of amine for each 190 grams of epoxy.

When several epoxies or several amines are blended, the following averaging process is used to determine the overall EEW of the mixed epoxies or AEW of the mixed amines. The equation below demonstrates the averaging of EEW's for two epoxies but works in the same way for any number of epoxies or amines.

EEW of mix =

$$\frac{\text{Total Weight}}{\frac{\text{Weight of epoxy A}}{\text{EEW of epoxy A}} + \frac{\text{Weight of epoxy B}}{\text{EEW of epoxy B}}}$$

Any non-reactive materials premixed with either the epoxy or amine component of a formulation must be included in "total weight."

Many commercial epoxies and curing agents are supplied as mixtures of materials of slightly different molecular weight, of which the molecular weight quoted by the manufacturer is simply an average. Therefore, the actual weight

per epoxide or weight per active hydrogen may vary from what would be calculated from the idealized formula of the pure material. Ideally, 1,4-butanediol diglycidyl ether would have a molecular weight of 202, and, being a diepoxide, an EEW of 101. However, the commercial product, being impure, has an EEW in the range of 130-140.

Mixing

Epoxides and amines should be vigorously mixed to insure that each epoxy group "finds" an amine group. A two-minute thorough mixing with a spatula is not excessive for a small test quantity. For larger amounts, an electric drill fitted with a propeller-shaped mixing blade is more efficient. Vigorous shaking is appropriate for low-viscosity formulations.

Where several epoxies or several amines are to be used in a formulation, all the epoxies can usually be premixed and stored, and all the amines likewise. Thus an entire formulation can be sent to the job in two containers, and a simple ratio given for the mixing of these two fractions of the formulation by volume of material rather than by weight. Such volume ratios can be derived by specific gravities from the weight units in which formulas are normally written. Specific gravities are usually given in the manufacturers' literature. Weight/volume conversions can also be made easily on a balance. Although simple volume ratios are convenient on the job, the accurate measurement of materials present in small proportions is much more easily done by weight. Thus premixing of the components of complicated formulas is best done by weight.

Good balances for weighing the ingredients are available at low cost from such firms as Ohaus. The type of balance needed is not the highly sensitive type made for analytical work, but one accurate only to a tenth of a gram and capable of weighing out at least 1,600 grams.

A simple procedure is used to save time in weighing out a formulation. Some balances have a "tare" weight

that permits the balance to be zeroed with an empty container on the platform. The balance weights are then pre-set to the desired weight of the first component to be put in the container. This first component of the formulation is then added until the balance needle is centered. The weights are then reset to read the total of the first and second components, and the second component is then added up to the balance point. This process is continued until all the components have been added.

Storage

The amount of material that should be premixed and stored is governed by the rate it is used and by the so-called "shelf life" of the most unstable material in a mix. The shelf life of most epoxies and amines is good, but the formulator should study the manufacturer's literature on each product. In addition, some mixtures of otherwise stable materials may separate on standing.

Some epoxy resins used in the consolidants suggested here—such as DER (Dow epoxy resin) 332—are so pure that they can crystallize in the container. Storage at a steady and not too cold temperature helps minimize this tendency. If crystallization occurs, these resins can be melted by warming. Once diluted with reactive diluents or other epoxy resins, they lose their tendency to crystallize.

Application

The essence of successful application of a consolidant is to get it into the wood as effectively as possible. Conditions—and pieces of wood—vary so much that there can be no complete manual of instructions in such a brief study as this. Paul Stumes discusses some application techniques (see bibliography). A few basic rules can be given here:

1. **Exploit the end grain.** Wood is much more permeable along the grain than across it. Thus the best place to introduce a liquid consolidant is on the end grain where capillarity pulls it along through the cells of the wood. When a long piece must

be consolidated, one cannot expect to get all the resin in through one end or the other. In this case one can drill 1/8" to 1/4" diameter holes into the wood along its length, and pour the resin into the holes, repeatedly refilling the holes as the resin is absorbed (figure 7). The holes thus act as reservoirs. The holes should be drilled across the grain and should be staggered so as to expose the maximum amount of end grain with the minimum number of holes. Holes can be slanted across a piece of wood at an oblique angle in cases where this will extend the maximum length of each hole, exposing more end grain. Where penetration is found to be difficult, the holes in one staggered row can be made to overlap those in the next.

2. **Avoid trapping air.** Generally one should work from one end of a piece to the other, since resin entering a piece of wood from two ends can trap air inside the grain between the two advancing fronts of liquid. This air can then prevent resin from penetrating further.
3. **Prevent leakage.** A consolidant may occasionally flow out of pre-existing holes or cracks in a piece of wood. Holes or cracks can be plugged with modelling clay, melted wax, or any of a number of other materials. Melted wax can be brushed over a whole piece where there are many holes, and later scraped off. (Wax should not be used on a piece that must be painted because the residue will interfere with the adhesion of paint.) It is best to plug holes before wetting the piece with resin, since it may be difficult to make the plugs adhere to a wet piece.
4. **Be prepared for "exotherm."** The reaction of epoxies and amines liberates heat. Chemical reactions producing heat are called exothermic reactions, and, in the epoxy industry, the phenomenon is referred to as "exotherm." When epoxies and

amines are mixed and used in small quantities, the heat is rapidly dissipated. In larger quantities the temperature may build up to high levels. Epoxies and amines that react rapidly with each other reach much higher temperatures than slow-curing ones because there is less time for heat to be dissipated. Since the heat evolved further accelerates the reaction, heat build-up is a vicious circle and can lead to scorching of the resin. The easiest ways to control heat are to use slow-curing materials and mix them in small batches. With slow-curing materials heat can be used constructively as an accelerator. Once a member has been consolidated, it can be gently warmed to speed up the cure.

5. Use wood preservatives correctly.

Water-repellent wood preservatives contain waxes or other water-repellent materials that may adversely affect the penetration of consolidants or the bond of patching compounds applied after the preservative. Accordingly this type of preservative should be used only after consolidation and patching. Treatment of wood before consolidation or patching can be done with solutions of fungicides in a solvent, without added water-repellents. A solution of 7% (by weight) orthophenylphenol in ethanol has been used.

Fungicides can be added directly to epoxy consolidants. Git-Rot®, a well-known commercial epoxy consolidant, contains pentachlorophenol⁷

RESULTS OF TESTS ON CONSOLIDANTS

Consolidants cured at room temperature were tested for visible or mechanical deterioration after a week of soaking in water. Both the consolidant itself and rotted wood treated with consolidant were soaked. Weight gain during soaking was not measured since no emphasis was placed on reducing water

⁷U.S. Patent 3,389,037; June 18, 1969.

absorptions to really low levels: in service, painted wood is not expected to be soaked.

The flexibility was only roughly assessed, by manual flexing. All formulations were cured at room temperature, and some samples of each were then postcured in an oven at about 230°F for 12 hours. This postcure was intended to insure that the curing reaction was driven to completion, so that samples inspected after postcuring would probably be at least as fully cured and as rigid as the same formulations might be expected to become after long cures at normal temperatures.

Weathering tests were not carried out on consolidants, since, in service, the materials are meant to be painted and not exposed to ultraviolet light. Weathering tests therefore take a lower priority than the other tests described and can be done at a later stage in the study of these systems. However, weathering tests and laboratory tests of photochemical stability should be done.

Probably the most important test remaining is some test of paint adhesion under exterior conditions. If unreacted epoxy or amine is present in any of the formulations it could stain or chemically attack paint layers. The extent to which all ingredients in a test formulation have reacted should ideally be measured. Adjustments could then be made in the proportions of materials used in order to effect more complete reaction. Two of the consolidants (strong consolidants Nos. 1 and 2) have been in actual service for about a year and have not yet adversely affected paint layers.

At this preliminary stage in the study of these systems, no attempt was made to quantify test results. The suggested formulations are those which passed the simple tests described above. A much larger number of samples were rejected.

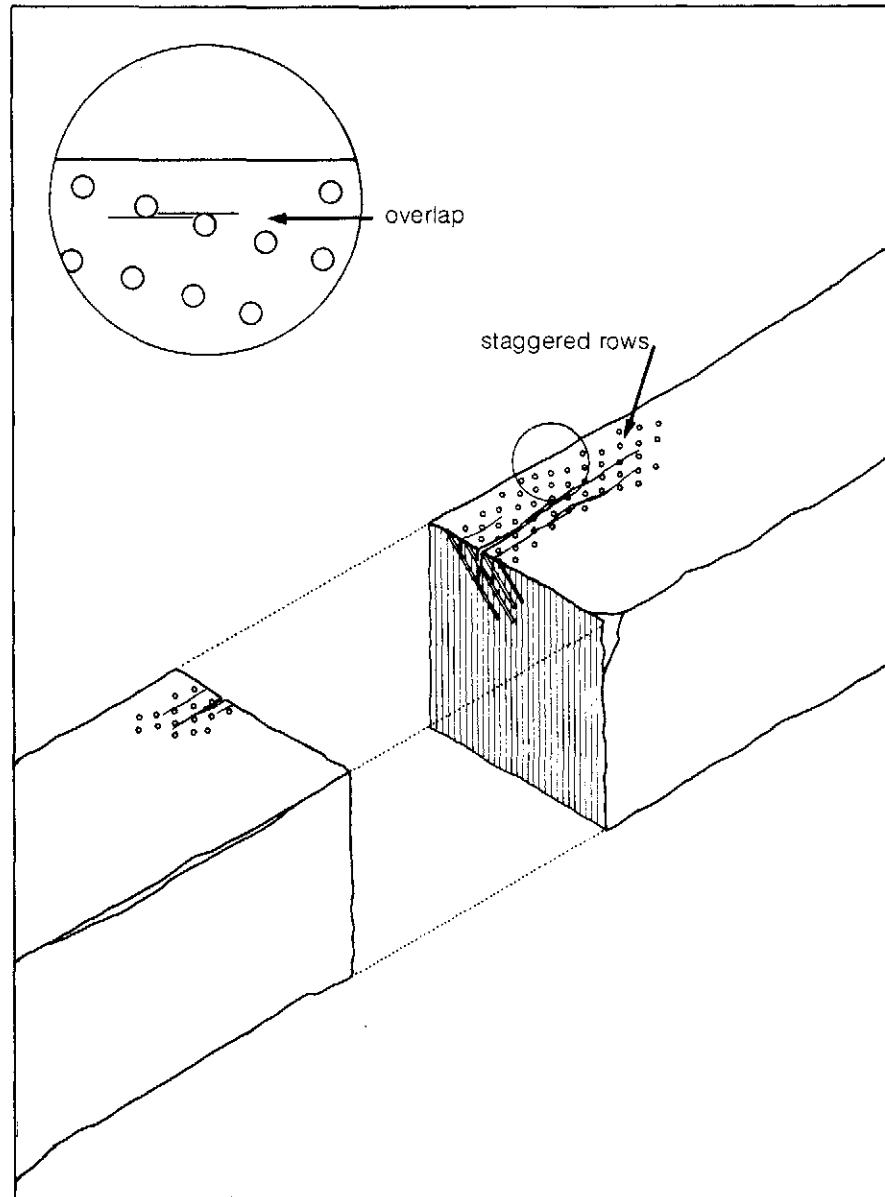


Figure 7. Pattern for holes drilled into rotted wood.

FORMULATIONS

Strong consolidants

Although not nearly as strong as epoxies can be, these consolidants are generally stronger than wood. These two consolidants are the only ones now in actual service. They are easy to apply and appear to be durable. They are recommended as practical materials subject to observation of their long-term performance.

Strong consolidant No. 1:

| | Material | Commercial Designation | Pts. by Weight | Pts. by Volume |
|--------|----------------------------------|--------------------------|----------------|----------------|
| PART A | Low-viscosity epoxy resin | Dow DER 332 | 100 | 6 |
| | Low-viscosity epoxy diluent | Ciba-Geigy RD2 | 50 | 3 |
| PART B | Flexibilizing amine curing agent | Jefferson Jeffamine D230 | 55 | 4 |

This formulation cures to a serviceable product in about three days at room temperature; curing and rigidification then continue for a long time. The end result is a rather rigid material. Much faster cures can be obtained with mild heating or by the use of accelerators, such as Jefferson Accelerator A398.

Strong consolidant No. 2:

| | Material | Commercial Designation | Pts. by Weight | Pts. by Volume |
|--------|----------------------------------|--------------------------|----------------|----------------|
| PART A | Low-viscosity epoxy resin | Dow DER 332 | 100 | 1 |
| | Low-viscosity epoxy diluent | Ciba-Geigy RD2 | 100 | 1 |
| PART B | Flexibilizing amine curing agent | Jefferson Jeffamine D230 | 75 | 1 |

This formulation is similar to No. 1 but more flexible. Postcuring at 230°F for 12 hours yields a fairly rigid material, indicating that it should probably be considered a "strong" consolidant.

The volume proportions given here, although convenient to use, are only approximate conversions from the weight proportions. The weight proportions are more nearly correct in respect to stoichiometry. In using the volume proportions there is some possibility that excess amine will be present and will remain unreacted.

Semi-flexible consolidant:

| | Material | Commercial Designation | Pts. by Weight |
|--------|----------------------------------|--------------------------|----------------|
| PART A | Low-viscosity epoxy resin | Dow DER 332 | 100 |
| | Low-viscosity epoxy diluent | Ciba-Geigy RD2 | 200 |
| PART B | Flexibilizing amine curing agent | Jefferson Jeffamine D230 | 120 |

This formulation cures in about three days, but, like the strong consolidants, could be accelerated. It exhibits significant flexibility even after postcuring at 230°F for 12 hours. Although low temperatures drastically reduce the flexibility of the cured product, the flexibility achieved is probably greater than is needed for most applications. At present the strong consolidants are being used in preference.

BASIC APPROACH

All the materials suggested as consolidants are transparent. This is generally true of organic polymers, whether they are resins, rubbers, or other physical types. Opacity is usually imparted to polymer formulations by solid fillers and pigments. For example, the rubber of automobile tires is black and opaque only because of black pigment.

Epoxy patching compounds for wood are made by adding to an epoxy resin various fillers. These fillers lower cost and impart certain desired properties, creating a paste in the uncured state. The basic points made in previous sections about epoxies as consolidants apply to epoxies used as the binder in patching compounds and need not be repeated. The discussion of patching compounds will therefore concentrate primarily on the solid fillers. As with consolidants, the subject will be approached by outlining the required properties of a patching compound and the ways in which both the resinous binder and the fillers affect these properties.

DESIRED PROPERTIES OF PATCHING COMPOUNDS

Reasonable cost

Epoxy resins are expensive, and fillers can cut the cost per unit volume almost in half. The fillers suggested here are common in patching compounds and other composite materials. Woodflour (pulverized wood) was used in most of the test formulations, although by the end of the investigation it was felt to be unnecessary. The other fillers used were "microballoons" of phenolic resin and of glass. These are hollow spheres ranging in diameter from about .0002" to about .005". If purchased in bulk they are reasonably inexpensive. They are an effective means of lowering the cost of patching compounds, since, for two reasons, they can be used in high volume proportions and thus take up a lot of space, saving resin. The first of these reasons is that their round shape allows them to roll on each other so that patching compounds do not become stiff and hard to work even when highly loaded

with microballoons. Second, unlike woodflour, they do not absorb resin; thus a given amount of resin goes farther in wetting the surface of a given volume of filler.

Low shrinkage

Significant shrinkage during solidification is most undesirable in patching compounds used to fill holes. Shrinkage causes the compound to pull away from the sides of the hole, thus losing an intimate bond. Shrinkage is avoided principally by using solvent-free systems. "Plastic Wood" is an example of a system which contains solvent: as the solvent evaporates this material shrinks badly. A principal reason why solvent systems are popular, in spite of shrinkage, is that the entire formulation is packaged in one container and requires no mixing before use.

Most solvent-free systems shrink a little as a result of the chemical reactions by which they cure. However, epoxies have low shrinkage on curing—generally lower than unsaturated polyesters—which is part of the reason for their excellent adhesion.

One type of shrinkage is hard to avoid, although its effect on the adhesive bond is not so drastic as with the types of shrinkage already described. This is shrinkage caused by absorption of some of the binder into the surrounding wood during the cure. This can be minimized by using resins of higher viscosity than those suitable as impregnants. Also, a hole can be slightly overfilled to compensate for this, and any excess can be planed or sanded off after cure. Another way to reduce this type of shrinkage is to reduce the wood's absorbency by priming it with an epoxy consolidant and allowing this to cure before applying the patching compound. Shrinkage-compensating ingredients, such as materials that produce gas bubbles, could be investigated as a means of eliminating shrinkage in many types of patching systems.

Controllable curing mechanism

Just as with consolidants, the binder in a patching compound should harden by a chemical reaction that is reliable and that entails the minimum inconvenience in use. Epoxies meet this requirement.

High adhesion

Good adhesion to wood is obviously important for a patching compound and is an established property of epoxies. Their good adhesion is the result of several chemical factors, as well as the factor of low shrinkage.

Reversibility; machinability

Consolidation by epoxy resins is technically not reversible, since the cured resin is not soluble to any practical extent and thus cannot be "washed" out of the wood. Fortunately, the patching compounds suggested here, although not redissoluble, are mechanically removable: they are easily cut with a knife or chisel, so that a carpenter can later remove them without difficulty (figure 8). They also are easily carved or sanded when cured, which is of major practical importance. By contrast many commercial epoxy patching compounds set so hard that they are difficult to sand or carve.

The general machinability of the suggested materials is derived partly from the choice of resins that are not excessively strong and partly from use of the microballoons as filler. Microscopic inspection of the machined surfaces of samples indicates that a knife blade or sandpaper readily breaks the walls of the microballoons. The cured patching compounds have little tendency to gum up sandpaper.

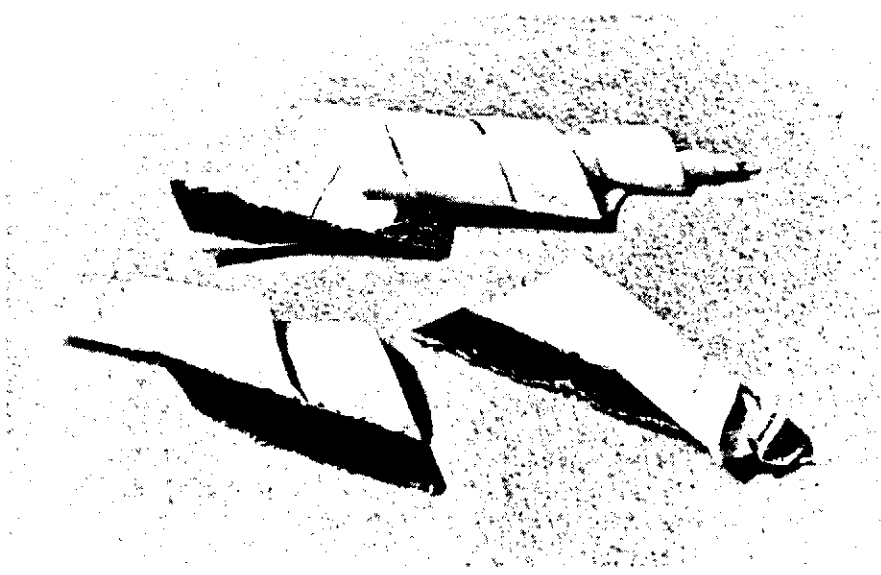
Durability; protection by pigments; silane coupling agents

Many traditional patching compounds lack durability under exterior conditions. A typical example is "wood putty." A typical brand of wood putty contains woodflour, gypsum, and vegetable gum binder. The latter two components are drastically affected by water, so that imperfections cannot be tolerated in a

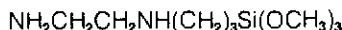
paint film over the putty.

Epoxies have good weather resistance except for the susceptibility of most types to degradation by ultraviolet light. Since even an imperfect coat of paint gives adequate protection against this, it is not a problem for painted woodwork. However, pigments or fillers that absorb ultraviolet light can be incorporated into a patching compound as a second line of defense. The patching compounds described here made with glass microballoons all contain lampblack in the proportion of about 2%, by weight, of the total binder (epoxies, curing agents, diluents). Pigments should not be stirred in as dry powder, since they cannot be properly dispersed in the medium without milling equipment and will remain in the material as agglomerates, or clumps. Pigments can be purchased predispersed in epoxy resin or in plasticizers such as dioctyl phthalate. Since these dispersions are concentrated, only small amounts are needed. Thus the effect of the dispersion vehicle can be ignored. Two suppliers of concentrated dispersions are CDI Dispersions and Daniel Products Company (see appendix).

The incorporation of glass microballoons into epoxy patching compounds may involve problems of bonding the resin to the glass. In particular, the interface between the two materials may be susceptible to penetration by water. This difficulty arises from certain chemical and physical differences between the resin and the glass. Accordingly, it is common practice to use coupling agents in many types of polymer/glass composites.⁸ In the case of epoxy/glass composites, such as the patching compounds described here, the coupling agent is usually an amino-functional silane or an epoxyfunctional silane. As the names suggest, the molecules of these substances incorporate silane groups capable of bonding well to glass



or other silica, and also possess epoxy groups or amine groups capable of reacting with amines or epoxies, respectively, in the polymer formulation. Silane coupling action greatly increases the water resistance of the bond of the polymer to glass. A common aminofunctional silane is Dow-Corning Z-6020:⁹



The inconvenience and sometimes technical difficulty of using silanes is a disadvantage of glass balloons as compared to phenolic ones, which require no coupling agents. However, no comparative tests were made to assess the relative durability of systems made with the two types of microballoons.

Adjustable strength

It is probably unrealistic to hope that the expansion coefficients of a patching compound can be made to equal those of the surrounding wood, since the complexities of the wood's expansion characteristics include the effects of temperature, humidity, species and condition of wood, and direction relative to the grain. Accordingly, it is desirable that the patching compound be more flexible than the wood in order to comply with the wood's movements without

Figure 8. The epoxy patching compounds described in this report can be readily worked with hand tools, such as chisels, drills, and hand planes. The shavings pictured here were planed from a wooden member that had a crack filled with patching compound (the dark colored portion of the shaving). (Photo: Author)

imposing stresses on it. As already discussed in reference to consolidants, this is accomplished by adjusting the formulation of the polymer in the patching compound. The term flexibility requires clarification. A low modulus of elasticity is desirable: this refers to the

⁸Lawrence J. Broutmann and Richard H. Crock, *Composite Materials*, vol. 6, edited by Edwin P. Plueddemann, *Interfaces in Polymer Matrix Composites* (New York and London: Academic Press, 1974), passim; Edwin P. Plueddemann, "Catalytic Effects in Bonding Thermosetting Resins to Silane-Treated Fillers," *Advances in Chemistry series*, no. 134, pp. 86-94; Dow Corning Corporation, "Silane Coupling Agents," brochure, 1970; Dow Corning Corporation, "Dow Corning Organosilicon Chemicals," bulletin 23-181, 1974.

⁹Dow Corning Corporation, "Dow Corning Organosilicon Chemicals."

ratio between imposed stress and observed strain (deformation) of the patching compound. Fortunately, wood expands and contracts slowly, so that rapid deformation of patching compounds is not required. More relevant is the deformation after some hours under stress. This slow compliance with imposed forces is called "creep." Creep is probably the best word to describe the type of flexibility required, since it relates deformation to time. Elongation is a term that describes the total distance over which a material can be deformed before yielding, stated as a percentage of the length of a sample before stressing. High elongation is not required in patching compounds, because they are not recommended for use in actively moving joints where flexing takes place over a large distance. In these instances elastomeric sealants are more suitable.

Creep is a typical characteristic of linear or lightly cross-linked polymers. As a polymer creeps, the polymeric chains slip and slide relative to each other. Cross linking between chains reduces the rate and extent of chain slippage; the presence of aromatic rings or bulky side chains in an epoxy structure also generally reduces chain slippage.

An important point concerning the flexibility of most of the suggested fillers is that it is highly dependent upon temperature: the cured patching compound is far more rigid at low temperatures than at high temperatures. High temperature facilitates chain slippage in much the same way as it lowers the viscosity of liquids by permitting the molecules to move about more easily. Thus it would be unwise to evaluate the flexibility of a patching compound only at room temperature, since low temperatures may stiffen it excessively; conversely, a formulation found to possess sufficient rigidity at room temperature may deform unduly if heated to the temperatures found in such hot locations as boiler rooms or attics.

Apart from the flexibility of the poly-

mer used as binder in the patching compounds, the fillers also are chosen for compatibility with a flexible system. Elongated fillers, such as chopped glass fibers that reinforce and rigidify polymer systems are avoided. Angular mineral fillers are also avoided. The roundness of microballoons insures that they will have little or no reinforcing effect, especially since their thin walls render them individually flexible.

Good working properties

The suggested patching formulations, in the uncured state, have outstanding working properties. Polymers having unduly high viscosity in the uncured state are avoided, since they make the paste heavy, sticky, and awkward to use. The microballoons offer extremely easy working as compared to angular or fibrous fillers because of their round shape: they function almost like ball bearings. Thus, under the force of a knife or spatula, the suggested compounds move easily.

On the other hand, the suggested compounds are designed not to move at all under a load which is below a certain threshold value. Thus, once placed in a hole in a vertical or overhead location, these compounds are not affected by gravity unless the patch is abnormally large. The viscosity of the compound is great up to a certain threshold value of applied force above which their viscosity is dramatically reduced. This inverse dependence of viscosity on applied force is called **thixotropy**. It is imparted mostly by the fumed silica (Cabosil® M5) present in all the formulations. Materials used for this purpose are called "thixotropic agents" in industrial literature. Cabosil® is one of the most common.

An added advantage of the microballoons is that being hollow and very light, they make the entire patching compound light and thus less affected by gravity once put in position.

Low toxicity

In general, the resins, curing agents, and modifiers used in the patching compounds require the same degree

of handling care as consolidants, but are safe if handled properly. Fumed silica and microballoons should not be inhaled. (A particle breather is necessary when mixing these two components into the formulations.) Once mixed in, they are harmless since they can no longer drift into the air.

Ability of compound to "breathe"

The ability to pass water vapor is a feature that has not been achieved in the present formulations. As explained later in this paper, vapor-permeability is probably not important if the material is used where it cannot trap water.

Expansion characteristics matched to wood

Under the influence of changing temperature and humidity, the suggested patching compounds do not exhibit characteristics of expansion and contraction closely matched to those of wood. This will be discussed further, and test results are given which indicate that the more promising patching compounds can be expected to perform well in spite of this limitation.

Good retention of paints

Fully cured epoxies form a good substrate for paint. Tests described later in this report indicate that paint adheres well to the general types of compounds suggested.

EPOXY/POLYSULFIDE BLENDS

A number of proposed patching compounds are blends of epoxy resin and polysulfide rubber. Because these components react with each other in rather complex ways, epoxy/polysulfides are described in this separate section.

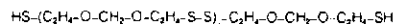
In this project, perhaps undue emphasis was initially placed on finding means to make highly flexible patching compounds. Polysulfides used as flexibilizers have permitted highly flexible compounds to be made without some of the difficulties encountered when

using high proportions of certain other flexibilizers. Such problems are high viscosity or a slow rate of cure.

The weathering tests done during the project have tended to indicate that extreme flexibility is not desirable for most applications. The advantages of polysulfides thus seem less significant than they did initially; some disadvantages, such as a strong odor, should be considered. (Fortunately the fumes are not so much toxic as merely obnoxious.)

Basic description of system

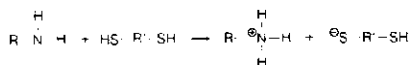
The first liquid polysulfide (LP) rubber was marketed by the Thiokol Chemical Corporation in 1943.¹⁰ Among many uses, LP rubbers have served extensively as flexibilizers for epoxies. Those LP rubbers intended for use with epoxies have the following generalized structure,¹¹



The value of n varies to give different molecular weights and viscosity grades. Thiokol LP-3 is the grade most commonly used with epoxies, having an n value averaging about 6 and an average molecular weight of about 1,000.

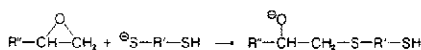
Because polysulfide rubbers react with epoxies, they serve as internal flexibilizers, rather than inert plasticizers. Several reaction mechanisms have been described^{12,13}. These reactions can occur together in epoxy/polysulfide systems. They will be summarized here in greatly simplified form.

Mercaptans alone react only very slowly with epoxies. (A mercaptan is any compound containing the group SH.) A faster cure can be accomplished by adding a base, (such as an amine) which extracts the proton (H^+) from the mercaptan group, producing the mercaptide ion (RS^-):

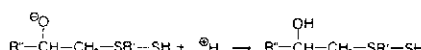


The mercaptide (RS^-) ion is highly reactive toward the epoxy group; this reaction is considered the basis of al-

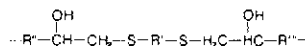
most all epoxy/polysulfide curing mechanisms. The RS^- ion opens the epoxy ring:



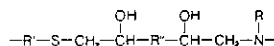
The opened epoxy ring abstracts a proton (H^+) from any of a number of sources, such as an unreacted SH group or the substituted ammonium ion formed by the reaction of an amine and a mercaptan:



In the final formula above, one SH group is shown unreacted. This can react in exactly the same way to produce a continuous chain of epoxy and polysulfide units:



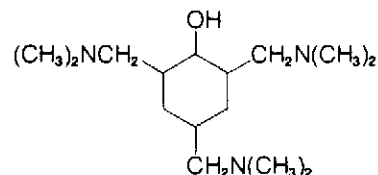
However, some of the epoxy groups can react with the amine, producing a terpolymer incorporating epoxy, amine, and polysulfide units:



Thus, in the above reactions, the amine serves a dual role. First, it catalyzes the polysulfide/epoxy reaction by abstracting a proton from the mercaptan group. Second, it can enter into the final cured polymer in the conventional way. Many factors influence the relative rates of these different reactions. Triethylene tetramine (TETA) has been found highly effective in curing mixtures of epoxy with even large amounts of polysulfide. In one study, a 2 to 1 blend of polysulfide/DGEBA epoxy was cured at room temperature with TETA, used in the amount of 1/10 the weight of epoxy: 92% of the mercaptan groups were reacted.¹⁴

The amine most commonly recommended for epoxy/polysulfide systems

is a tertiary amine, 2, 4, 6-tris (dimethylaminomethyl) phenol.¹⁵



This is sold by Rohm and Haas as DMP-30, and by Thiokol as EH 330. Its popularity in these systems is based on several factors. It provides rapid curing. As an aromatic compound, it has been found to produce more stable mixtures with uncured polysulfides than do many aliphatic amines. In addition, DMP-30 is particularly effective in promoting a complete reaction of polysulfides with epoxies. In the study cited above, when a 2 to 1 blend of polysulfide/DGEBA epoxy was cured at room temperature with DMP-30, over 99% of the mercaptans were reacted.¹⁶

As already discussed tertiary amine curing agents act principally to initiate reactions of epoxy groups with each other or with other functional groups, such as mercaptan groups. There might be some concern about whether all the amine is bonded into the cured product; there may also be concern about the partially ionic character of the polymer

¹⁰Norman G. Gaylord, ed., *High Polymers*, vol. 13, part 3, Polyalkylene Sulfides and other Polythioethers (New York: Wiley-Interscience, 1962), p. 116.

¹¹Henry Lee and Kris Neville, *Handbook of Epoxy Resins*, rev. ed. (New York: McGraw Hill, 1967), p. 16:21.

¹²Gaylord, *High Polymers*, pp. 195ff.

¹³Lee and Neville, *Handbook of Epoxy Resins*, pp. 16:21ff.

¹⁴*Ibid.*, p. 16:22.

¹⁵Thiokol Corporation, "Thiokol EH 330," bulletin TD455-J, 1974.

¹⁶Lee and Neville, *Handbook of Epoxy Resins*, p. 16:22.

at points where the amine is reacted. Accordingly, it may be preferable to use primary amines as curing agents for epoxy/polysulfides. Aromatic primary amines are more favorably recommended for this purpose than aliphatic ones, since mixtures of polysulfide rubber and primary aliphatic amines can develop problems of separation if allowed to stand a long time before use.¹⁷ Coupling agents can sometimes be used to prevent this separation.¹⁸

Formulation of epoxy/polysulfides

functionality—Each mercaptan group (SH) can react with only one epoxy group. Although polysulfides sometimes contain extra mercaptan groups along the length of the molecule, in general there are only the two terminal mercaptan groups. In other words, the functionality is two. This is low as compared, for example, with a primary diamine ($H_2N-R-NH_2$) having four active hydrogens (a functionality of four), and thus capable of reacting with four epoxy groups. We have already seen that a cross-linked structure cannot be formed in a cured epoxy formulation unless either the epoxy or the curing agent has a functionality greater than 2: only a long-chain structure is formed, without the cross links between chains that impart strength. A major purpose of amine curing agents in epoxy/polysulfides is to increase the functionality of the total system to produce the desired degree of cross linking.

stoichiometry—Since typical polysulfides have low functionality relative to the size of their molecules, over twice as much polysulfide as DGEBA epoxy would generally be required to achieve stoichiometry in a simple epoxy/polysulfide blend without added amines. In amine-cured epoxy/polysulfide systems, the proportion of amine is generally chosen without regard to the effect of the mercaptan groups on stoichiometry.¹⁹

When using tertiary amines, a somewhat empirical approach is often used to determine the best proportion of amine, the desired cure rate often being the determining factor. The product DMP-30 is generally used in the proportion of 6-12 parts by weight for each 100 parts of epoxy. High concentrations of polysulfide tend to reduce the cure rate; to compensate for a high polysulfide level, DMP-30 may be used at the higher end of the concentration range given above.

PROCEDURES

Formulation

polymer component—The considerations and procedures involved in formulating consolidants apply equally to formulating the polymer portion of patching compounds. Some of the polymers used in the patching compounds can be used in proportions deviating significantly from stoichiometry. Close adherence to stoichiometry is not important in epoxy/polyamide blends.²⁰ In epoxy/polysulfide blends and epoxy/butadiene-acrylonitrile blends, the proportions of epoxy, rubber, and secondary curing agents are all chosen with less regard to achieving careful stoichiometry than to obtaining desired cure rates and other properties.²¹

proportion of fillers—A good proportion of filler can be judged roughly as follows: an excess causes the material to feel "dry" when applied and results in a poor bond to the substrate. An insufficiency of filler causes the uncured material to flow out of place, and makes the cured product difficult to sand or carve.

In paints, putties, patching compounds, and other polymeric binder/filler systems, the proportion of filler is often expressed by the pigment volume concentration, or PVC. The PVC is the percentage of pigment (or filler), by volume, of the total formulation, excluding volatile solvents and thinners. Thus, a dried paint or patching compound with a PVC of 50% is half pigment or filler

by volume.

The concept of critical pigment volume concentration (abbreviated CPVC) is also useful. It is that PVC at which the amount of binder present is just sufficient to fill the spaces between the particles of pigment or filler. Above the CPVC, air spaces exist in the material, vapor permeability increases, susceptibility to damage by water usually increases, and many mechanical and other properties change drastically.

For most of the test formulations using glass microballoons, the balloons and woodflour were incorporated together in a proportion of two parts microballoons to one part woodflour, and used together at a constant PVC safely below the CPVC. In calculating proportions of fillers, the formulator must carefully distinguish between volume and weight and must also distinguish between the actual volume of a filler (which excludes the spaces between filler particles) and the bulk volume of a dry filler (which includes the air spaces between particles).

In the formulations using glass microballoons, fumed silica (Cabosil® M5) was used in the proportion of 5%, by weight, of the total liquid binder (epoxies, curing agents, diluents). A weight proportion was used, rather than a volume proportion, because values permitting volume calculations were not available for this material. Cabosil® was not counted in the PVC calculations.

As the project developed, phenolic microballoons were used more than glass ones because of the inconveni-

¹⁷*Ibid.*, p. 16:23.

¹⁸Thiokol Corporation, "Polysulfide Liquid Polymer/Epoxy Resin Systems," bulletin TD451-J [n.d.].

¹⁹Lee and Neville, *Handbook of Epoxy Resins*, p. 16:21.

²⁰Potter, *Epoxide Resins*, p. 67.

²¹Lee and Neville, *Handbook of Epoxy Resins*, p. 16:22; B. F. Goodrich Chemical Company, "Hycar Elastomers," brochure, 1975.

ence of having to use silanes with glass microballoons. At the same time more attention was being given to epoxy/polysulfide blends. Woodflour was increasingly felt to be superfluous. Accordingly, phenolic microballoons were used with fumed silica, and without woodflour, for some of the epoxy/polysulfides. No PVC calculations were made for these blends. Fumed silica was premixed with phenolic microballoons in the ratio of one silica to three balloons, by weight. The two powders were shaken together in a polyethylene box with ceramic marbles to obtain a uniform mixture. The mixture of powders was then used in the amount of 25%, by weight, of the total liquid binder (4 parts binder to 1 part powder). The ratio was found to produce good pastes, but after the test program, a figure of 24% was adopted.

proportion of lampblack—In formulations containing lampblack, this pigment was used consistently at about 2%, by weight, of the total liquid binder. This is a typical value where lampblack is used to provide protection against ultraviolet light. The lampblack was purchased pre-dispersed in dioctyl phthalate at a concentration, by weight, of 45% of the total dispersion. Accordingly, to achieve the desired concentration of lampblack, the total dispersion of lampblack was used consistently at 5%, by weight, of the total liquid binder.

selection and proportioning of silane—In formulations containing glass microballoons, silane coupling agents were used consistently in the proportion of 0.75% of the total liquid binder, by weight. No attempt was made to optimize the proportion of silane by a program of testing. The proportion was chosen based on typical practice in the field of polymer/glass composites.

Silane couplers mixed together with polymers and fillers migrate to the surface of glass fillers during the cure. The proportion of silane used

should be adjusted so that the layer of silane deposited on the glass surface is thin. A thick layer is likely to give a weaker product than a thin layer.

A wide variety of amino-functional and epoxy-functional silanes are available. The considerations in choosing among these are complex. No attempt was made to choose the ideal coupling agent for each formulation. In general, when the epoxy component is present in excess of the stoichiometric amount, as compared to all curing agents and other materials reactive with epoxies, an amino-functional silane is a better choice than an epoxy-functional one. Under these conditions, an epoxy-functional silane would compete with the other epoxy ingredients for curing agents, which are in short supply, and there is a possibility that not all of the epoxy-silane will be reacted. An amino-silane, by contrast, is likely to be fully reacted, since there is more than enough epoxy with which to react. Because the polymer/glass interface is a weak point in the system, it is important that the silane coupling agent should be fully reacted for maximum effect.

In the reverse situation, where curing agents are present in excess of epoxy, an epoxy-functional silane is likely to be a better choice.

Mixing

premixing—As we have already discussed in relation to consolidants, the epoxy portion of a formulation can usually be premixed and stored in one container: the one or more epoxy resins, epoxy-functional reactive diluents, and epoxy-functional silanes. In the same way all the curing agents, amines and amino-functional silanes can usually be premixed. Polysulfide rubber and amine-terminated butadiene/acrylonitrile rubbers can be premixed and stored with amine curing agents, provided the manufacturer's guidelines as to compatibility are observed.

The advantage of premixing is that one goes to the job site with the entire liquid portion of the formulation in two containers, rather than in five or more.

The mixing of these two "halves" of the polymer system can usually be done by simple volume proportions, translated in any convenient way from the weight proportions. By convention, the epoxy components together are called part A, and the amines or other materials reactive with epoxies are part B.

Pigments dispersed in non-reactive plasticizers—for example, lampblack in dioctyl phthalate—can be premixed with either the epoxies or the curing agents.

Contrasting color pigments can be dispersed in parts A and B; when part A and part B are mixed together, the completeness of intermixing can be judged by observing the uniformity of color mixture. Pigments used to indicate completeness of mixing have not been incorporated into the present formulations.

Fillers can be premixed with each other in dry form and added on the job as a third component, part C, after parts A and B have been mixed. The alternative is to premix part of the filler with part A and part with part B, reducing to two the number of containers carried to the job. This second alternative is the one usually employed in commercial patching compounds and provides greater convenience at the job site. An added advantage may be improved wetting of the fillers during storage. This method has two possible disadvantages, however. First, it may require a little more care to achieve a good thorough mix of epoxies and curing agents if they are already in paste form, rather than freely flowing liquids. There may be a real problem in this respect if absorbent fillers like woodflour are used: epoxy or curing agents soaked into woodflour may not be easily accessible for a subsequent curing reaction. The second possible disadvantage of premixing the fillers into parts A and B is that the thixotroping effect of fumed silica is reputed to diminish with time after the silica is mixed into the liquid portion of a formulation. This is attributed to overly thorough wetting of the

silica. It may occur only after long periods of storage. In the case of most of the test materials described here, all liquid components were mixed before adding fillers. However, fillers are being successfully premixed into parts A and B in the case of several of the suggested compounds that do not contain woodflour, and are now serving well.

Dry powders can be uniformly premixed with each other by shaking them together with ceramic marbles in a shock-resistant polyethylene container with a snug cap.

technique for incorporation of silanes—When silanes are used, they are present in very small proportions. When premixing silanes into either the epoxies or the curing agents, it is essential to secure a uniform dispersion of the silane. Where viscosities of some of the epoxies or curing agents are high, there may be problems getting the silane uniformly blended into the formulation. Three methods can be used to alleviate this problem. High-viscosity ingredients can be warmed to reduce their viscosity and make mixing easier. Alternatively, the premixed formulation can be allowed to stand for some time after admixture of the silane, so that the silane can disperse itself by diffusion. A third alternative is to mix the silane first with some of the low-viscosity materials and then to add those of higher viscosity. Such procedures are unnecessary for most of the formulations given here, since most do not have the problem of high viscosity.

mixing of fillers into liquid components—Solid fillers should be worked vigorously into the liquid component. This is especially important for the fumed silica. The Cabot Corporation advocates the use of high-speed rotary mixing equipment, such as food blenders to incorporate fumed silica. Ball milling is considered to diminish the effectiveness of Cabosil® M5. If hand mixing is used, this should be done vigorously until the worker is convinced

that a good dispersion has been obtained; then the mixing should be continued by an equal amount of time.

Mere stirring is inadequate. A kneading action is required, as may be accomplished with a good spatula on a smooth surface or in a small container of which all parts are easily accessible, such as a polyethylene bowl with a rounded bottom.

Once a person has become familiar, by feel, with the proper amount of filler, there may be no need to measure the filler. It is advised that, at first, fillers be measured according to the suggested weight proportions, since the filler can be deceptive in respect to the proportions in which it can be used when vigorously kneaded into the mixture. Seemingly enormous amounts of filler disappear into small amounts of liquid.

final mixing of epoxy and amine components—Thorough mixing of all liquid ingredients is essential for a good cure. A good rule is to mix vigorously until convinced that a thorough blend is achieved, and then to double that mixing time.

Application

substrate—All the suggested formulations can be used without primers on clean solid wood. Problems may arise when filling holes or cracks where the surfaces are weathered. Weathered wood can have a thin surface layer that is not easily wetted by adhesives such as epoxy binders in patching compounds. This problem is familiar to carpenters who have worked with various glues. Such a surface should be removed, or else the wood should be primed with a penetrating epoxy consolidant, which can soak through the surface of the wood and form a new epoxy surface on which to bond the patching compound.

Weak and overly porous wood should be consolidated before patching, because the bond of a patching compound can only be as strong as the wood beneath. When wood has been consolidated, stronger patching compounds can often be used than in un-

consolidated old wood.

Problems might arise if a fast-curing patching compound is applied over a slow-curing epoxy consolidant, unless enough time is first allowed for the consolidant to set. The consolidant, like a priming coat in paint terminology, may act as the bonding agent between the wood and the patch. If the patch sets to some appreciable strength before the consolidant has set, stresses may cause the patch to pull away from the wood.

The liquid binders in most of the suggested patching compounds are of sufficiently low viscosity to be used as a primer when this is felt to be desirable for any reason. Although viscosity will be too high for deep penetration, an advantage is the convenience of using materials that are present on the job and that will cure more rapidly than the consolidants described in this paper.

overfilling—Some of the liquid binder in the suggested patching compounds will be absorbed into wood during the cure, especially if the wood is unprimed. It may be preferable to accept this disadvantage than to use higher-viscosity liquids, which would have made the paste harder to mix and harder to put in place. Accordingly, holes should be overfilled slightly and the excess patching compound sanded off after the cure. The absorbency of the wood can be reduced by priming with epoxy and allowing this to cure before applying the patching compound.

RESULTS OF TESTS ON PATCHING COMPOUNDS

Selection of pigment volume concentration for test samples made with glass microballoons and woodflour

Emerson and Cuming glass microballoons IG 101 are described in the product literature as having an approximate

packing factor of 0.624.²² This means that when closely packed (after 1000 cycles in a tamping device), 62.4% of the over-all (bulk) volume of a quantity of the balloons is the balloons themselves and 37.6% is space between the balloons. Since tamping reproduces, more or less, the degree of packing in a filled system at the critical pigment volume concentration, the CPVC was taken to be 0.624. It was found that good pastes were made using glass microballoons (without woodflour) in the range of 80% of the CPVC or $0.624 \times 0.8 = 0.4992$, or 0.5. This meant that, at 80% of the CPVC, 50% of a total volume of paste would be microballoons. Thus, the balloons and the polymer would be present in equal proportions by volume. In each formulation the total volume of liquids (resins, diluents, and curing agents) was calculated by specific gravity values given in the manufacturers' literature. To find the weight of microballoons having the same volume as the total of liquids, the total volume of liquids was simply multiplied by 0.311, the true density of the microballoons in gm./cc. (that is, the density not counting the space between the balloons).

In test formulations using glass microballoons, 100 mesh white pine woodflour was substituted for a portion of the microballoons. It was felt to be almost impossible to make PVC calculations on woodflour, because it is absorbent and no figures are available for its true density or packing factor. Therefore, arbitrarily, $\frac{1}{3}$ of the quantity of microballoons arrived at by the process described above were omitted and an equal weight of woodflour substituted.

Description of tests

Water-soaking tests, similar to those used for consolidants, were carried out on only a few of the patching compounds, since outdoor weathering tests were used instead.

As with consolidants, no need was felt to test UV-resistance, since the patching compounds are all meant to be painted. Accordingly, lampblack (a

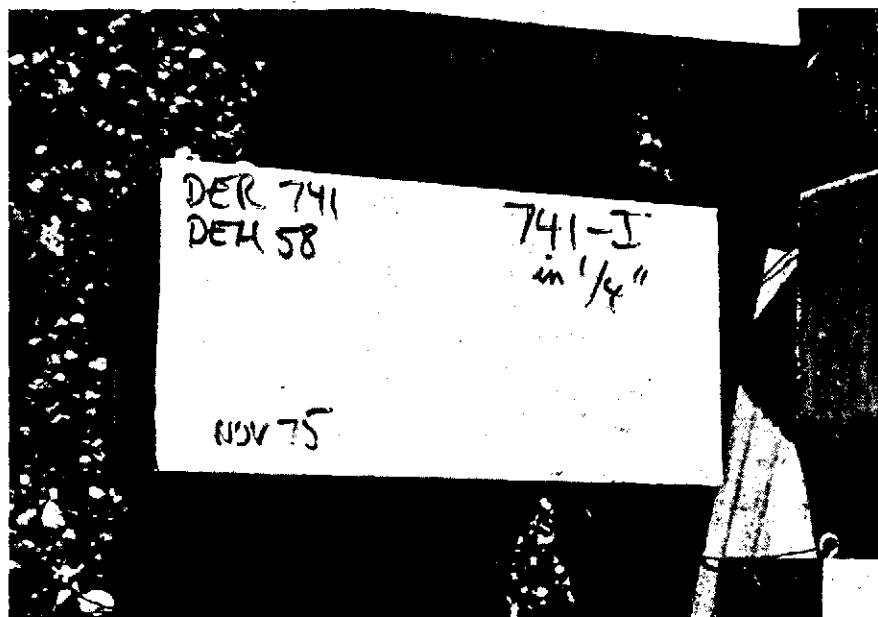


Figure 9. Fully painted block sample.
(Photo: Author)

UV-absorber) was used in most patching compounds, so that the performance of the compounds would be largely unaffected by UV, as would be the case in normal service under coats of paint. The use of lampblack obviated the need to paint samples in order to negate the effect of UV: paint would have protected the samples from water and thus would have spoiled the weathering tests altogether. Some samples, however, were painted to test paint adhesion (figure 9). Others were half-painted so that the lifting of paint by water penetration along an unprotected edge of paint could be tested, and compared to the same effect on adjacent wood (figure 10). The paints used were an alkyd resin house paint primer followed by two coats of an alkyd resin finish house paint.

²²Emerson and Cuming, Inc., "Eccospheres IG-101," bulletin 14-2-1, 1972.

Patching Compounds For Wood

Samples were placed out to weather in two forms. Blocks of pine were made as shown in figure 11, with a hole drilled in the flat side (which was also the flat side of the grain). The holes measured 1" in diameter and either $\frac{3}{4}$ " or $\frac{1}{2}$ " in depth. In the case of unpainted blocks, the ends of the blocks were treated with a thin brush coat of Hydrozo® water-repellant solution: this reduced the overall water absorbency of the block to what was considered a realistic level. Figure 12 shows an unpainted block sample on the weathering rack.

Other samples put out to weather consisted of two sticks of pine, measuring 1" by 1" by 8", adhered together at the ends by means of a 1" cube of patching compound, which was cast in place and sanded to shape, (figure 13). An important difference between this form of sample and the blocks is that with the sticks, the patching compound was restrained only on two sides: as the wood expands and contracts, the patching compound can draw in or bulge out on four sides to compensate for moving with the wood; it can also draw the wood sticks closer together or push them farther apart. In the case of the blocks, the patching compound is restrained on all sides except the top. Thus the top surface is the only place where the compound can deform to make up for expansion and contraction where bonded to the wood.

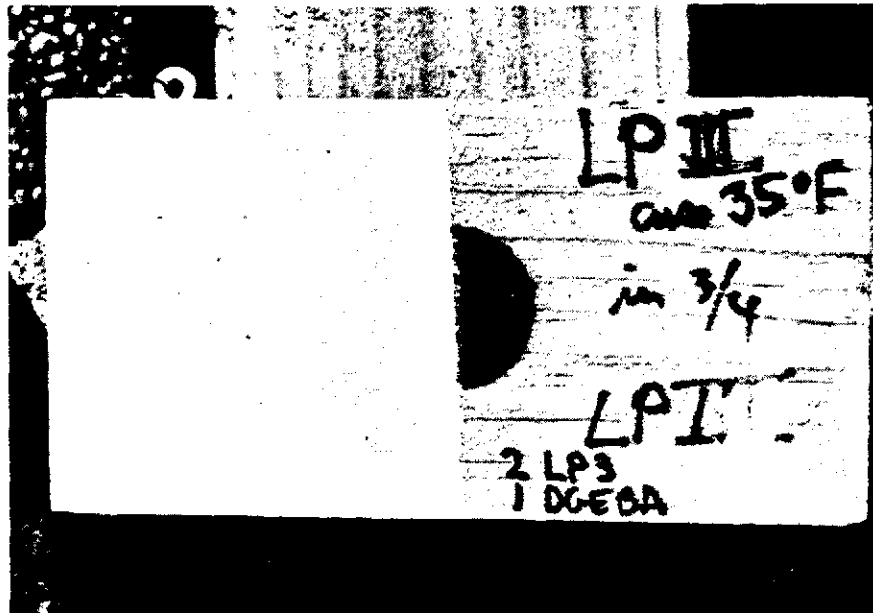


Figure 10. Half-painted block sample. This test compares paint adhesion on wood with paint adhesion on patching compound. Hole filled by sample is $\frac{3}{4}$ " deep. (Photo: Author)



Figure 11. Empty "block" samples. Holes are 1" wide and either $\frac{3}{4}$ " or $\frac{1}{2}$ " deep. (Photo: Author)

Patching Compounds For Wood

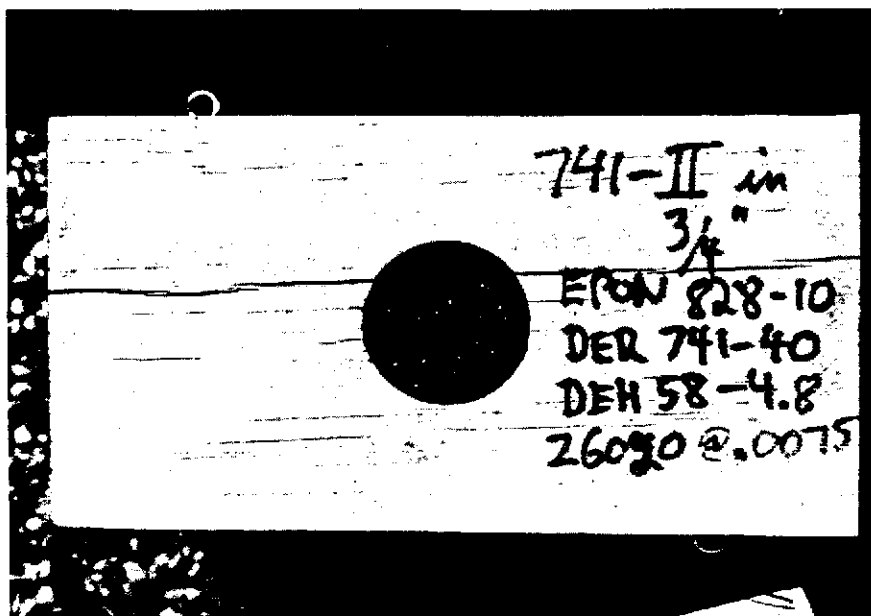


Figure 12. Block sample after weathering during winter and spring of 1975-1976. Split in wood is caused by moisture changes, not by expansion of patching compound (which is flexible). This compound has followed the expansion of the wood without losing its bond at any point. Hole filled by sample is $\frac{1}{2}$ " deep. (Photo: Author)

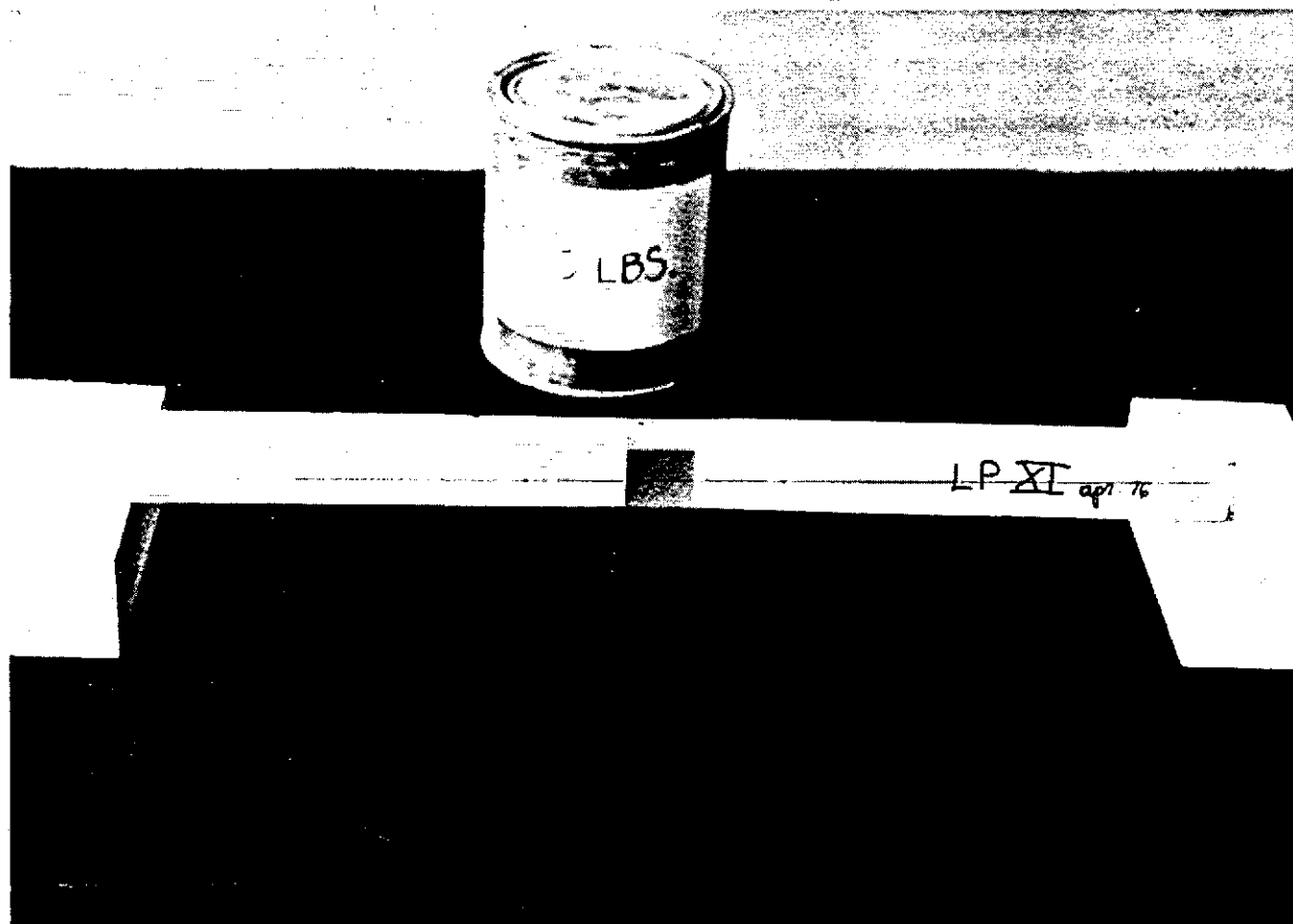


Figure 13. "Stick" sample. Straight line is drawn on sample prior to loading in "creep" test. (Photo: Author)

The sticks served not only as an adhesion test but also as a flexibility test. Flexibility was assessed by manually flexing the sticks (figure 14). Creep was observed by placing the sticks under a prolonged bending load (figure 15). Upon failure of a sample, convenient observation could be made of the location and character of the break: whether in the wood, in the patching compound, or, approximately, at the bond line. As with consolidants, at least one sample of each patching compound was postcured at 230°F for 12 hours or more in order to make a rough assessment of the reduction of flexibility to be expected after long-term aging. These postcured samples were cooled well below freezing to observe the degree of stiffening by cold.

Both types of samples, blocks and sticks, were placed on a rack on a fully exposed flat roof 5 stories above the ground in Boston, Massachusetts. Blocks were placed with the filled holes facing directly upward (figure 16). Most samples were observed for approximately one year, from the fall of 1975 to the fall of 1976. As with consolidants, it was considered impossible to quantify test results during this preliminary project. Compression testing of patching compounds was considered too complicated at this stage, because most of the samples creep under a steady load, and because the rate of creep is dependent on temperature.

Test results

possible superiority of more rigid formulations—The formulations listed in this paper are, with some minor modifications, those which evidenced good weather resistance and adhesion, as judged by visual observation and manual inspection. Many other formulations were rejected. Formulations were roughly classed into three categories of flexibility, and are listed below in this way. In general, the testing has indicated that the more rigid samples have performed at least as well as the more flexible ones in respect to retention of bond. Thus, the efforts to achieve a high



Figure 14. Some formulations are very flexible even after aging some months. (Photo: Author)

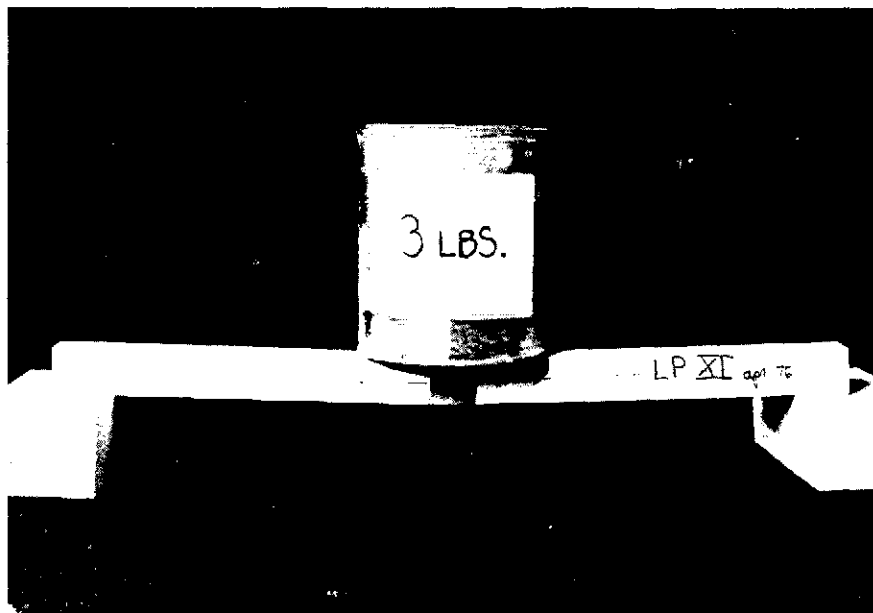


Figure 15. Bend in line indicates extent of creep of "stick" sample. This is dependent on size of load, length of time load is applied, temperature and formulation of sample. (Photo: Author)

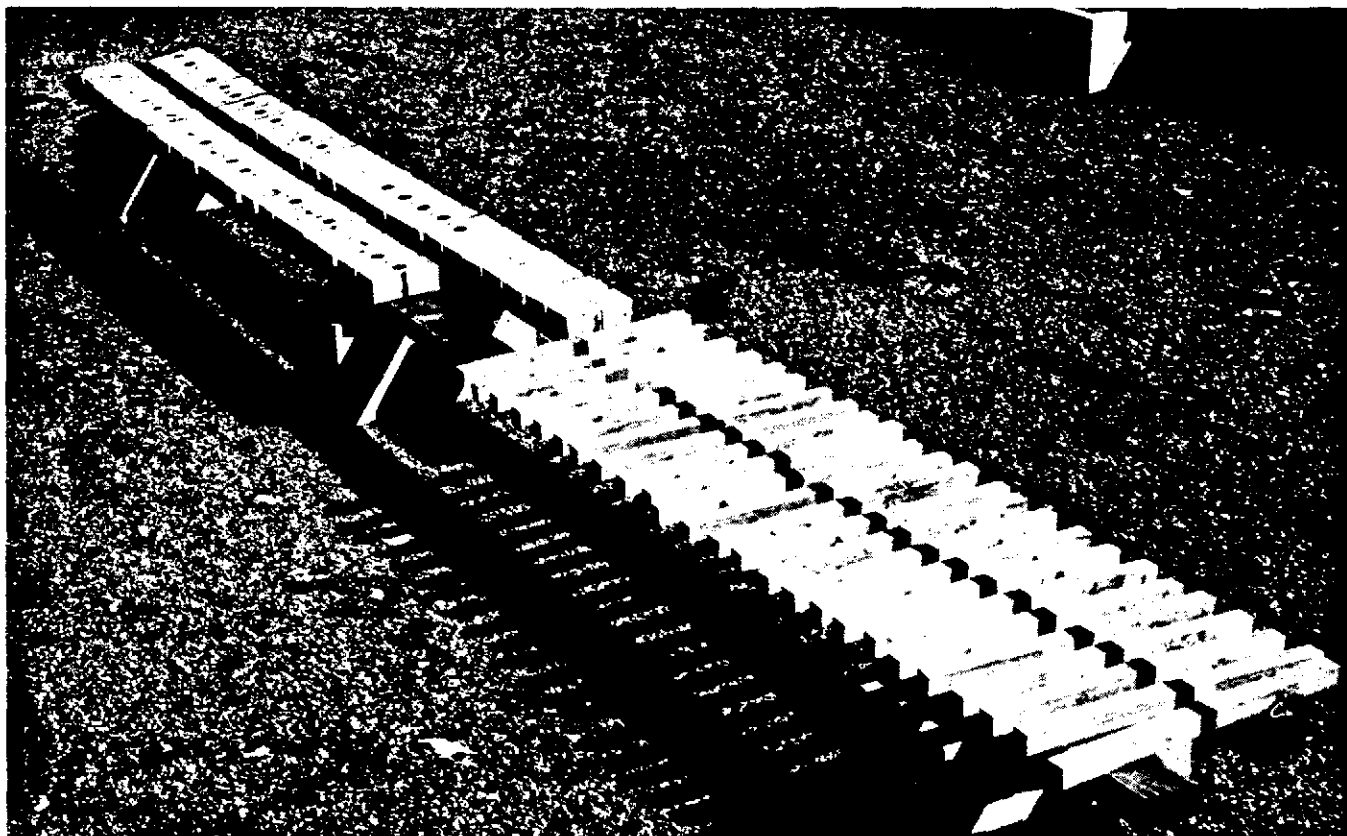


Figure 16. Weathering rack on the roof of the SPNEA Museum building in Boston. (Photo: Author)

degree of flexibility—and the sacrifices in respect to curing rate—were probably unnecessary, except as exercises to explore the limits of flexibility to which epoxy formulations can be carried.

The next step in developing patching compounds would be to produce a second generation having degrees of flexibility equal to or less than the semi-rigid ones described in this paper. More sophisticated formulation, and the use of lower proportions of flexibilizers, should offer faster rates of cure.

performance of painted samples—

None of the fully painted block samples have shown failures at the time of writing, since the wood does not expand and contract nearly as much or as fast as when unpainted. It is felt that there will be no problems in normal service where wood is kept painted and where wood members have few surfaces which face directly upward and do not drain

well. After some months, all painted and half-painted samples appeared to be performing well in respect to paint adhesion.

summary of test results—A longer testing period would be desirable; however, testing to date has shown that the formulations perform better than the most common household wood patching compounds, which were similarly tested. Thus their usefulness for filling holes is virtually certain. Also, it is anticipated that they will find higher levels of usefulness than simply filling holes. Although severely limited for structural purposes, the good performance of the

stick samples indicates that the compounds can serve a nonstructural but self-supporting function. On the test rack the 1" cube of patching compound is unsupported over open space and also serves to hold the entire stick assembly together. Good performance observed under these conditions indicates that the compounds can be used to fill in small pieces of moulding and in other self-supporting roles.

FORMULATIONS

Semi-rigid patching compounds

Although flexible when warm, these formulations are fairly stiff at or below room temperature. Compared with most epoxy formulations they are very flexible. More rigid systems would be easy to design. As described earlier, the semi-rigid patching compounds seem to be performing at least as well as the more flexible ones.

1

Patching Compounds For Wood

Semi-rigid patching compound No. 1:

| | Material | Commercial Designation | Parts by Weight |
|------------|--|------------------------|-----------------|
| PART A | Epoxy resin | Dow DER 331 | 100 |
| PART B | Polysulfide rubber | Thiokol LP-3 | 96 |
| | Amine curing agent | Thiokol EH 330 | 10 |
| PART C | Phenolic microballoons | Union Carbide BJO-0930 | 36 |
| | Thixotroping silica | Cabosil M5 | 12 |
| Pot Life: | About 20 minutes. | | |
| Cure Rate: | Medium—can be sanded after about 16 hours. | | |

Preparation

The ingredients can be mixed by the weight proportions as shown here. Alternatively, parts A and B can be pre-mixed by weight and then (on the job) mixed with each other in equal parts by **volume**. The weight proportions given above are adjusted so that A and B have the same volume. Part C should be used in the proportion of 24% of the **weight** of A and B combined. Part C can be divided into two equal portions, one portion pre-mixed with part A and one portion with part B. The formulation can be stored in this paste form and mixed in a one-to-one ratio by volume at the time of use.

At the job site, a small batch can be measured out by volume as follows:

2 medicinal tablespoons of
Part A

2 medicinal tablespoons of
Part B

6½ fluid ounces of Part C
(untamped).

General evaluation; possible improvements:

This formulation has the advantages that it is prepared in convenient mixing ratios and cures fast enough to be practical. It seems to be performing well in actual service.

Semi-rigid patching compound No. 2:

| | Material | Commercial Designation | Parts by Weight |
|------------|--|--------------------------|-----------------|
| PART A | Epoxy resin | Dow DER 331 | 100 |
| PART B | Polysulfide rubber | Thiokol LP-3 | 100 |
| | Amine curing agent | Triethylenetetramine | 11 |
| | Aminosilane | Union Carbide A1100 | 2 |
| | Lampblack dispersion | CDI 4585 | 11 |
| PART C | Thixotroping silica | Cabosil M5 | 11 |
| | Glass microballoons | Emerson and Cuming IG101 | 36 |
| | Woodflour | 100 mesh white pine | 18 |
| Cure Rate: | Medium—can be sanded after about 16 hours. | | |

General evaluation; possible improvements:

The objective of making this formulation was to use a primary amine, rather than a tertiary amine, as a curing agent in an epoxy/polysulfide blend. Although the performance appears to be good, an aromatic primary amine might have been preferable to TETA.

Patching Compounds For Wood

| Semi-rigid patching compound No. 3: | | | Parts by Weight | General evaluation; possible improvements: |
|-------------------------------------|----------------------------------|---------------------------|--------------------|--|
| | Material | Commercial Designation | | |
| PART A | Epoxy resin | Shell Epon 828 | 100 | This formulation would be far more useful if it could be altered to cure faster. |
| | Flexibilizing epoxy | Dow DER 732 | 43 | |
| PART B | Flexibilizing amine curing agent | Jefferson Jeffamine D400 | 34 | Cure Rate: Low—cannot be sanded before at least 48 hours. |
| | Amine-type accelerator | Jefferson A398 | 21 | |
| | Aminosilane | Union Carbide A1100 | 1.5 | |
| | Lampblack dispersion | CDI 4585 | 10 | |
| PART C | Thixotroping silica | Cabosil M5 | 10 | |
| | Glass microballoons | Emerson and Cuming IG101 | 37 | |
| | Woodflour | 100 mesh white pine | 19 | |

Semi-flexible patching compounds

These are intermediate in flexibility between the semi-rigid formulations and the fully flexible. They are suitable for most applications in patching woodwork, although the more rigid formulations are probably better. The ingredients used in these formulations could all be easily recombined in different proportions to obtain faster cures and greater rigidity.

Semi-flexible patching compound No. 1:

| | Material | Commercial Designation | Parts by Weight |
|--------|----------------------|---------------------------|--------------------|
| PART A | Epoxy resin | Shell Epon 828 | 100 |
| | Flexibilizing epoxy | Dow DER 741 | 400 |
| | Lampblack dispersion | CDI 4585 | 27 |
| PART B | Amine curing agent | Dow DEH 58 | 48 |
| | Aminosilane | Dow Corning Z6020 | 4 |
| PART C | Thixotroping silica | Cabosil M5 | 27 |
| | Glass microballoons | Emerson-Cuming IG101 | 102 |
| | Woodflour | 100 mesh white pine | 51 |

Cure Rate: Medium—can be sanded after about 24 hours.

General evaluation; possible improvements:

Even after several days' cure, this material is still slightly subject to damage by soaking in water. It was not determined whether the resin itself was affected, or possibly the bond of the resin to the glass. This effect does not seem to be serious, since the material is weathering well. Tests using phenolic microballoons would be worthwhile. The formulation is currently performing well in actual service, with phenolic microballoons used in place of the glass balloons and woodflour.

For most uses a more rigid and faster-curing material might be better. Increasing the proportion of Epon 828 (with appropriate adjustments to maintain stoichiometry) would improve the product in these respects.

Patching Compounds For Wood

Semi-flexible patching compound No. 2:

| | Material | Commercial Designation | Parts by Weight |
|--------|----------------------------------|---------------------------|-----------------|
| PART A | Epoxy resin | Dow DER 331 | 100 |
| | Lampblack dispersion | CDI 4585 | 9 |
| PART B | Flexibilizing amine curing agent | Jefferson Jeffamine D400 | 38 |
| | Flexibilizing amine curing agent | Jefferson Jeffamine D2000 | 25 |
| | Amine-type accelerator | Jefferson A398 | 10 |
| | Aminosilane | Union Carbide A1100 | 1.4 |
| PART C | Thixotroping silica | Cabosil M5 | 9 |
| | Glass microballoons | Emerson Cuming IG101 | 33 |
| | Woodflour | 100 mesh white pine | 17 |

Cure Rate: Low—can be sanded after 36–48 hours.

General evaluation; possible improvements:

A faster cure rate would improve this material. This could be achieved, in part, by decreasing the proportion of Jeffamine D2000, which would also have the effect of making the material more rigid.

Semi-flexible patching compound No. 3:

| | Material | Commercial Designation | Parts by Weight |
|--------|--------------------------------------|-----------------------------|-----------------|
| PART A | Low-viscosity epoxy resin | Dow DER 332 | 100 |
| | Flexibilizing epoxy diluent | Dow DER 736 | 67 |
| PART B | Flexibilizing polyamide curing agent | General Mills Versamid V125 | 167 |
| | Aminosilane | Union Carbide A1100 | 2.5 |
| | Lampblack dispersion | CDI 4585 | 17 |
| PART C | Glass microballoons | Emerson Cuming IG101 | 66 |
| | Woodflour | 100 mesh white pine | 33 |

Cure Rate: Medium to low—can be sanded after about 36 hours.

General evaluation; possible improvements:

This formulation was not tested but is closely related to one that was. The objective of this formulation is to achieve good flexibility by using a high proportion of a polyamide. Since Versamid V125 is highly viscous and is used in a high proportion, DER 736 is included to help maintain a low enough viscosity for easy working. The DER 736 also serves as an additional flexibilizer. A low-viscosity grade of DGEBA resin (DER 332) is used to help reduce viscosity.

The cure rate could be increased and the viscosity further reduced by the use of an accelerator, such as Monsanto Mod-Epox, (triphenyl phosphite).

Patching Compounds For Wood

| Semi-flexible patching compound No. 4: | | | | General evaluation; possible improvements: |
|---|----------------------------------|-----------------------------|-----------------|--|
| | Material | Commercial Designation | Parts by Weight | |
| PART A | Epoxy resin | Shell Epon 828 | 100 | The objective of this formulation was to gain some experience with Epon 871. The system seems promising. |
| | Flexibilizing epoxy | Shell Epon 871 | 67 | |
| PART B | Flexibilizing amine curing agent | General Mills Versamid V140 | 167 | |
| | Aminosilane | Union Carbide A1100 | 2.5 | |
| | Lampblack dispersion | CDI 4585 | 17 | |
| PART C | Thixotroping silica | Cabosil M5 | 17 | |
| | Glass microballons | Emerson Cuming IG101 | 66 | |
| | Woodflour | 100 mesh white pine | 33 | Cure Rate: Medium—can be sanded after about 24 hours. |

| Semi-flexible patching compound No. 5: | | | | General evaluation; possible improvements: |
|--|---|--------------------------|-----------------|--|
| | Material | Commercial Designation | Parts by Weight | |
| PART A | Epoxy resin | Dow DER 332 | 100 | <p>This formulation was not tested but is closely related to one that was. The purpose of this formulation was to explore the use of Hycar ATBN as a flexibilizer. It was found that significantly higher proportions of Hycar than that shown above made trial formulations unduly viscous and hard to mix unless heated. Even in the formulation shown above, all the other liquid components had to be low-viscosity materials to bring the over-all viscosity of the formulation down to a good level. This is the reason for the incorporation of a reactive diluent and for the use of DER 332 (a low viscosity DGEBA resin) as opposed to the more common 331.</p> <p>An epoxy-functional silane mixed into the epoxy component is suggested instead of an amino-functional silane because of the difficulty of premixing an aminosilane into the very viscous Hycar.</p> <p>Hycar has a very high amine equivalent weight (average about 882). Thus the amount of Hycar suggested above is much less than the stoichiometric amount required to cure the epoxy. Therefore, two additional amines are shown: Jeffamine D230 and n-aminoethylpiperazine. This latter has a pronounced accelerating effect on Hycar systems. It should be possible to increase the cure rate by eliminating the D230 and increasing the proportion of n-aminoethylpiperazine.</p> |
| | Reactive diluent | Ciba-Geigy RD2 | 100 | |
| | Epoxy silane | Dow Corning Z6040 | 3.4 | |
| | Lampblack dispersion | CDI 4585 | 23 | |
| PART B | Rubber-amine | B.F. Goodrich Hycar ATBN | 200 | |
| | Flexibilizing amine curing agent | Jefferson Jeffamine D230 | 27 | |
| | Accelerating amine curing agent | n-aminoethylpiperazine | 27 | |
| PART C | Thixotroping silica | Cabosil M5 | 23 | |
| | Microballoons | Emerson-Cuming IG101 | 93 | |
| | Woodflour | 100 mesh white pine | 46 | |
| Cure Rate: | Medium to low—can be sanded after about 36 hours. | | | |

Patching Compounds For Wood

Highly flexible patching compounds

These compounds are very flexible, even at low temperatures and after postcuring at high temperatures. They are too rubbery for most practical applications in patching woodwork, but they may be useful for other purposes. The ingredients used in these formulations could all be easily recombined in different proportions to obtain faster cures and greater rigidity.

Highly flexible patching compound No. 1:

| | Material | Commercial Designation | Parts by Weight |
|--------|----------------------|------------------------|-----------------|
| PART A | Flexible epoxy resin | Dow DER 741 | 100 |
| PART B | Amine curing agent | Dow DEH 58 | 8 |
| | Aminosilane | Union Carbide A1100 | 0.75 |
| | Lampblack dispersion | CDI 4585 | 5.4 |
| PART C | Thixotroping silica | Cabosil M5 | 5.4 |
| | Glass microballoons | Emerson Cuming IG101 | 20 |
| | Woodflour | 100 mesh white pine | 10 |

Cure Rate: Medium to low—can be sanded after about 24 hours.

General evaluation:

This is a more flexible (and less practical) version of semi-flexible patching compound No. 1. It has interest because it is a highly flexible material that has been weathering well, in spite of the fact that it is definitely affected by water soaking. (It is more seriously affected by soaking than semi-flexible patching compound No. 1).

Highly flexible patching compound No. 2:

| | Material | Commercial Designation | Parts by Weight |
|--------|---------------------------------------|--------------------------|-----------------|
| PART A | Flexibilized epoxy resin | Ciba-Geigy Araldite 508 | 100 |
| PART B | Flexibilizing amidoamine curing agent | Ciba-Geigy Araldite 9130 | 21 |
| | Aminosilane | Union Carbide A1100 | 1 |
| | Lampblack dispersion | CDI 4585 | 6 |
| | | | |
| PART C | Thixotroping silica | Cabosil M5 | 6 |
| | Glass microballoons | Emerson Cuming IG101 | 23 |
| | Woodflour | 100 mesh white pine | 11 |

General evaluation:

This material is included because it combines extreme flexibility with good performance in the weathering tests. Some means to increase the cure rate while retaining these good properties would be desirable. Also, Araldite 508 seems very promising for use in more rigid patching compounds, made with a proportion of a DGEBA resin. Such a patching compound would cure much faster.

Cure Rate: Extremely slow—a matter of weeks.

Limitations and Precautions in Using Suggested Consolidants and Patching Compounds

STRUCTURAL LIMITATIONS

Emphasis has been placed on the importance of flexibility in consolidants and patching compounds, except when an entire piece of wood is to be consolidated. To some extent this flexibility must compromise the usefulness of consolidants, and especially patching compounds, for structural purposes or in respect to nail-holding power. A consolidated area or a patch made flexible enough not to stress surrounding untreated wood is unlikely to equal the wood in structural usefulness.

The softening effect of heat on flexible epoxy patching compounds used structurally may lead to early failure in a fire, long before the surrounding wood burns through. Patching compounds rigid enough to resist this may break loose from the wood for reasons already explained. The structural use of epoxies with wood—especially old, weakened wood—involves problems of chemical formulation and mechanical design that were beyond the scope of this study.²³

For all these reasons, most of the materials suggested here may not be useful when placed in structural shear or bending. One may feel more confident about their limited use in simple compression (figure 1). Good structural strength can be developed when an entire piece of wood is being consolidated. Then consistently strong consolidants and patching compounds can be used throughout. In thoroughly consolidated wood, temperature and humidity expansion values probably approach those of the epoxy consolidant, rather than those of the original wood, making the treated wood mechanically more compatible with strong epoxy patching compounds.

LOW VAPOR PERMEABILITY

At the present stage in this project the consolidants and patching compounds have not been made permeable to water vapor. Thus there may be some risk that water can be trapped beneath a patch or a consolidated area in an otherwise untreated wooden member.

The ability to "breathe" could be built

into consolidants by using volatile solvents, which, upon evaporating, leave the treated wood porous to some degree. In patching compounds, one could create a porous structure by increasing the loading of fillers above the critical pigment volume concentration. Volatile solvents might then be needed to make the mix wet enough to be worked and bonded to the wood. One trial consolidant was made this way, using a small proportion of solvent, and was highly permeable to both water vapor and liquid water. The amount of volatile solvent needed did not produce unmanageable shrinkage.

However, there is bound to be some shrinkage if solvents are used in patching compounds, unless special shrinkage-compensating ingredients are also used. An additional disadvantage is that the resulting porosity probably renders the material much more susceptible to damage by water than if it were non-porous. Water repellent porous patching compounds might be investigated. More work is needed to achieve good flexibility and weather resistance in patching compounds loaded above the critical pigment volume concentration.

Impermeability probably entails no risks if consolidants and patching compounds are used in locations where water cannot be trapped. Certain materials long and successfully used in wood construction are no more permeable than the suggested formulations. Resorcinol/formaldehyde waterproof glue is a perfect example; high-grade elastomeric caulking compounds are another. There are many such impermeable materials that have created no problems when used on exterior woodwork that is kept painted—especially vertical or downward-facing woodwork where rain water cannot stand in holes or cracks.

The risk of trapping water is much more serious on upward-facing wood members such as window sills and

water tables. Where water is likely to penetrate wood and become trapped under a consolidant or patching compound, the safest route is to consolidate the entire piece of wood, rendering it highly resistant to water damage.

Where there is concern about water entering the bond line of a patching compound and then being trapped, one precaution might be to apply a penetrating consolidant to the wood surface of the hole to be filled, thus making it resistant to penetration or damage by water.

It may be that even in the case of consolidated or patched window sills, the maintenance of a good coat of paint on the wood will in itself prevent water damage.

INABILITY TO CHANGE VOLUME

When untreated wood expands and contracts because of variations in the level of humidity, it changes total volume. Patching compounds, or areas of wood saturated with a consolidant, will not change in total volume under these conditions, but will only change shape in order to follow the movement of the wood. When a material that only changes shape is bonded to one that changes total volume, their movements may be incompatible. This is easily seen in figure 17a which shows, in cross-section, a hole in a piece of wood filled with a patching compound. The sketch on the left shows the hole before expansion of the wood; that on the right, greatly exaggerated, shows it after expansion. The volume added by expansion is represented by the heavily hatched area. This additional volume has to be filled by the patching compound, but the compound cannot increase its total volume in order to do so. Therefore, in order to expand in the areas indicated, the compound must contract by an equal amount in some

²³Paul Stumes, "Testing the Efficiency of Wood Epoxy Reinforcement Systems," *Bulletin of the Association for Preservation Technology*, vol. 7 (no. 3, 1975): 2-35.

Limitations and Precautions in Using Suggested Consolidants and Patching Compounds

other place. This can only be at the top surface, where a cupped deformation is shown in the right-hand sketch. This cupping leads to high stresses where indicated on the sketch; failure is likely to occur here first.

All these phenomena were observed in the samples placed on the roof and subjected to rain. The depth of cupping changed with weather conditions, almost providing a rough measure of the moisture content of the wood at any time. Also, observed, as would be expected, were less cupping and a lower rate of failure in samples placed in holes of the same width (1") but not as deep ($1/4$ " as opposed to $3/4$ "). This improvement is due to the fact that the total volume change of the hole, relative to the exposed upper surface area of the

patch, is much less for a shallow hole than for a deep one. A comparison of figure 17a showing a deep hole and figure 17b showing a shallow hole reveals this clearly. Thus, less deflection at the surface is needed to make up for expansion or contraction.

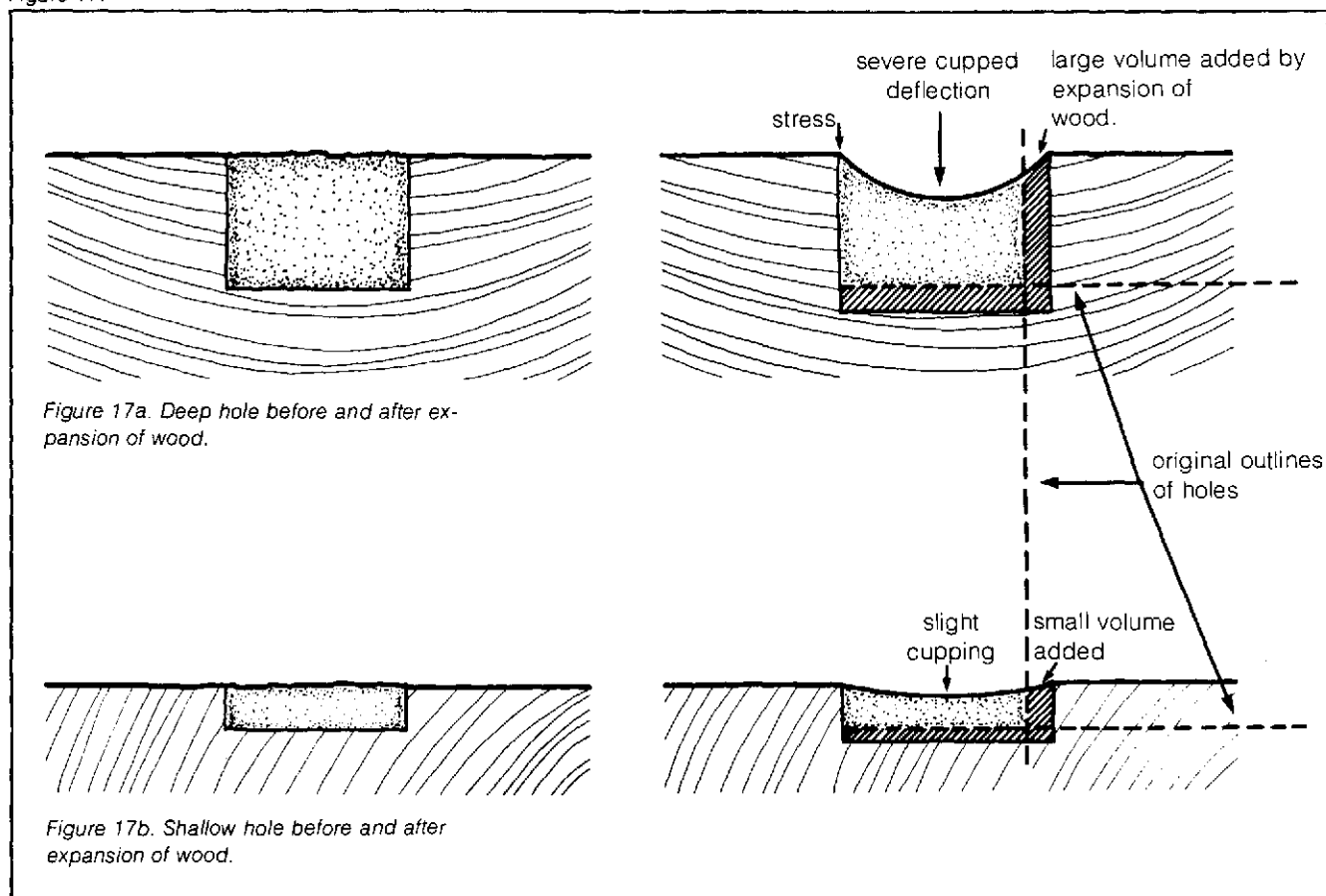
All these principles are well known and widely applied to the design of caulking joints.²⁴ The result of these effects is that less trouble may be expected in filling shallow holes than in filling deep ones. Accordingly, it is advised that where large holes are to be filled, and where volume change of the wood is expected, the patching compounds might be used not as the only filler, but as gap-filling adhesives to hold roughly fitted wood patches. Wood in the hole will probably supply a certain amount of desirable volume change

perhaps matching fairly well the movements of the wood in which the hole exists.

Under the influence of changing temperatures, the patching compound, or consolidant-impregnated area, changes volume to a much greater extent than the surrounding wood because its coefficient of thermal expansion is much greater. However, in most woodwork applications, conflicting movements due to thermal changes are probably much smaller than those due to changing levels of humidity.

²⁴John P. Cook, *Construction Sealants and Adhesives* (New York: Wiley-Interscience, 1970), pp. 27-39.

Figure 17.



The following are only a few of the many possible uses of epoxies in architectural conservation.

PLASTER CONSOLIDANT

One of the consolidants described in this paper (strong consolidant No. 2) has been used effectively to consolidate ornamental gypsum plasterwork damaged by fire. Penetration up to 1½" was obtained by brush application.

FLEXIBLE ADHESIVES

Many of the epoxies and curing agents described in this study are commonly found in conventional epoxy adhesives. Such adhesives are usually formulated for high strength and contain small particle fillers such as fine chalk, rather than hollow microballoons. A knowledge of epoxies in respect to patching compounds for wood gives the conservator a better understanding of epoxy adhesives.

Flexibility, adjustable as desired, is probably the biggest advantage of flexibilized epoxies over typical waterproof construction glues based on resorcinol/formaldehyde or phenol/formaldehyde resins. These latter materials are rigid and even rather brittle.

CLAMP-FREE ADHESIVES

The commonly used resorcinol/formaldehyde waterproof glue loses water during drying. Many other types of glue give off volatiles during curing or drying. The resulting shrinkage and production of gases can disturb glue joints during the curing process unless pressure is maintained on the joint by clamps or other means.

Epoxy adhesives by contrast, do not require pressure clamping, since they shrink very little during the cure and give off no volatiles. Only as much clamping is needed as to immobilize the joint during cure. In awkward locations on a building it is a convenience to be able to use pieces of wire or other minimal devices rather than proper clamps.

GAP FILLING ADHESIVES

Epoxies can serve as gap-filling adhesives because they shrink very little. The semi-rigid patching compounds described in this study can be so used, although they do not offer high strength.

ELASTOMERIC SEALANTS

Rubbery blends of epoxy and polysulfide have been used in elastomeric sealants.²⁵ As with adhesives, the fillers used in elastomeric sealants are generally of much smaller particles than the microballoons advocated here for patching compounds. However, a knowledge of epoxy/polysulfide rubbers based on experience with patching compounds is directly applicable to sealants.

GLAZING COMPOUNDS

With certain modifications some of the more flexible patching compounds described here would probably make excellent glazing compounds. They would be more flexible than typical compounds based on modified drying oils, and vastly more resistant to embrittlement with age. They would be easier to remove, because microballoons permanently insure the ability of the compound to be cut with a knife. The bond to wood is far better than with oil-based compounds and, with added silanes, the bond to glass should also be better. The possibility of damage to glass by acidic decomposition products of polysulfides should be investigated.

SOIL CONSOLIDANTS

The proposed wood consolidants would make expensive, but excellent, consolidants for soil having pores large enough to admit the material. Epoxies have been used for this purpose.

²⁵*ibid.*, p. 78.

Description of Components of Formulations

SOURCES OF SUPPLY; COSTS

Polymeric materials

Epoxy resins, diluents, modifiers, silanes, and curing agents are available from the sources listed in the appendix. There is wide variation in the minimum quantity that can be purchased directly from the manufacturer. When a manufacturer sells the item only in bulk, small amounts such as a gallon must be purchased through distributors. These are found by contacting the home or regional office of the manufacturer. The appropriate technical literature pertaining to each product should always be requested and studied.

Fillers and pigments

Glass microballoons can be purchased from Emerson and Cuming, Inc., phenolic microballoons from Union Carbide Corporation, and Cabosil from Cabot Corporation. Sources of woodflour are listed in the Thomas Register under Fillers: Plastic Materials. Color pigment dispersions can be obtained from a number of sources, two of which are CDI Dispersions and Daniel Products Company.

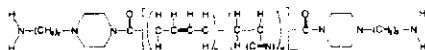
Approximate costs

Prepackaged epoxy consolidants and patching compounds sold in marine hardware or hobby stores are many times more expensive than the same materials bought as separate ingredients, in larger quantities, directly from a manufacturer or his distributor. Price lists should be requested.

If ingredients are purchased in amounts appropriate to most restoration projects (resin by the gallon or in 40 lb. pails, microballoons in 10 lb. batches, etc.) total material costs for the consolidants should run around \$20–\$30 per gallon and for the patching compounds perhaps \$15–\$20 per gallon. Substantial labor costs in preparation of patching compounds must be anticipated.

COMPOSITIONS AND PROPERTIES: POLYMER COMPONENTS

B. F. Goodrich Hycar ATBN (1300 × 16) is an amine-terminated butadiene/acrylonitrile rubber designed as a flexibilizer for epoxies. It is both an amine curing agent and a rubber. Its structure is represented as follows:²⁶



Where $x = 5$, $y = 1$, and $m = 10$

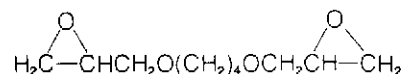
Its amine equivalent weight is very high (averaging about 882). In high proportions (several times that of the epoxy) it gives a cured product with truly elastomeric properties. Blends of Hycar and epoxies are used for upgrading plywood by filling knot holes. Its chief disadvantage for the purposes of patching compounds mixed by hand at room temperature is its high viscosity (Brookfield viscosity, cps @ 27°C : 200,000). This limits the proportion in which it can be used conveniently in patching compounds mixed by hand at or below room temperature.

One possible concern about Hycar is the existence of points in the molecular structure, such as the carbon-to-carbon double bonds, where the material may be more subject to reactions producing eventual embrittlement than some other materials considered in this study.

Ciba-Geigy Araldite 508 has been described as a mixture of a standard DGEBA resin and an epoxidized polyol.²⁷ Epoxidized polyols are typified by Dow DER 732 and 736.²⁸ The exact structure and molecular weight of the Ciba-Geigy product were not ascertained for this report.

Ciba-Geigy Araldite 9130 is a modified amidoamine that serves as both a flexibilizer and curing agent.²⁹ Its composition was not ascertained during this project. Its approximate AEW is 88. See the discussion of General Mills Versamids for a description of amidoamines.

Ciba-Geigy Araldite RD2 is a difunctional reactive diluent: 1, 4 butanediol diglycidyl ether. Its structure is



Its epoxide equivalent weight is 134.³⁰ Its purpose in the suggested consolidants is to reduce viscosity and, being aliphatic, to increase the flexibility of the cured resin. One of its advantages is its lower vapor pressure than some other common reactive diluents: consolidants made with this reactive diluent pose less problems of fumes than some commercial consolidants.

Dow DEH 58 is an amine adduct (reaction product) of diethylenetriamine and bisphenol A, having an amine equivalent weight of 30.³¹ Amine adducts have higher reactivity than most amine curing agents and are discussed in the *Handbook of Epoxy Resins* by Henry Lee and Kris Neville.

Dow DER 331 is a standard DGEBA resin.³²

Dow DER 332 (Dow Epoxy Resin) is a low-viscosity DGEBA resin (viscosity 4,000–6,000 cps at 25°C).³³ For similar products offered by other manufacturers see the *Epoxy Resin Manual* by Dow Chemical Company. The epoxide equivalent weight of DER 332 averages approximately 174.

²⁶B. F. Goodrich, "Hycar Elastomers."

²⁷Lee and Neville, *Handbook of Epoxy Resins*, p. 4:58.

²⁸*Ibid.*, p. 16:3.

²⁹Ciba-Geigy Corporation, "Araldite Hardener 9130," provisional data sheet [n.d.]

³⁰Ciba-Geigy Corporation, "Araldite RD2," provisional data sheet [n.d.].

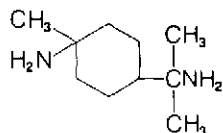
³¹Dow Chemical Company, "Dow Hardener DEH 58," technical data sheet, 1972.

³²Dow Chemical Company, "Dow Liquid Epoxy Resins," brochure, 1969.

³³*Ibid.*

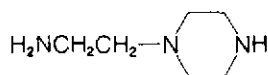
Description of Components of Formulations

Menthane diamine is a cycloaliphatic primary diamine having the structure



and an amine equivalent weight of approximately 43. It is available from a number of resin distributors and from chemical supply houses.

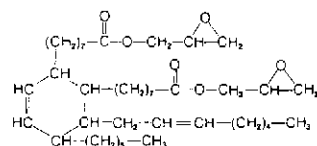
N-aminoethylpiperazine (available from many chemical supply houses and resin suppliers) is a cycloaliphatic amine having the structure



and an amine equivalent weight of 43. It is interesting in that it possesses primary, secondary, and tertiary amine groups. Tertiary amines can act as accelerators in many types of epoxy formulations.

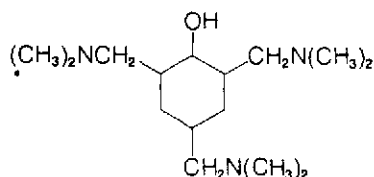
Shell Epon 828 is a standard DGEBA resin.⁴⁵

Shell Epon 871 is a diglycidyl ester of a dimerized linoleic acid.⁴⁶ Although it is an epoxy rather than an amine, its structure, shown below, is similar to that of General Mills Versamid curing agents.



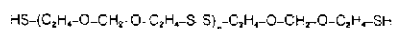
As with Versamids, a possible concern about Epon 871 is the presence of carbon-to-carbon double bonds, where oxidation or other reactions may be likely to occur over long periods of time, producing gradual loss of flexibility or other changes in a cured material.

Thiokol EH 330 is a tertiary amine, 2, 4, 6-tris (dimethylaminomethyl) phenol.⁴⁷



This is sold by Rohm and Haas as DMP-30.

Thiokol LP-3 is a liquid polysulfide rubber having the structure



where n averages about 6 and the molecular weight about 1000.⁴⁸

Triethylene tetramine has the follow-

ing structure:



Union Carbide A1100 is γ -amino-propyltriethoxysilane:



Union Carbide ZYL-0822 is a polyglycoldiamine of the structure:



Its amine equivalent weight is 55.⁵⁰

⁴⁵Shell Chemical Company, "Epon Resin 828," technical bulletin SC:69-77, 1969.

⁴⁶Shell Chemical Company, "Epon Resin 871," technical bulletin SC:64-52, 1964.

⁴⁷Thiokol Corporation, "Thiokol EH 330."

⁴⁸Lee and Neville, *Handbook of Epoxy Resins*, p. 16:21.

⁴⁹Union Carbide Corporation, *Chemicals and Plastics, Physical Properties*, 1975-1976 catalog, p. 42.

⁵⁰Union Carbide Corporation, "Bakelite Liquid Epoxy Hardener ZYL-0822," product information sheet F-44996, 1975.

Part II:

Case Studies

Dr. Judith E. Selwyn



Recently, developments in epoxy polymer technology have been used to advantage in the conservation and preservation of wooden members of historic buildings. Properly formulated epoxies may serve not only as glues but also as consolidants and patching compounds for wood.

As a working definition, a wood consolidant can be described as a mixture that can be introduced as a liquid into deteriorated wood and that later solidifies to form a composite wood-epoxy material. The purpose of the treatment is to strengthen weakened wood. Consolidation also effectively makes the treated areas impervious to wood's main enemies: water and insects. The process of wood consolidation should be regarded as irreversible; timber, once treated, cannot be returned to its original state. Therefore, epoxy con-

solidation should only be used on wood that otherwise would have to be discarded.

Epoxy wood patching materials or fillers are pastelike materials that functionally replace traditional wood fillers. Epoxy fillers not only have superior durability than presently available materials but also have a wide application. This is because epoxies can be made more self-supporting than traditional materials and are thus more useful in gap-filling and piecing-in applications. The epoxy patching compounds have been formulated to contain no volatile solvents and therefore shrink very little in setting. The epoxy patching compounds that have been developed may, when cured, be worked easily with standard woodworking tools. Unlike traditional materials, these are readily planed, sanded, or chiseled. Finally, epoxy fillers may also be used, when painted, in outdoor applications.

This paper is intended to supplement the information contained in Morgan Phillips' state-of-the-art technical paper

(Part I of this report). It also contains information on the essential aspects of formulating and applying epoxy consolidants and wood patching compounds, as well as a discussion of the advantages, disadvantages, and appropriateness of these methods of wood repair for historic buildings. After studying the information in this paper, it is expected that a craftsman could make his own repairs. Anyone desiring more technical information should refer to Mr. Phillips' paper and his accompanying references.

The techniques described in this report are for unreinforced epoxy repairs. The materials suggested have been selected to give consolidants and patching compounds a low modulus of elasticity compared to presently available epoxy materials. These epoxy formulations were developed in keeping with the philosophy that materials that possess some ability to move with the surrounding wood would produce minimal stresses on the historic building fabric.

Epoxy repair techniques frequently represent a viable alternative to traditional replacement methods for rotted wooden building members. The most appropriate action depends on 1) the structural requirements of the member, 2) the location and extent of rot, 3) the historical significance of the building member or the building as a whole, 4) the ability to obtain replacement pieces, and 5) whether or not the timber or object to be repaired is normally exposed to view.

STRUCTURAL REQUIREMENTS

Structural requirements frequently will rule out the use of an unreinforced epoxy repair. Epoxy consolidation of framing members is feasible only where members are subject to simple compression forces or where there is an adequate margin of safety. The materials and procedures to be described are not for application to members subject to bending or shear forces, unless reinforcement is introduced in some way. The discussion of various combinations of reinforced epoxy structural systems is beyond the scope of this paper.¹ Unreinforced epoxies should not be used for the repair of beams carrying brickwork, and thus subject to bending forces, or for the repair of tensions in girts, plates, or joists that represent points where shear forces act. However, the base of a post or a portion of a still frequently are acceptable candidates for consolidation based on this criteria.

EXTENT AND LOCATION

Obviously, wood that is so punky that it cannot absorb the liquid consolidant without excessive runoff cannot be consolidated. Thus, it must be determined whether the member in question still provides enough wood, although somewhat soft, to consolidate. As we shall describe later, the consolidation

of surrounding areas is often required when replacement of part of a timber is deemed necessary.

The criteria of location and extent are intimately connected with the cost aspects of a repair. Frequently, rotted or insect damaged areas can be made sufficiently accessible for consolidation purposes without the extensive dismembering of the structure necessary to expose an area for repair. Also, epoxy repairs can frequently be made without the need to provide structural shoring for parts of a building as is often necessary for wooden replacements. The epoxy treatment should not always be regarded as a cost saving treatment. For example, it should be noted that it may be cheaper to replace an entire sill and maybe even to splice it with new wood than to consolidate it. However, application of the other criteria might make the epoxy repair the preferred treatment in such a case. Finally, it

1. For further information see Paul Stumes, "Testing the Efficiency of Wood Epoxy Reinforcement Systems," *Bulletin of The Association for Preservation Technology*, vol. 7, no. 3 (1975), pp. 2-35.

would be unwise to use epoxy consolidants in areas where heat build-up may become significant. Epoxies weaken under fire and high heat conditions and evidence shows that it is likely to fail sooner than replacement wood in a fire.

The extent of damage can also determine if the patching compound should be used. Generally, as with traditional materials, only small holes are filled entirely with straight epoxy. Larger voids are usually filled with wood. However, the gap-filling and self-supporting properties of the epoxy patching compound, together with its low shrinkage, make it the patching material of choice for virtually all applications.

HISTORICAL SIGNIFICANCE

Epoxy wood repair offers the opportunity to conserve and thus retain important building members. In many historic buildings it is desirable to maintain as much of the original fabric as possible. In other cases, various architectural features may be judged unique or early examples of their kind and thus merit special preservation. An example of a repair where these sorts of considerations loomed large involved the consolidation of a post supporting the lean-

to at the Fairbanks House in Dedham, Massachusetts, the oldest wood-frame house in the United States. Frequently epoxy repairs made to maintain historic building fabric are made in conjunction with other methods of structural stabilization.

EXPOSED FRAMING MEMBERS

Many early buildings have hand dressed framing members that are exposed on the interior of the building. Frequently, these posts, sills, joists, rafters, etc., may appear visually sound although large sections of them are badly deteriorated. In such instances severely damaged areas should be removed prior to consolidation of the remaining shell. New wood is inserted to carry the load, although the visual aspects of the

member remain unchanged. The rafter repair at the Longfellow House that is described in this report is an example of a case where the desire to maintain historic fabric and visual integrity of an exposed member played a prominent factor in the decision to repair rather than replace.

AVAILABILITY OF REPLACEMENTS

Hand-carved or turned trim pieces, especially those on the exterior of a building, frequently are found to require repair and stabilization. Often, these elements deserve to be saved rather than replaced on the basis of historical considerations alone. Frequently, in addition, the cost of fabricating replacements makes consolidation and/or patching the more economic alternative. Certainly, modern replacement members frequently lose the irregular and individual character of the originals. Balusters, railings, capitals, ornaments, and interior trim details can be epoxy repaired for these reasons.

SAFETY, STORAGE AND CLEAN-UP

All chemicals recommended for use in this report should be handled with respect. If the cautions outlined are fully observed, no unusual health or safety hazards exist.

It is recommended that hands be covered when using the epoxies. Either rubber gloves or cloth gloves and a protective hand cream may be used. Although initial skin contact with the materials usually causes no discomfort, repeated exposure can lead to skin sensitization. A rubber respirator must be worn when the fillers for the patching compound are handled since care should be taken to avoid breathing Cabosil, a fumed silica, and/or the microballoons.²

Work surfaces are best covered with polyethylene or newspaper while preparing materials to simplify clean-up. Similarly, mixing in disposable containers will save time later in cleaning up. Clean-up solvents for epoxies are marketed by the distributors of the chemicals. Carefully scraping vessels with spoons or spatulas and wiping with newspaper or disposable rags will keep solvent use to a minimum. Of course, solvents should be used only in adequately ventilated areas.

Glass jars make excellent storage containers for the consolidants and wood patching materials. Clean metal cans without interior plastic coatings can also be used. Many plastics also seem to make acceptable storage containers. If reusable containers are used to mix together the two parts of the epoxy filler or consolidant, they must be cleaned before the material sets. Epoxy solvents and thinners will not remove cured materials. Materials are best stored at ordinary room temperatures.

PROPRIETARY PRODUCTS

Although the emphasis in this report is on specially developed materials, two proprietary (that is, commercially available and prepackaged) epoxy materials were used in the course of the repairs illustrated in this work. These materials, both products of the Allied Resin Corporation, East Weymouth, Massachusetts, are Arcon Seep-N-Seal[®] and Arcon E 152, Marine Epoxy Adhesive. Seep-N-Seal[®] is a penetrating consolidant. It is packaged as a two part material which is mixed to form a very fluid epoxy for consolidating rotted wood. It has a working time of approximately one hour and dries overnight at 70° to produce a rather hard product. Arcon E 152 is a two-component adhesive glue with a spreadable pastelike consistency. It can be applied thickly to irregular surfaces, requires little clamping, and dries to form a strong moisture resistant bond in about 24 hours at 70°.

NEW MATERIALS

The major aim of this section is the presentation of a practical description of the formulations for and preparation of three specially prepared epoxy based wood preservation materials. The reader will learn about the working details of the measurement and mixing of the raw materials necessary for making the formulations referred to as strong consolidant No. 1, strong consolidant No. 2, and semi-rigid patching compound No. 1 in Morgan Phillips' paper.

CONSOLIDANTS

Formulation

The formulations for the two wood consolidants follows. Both may be classed as strong consolidants and demonstrate good water resistance. The consolidants are prepared from two chemical classes of materials, epoxies and amines. The epoxy-functional components are by convention called part A while the amines or curing agents are called part B.

2. A good respirator is the Dupor rubber respirator bulb valve No. 4, available at most hardware stores.

Strong consolidant No. 1:

| | Material | Manufacturer | Parts by Volume | Total Part A |
|--------|---|---|--------------------|-----------------|
| PART A | DER 332 (epoxy resin) | Dow Chemical Midland, Michigan | 6 | 9 |
| | RD2 (epoxy resin) | Ciba-Geigy Ardsley, New York | 3 | |
| | Material | Manufacturer | Parts by Volume | Total Part B |
| PART B | Jeffamine D 230 (amine-functional curing agent) | Jefferson Chemical Company P.O. Box 4128 Austin, Texas | 4 | 4 |

Properties:

viscosity—pourable
 potlife—about 2 hours
 cure time—3 days at 70°F
 (will hold shape after 24 hours)
 physical characteristics—hard and
 rigid, can be nailed into, highly water
 resistant, cuts and sands with difficulty

Typical Uses: strengthening framing
 members in compression, consoli-
 dating the shell of rotted framing
 members prior to infill of new wood,
 repairing trim such as columns, bal-
 usters, sills.

Strong consolidant No. 2:

| | Material | Manufacturer | Parts by Volume | Total Part A |
|--------|---|---|--------------------|-----------------|
| PART A | DER 332 (epoxy resin) | Dow Chemical Midland, Michigan | 1 | 2 |
| | RD2 (epoxy resin) | Ciba-Geigy Ardsley, New York | 1 | |
| | Material | Manufacturer | Parts by Volume | Total Part B |
| PART B | Jeffamine D 230 (amine-functional curing agent) | Jefferson Chemical Company P.O. Box 4128 Austin, Texas | 1 | 1 |

Properties:

viscosity—very pourable,
 penetrates very quickly
 potlife—about 2 hours
 cure time—3 days at 70°F
 (will hold shape after 24 hours)
 physical characteristics—slightly re-
 silient, can be nailed into, somewhat
 less water resistant than No. 1.

Typical Uses: strengthening framing
 members in compression, consoli-
 dating the shell of rotted framing
 members prior to infill of heavy wood,
 repairing trim such as columns, bal-
 usters, sills.

Preparation and Application

It is most useful to premix the two ingredients of part A. This allows the craftsman to arrive at a job with only two containers, one containing part A and the other part B. Additionally, this procedure eliminates the inconvenience associated with the tendency of pure DER 332 to solidify in the container. The addition of a reactive epoxy diluent, namely RD2, produces a low viscosity fluid epoxy mixture (part A). The shelf life of the mixture can be regarded as at least several months and probably is actually much longer. If the DER 332 solidifies during storage, it should be gently warmed by placing the container near an oven, furnace, or

radiator. Spot heat sources, such as hair dryers, should be used with great caution.

The two ingredients of part A should be carefully measured according to the recipes given. A metal or glass container may be used as a measure. The storage container should be marked indicating that it is part A of strong consolidant Nos. 1 or 2 and the preparation date noted. The epoxy materials should be blended either by vigorously shaking the closed container or stirring with an propeller-shaped blade mounted on an electric drill. The drill blade can be cleaned adequately for further use by tapping against a hard surface to remove excess liquid and wiping with towels.

Parts A and B should be thoroughly

mixed on the job site immediately prior to use. Again, shaking or a mixing blade may be used to thoroughly blend the materials. It should be carefully noted for strong consolidant No. 1 that 9 parts by volume of part A are mixed with 4 parts by volume of part B. The strong consolidant No. 2 combines 2 parts by volume of part A with 1 part by volume of part B.

These wood consolidants are generally best applied to the wood by a series of closely spaced holes drilled to produce an overlapping absorption pattern (figure 1). It is recommended that holes be drilled at an angle and spaced approximately 2 inches on centers in staggered rows. The holes should

be approximately $\frac{1}{4}$ " diameter and placed so that the top of one is in line with the bottom of the next. This will exploit the superior absorption of the end grain. Timbers should be filled from one end so that the consolidant will not trap air pockets within the wood.

As a rule of thumb, badly deteriorated wood will absorb a volume of consolidant that is approximately one half of its total volume. Of course, stronger wood will absorb less.

Wood to be consolidated should not be perceptibly wet. Generally, a timber dry enough to be painted is suitable for consolidation. Often, checks or cracks in the exterior of the piece are sealed with wax, clay, or caulking to prevent runoff of the consolidant. These procedures will be elaborated in the case studies.

When parts A and B are mixed, heat is given off. The epoxy curing reaction is thus said to be exothermic. It is wise to cool the parts before they are mixed during warm weather to prevent excess heat buildup. The curing will be accelerated at high temperatures. Temperatures below 50° will result in excessively long curing time.

Wood preservatives, such as pentachlorophenol or orthophenylphenol can be applied to the wood prior to consolidation. This preservative should not contain a water repellent as this may retard absorption of the consolidant.

PATCHING COMPOUNDS

Formulation

The patching compounds are composed of three categories of materials; namely, epoxy materials (part A), curing and flexibilizing agents (part B), and fillers (part C). The fillers impart the properties that permit the patching compounds to be worked with ordinary tools in a manner similar to wood. Additionally, the filler imparts a resistance-to-flow property to the mixture. The chemical formulation of the patching compound follows.

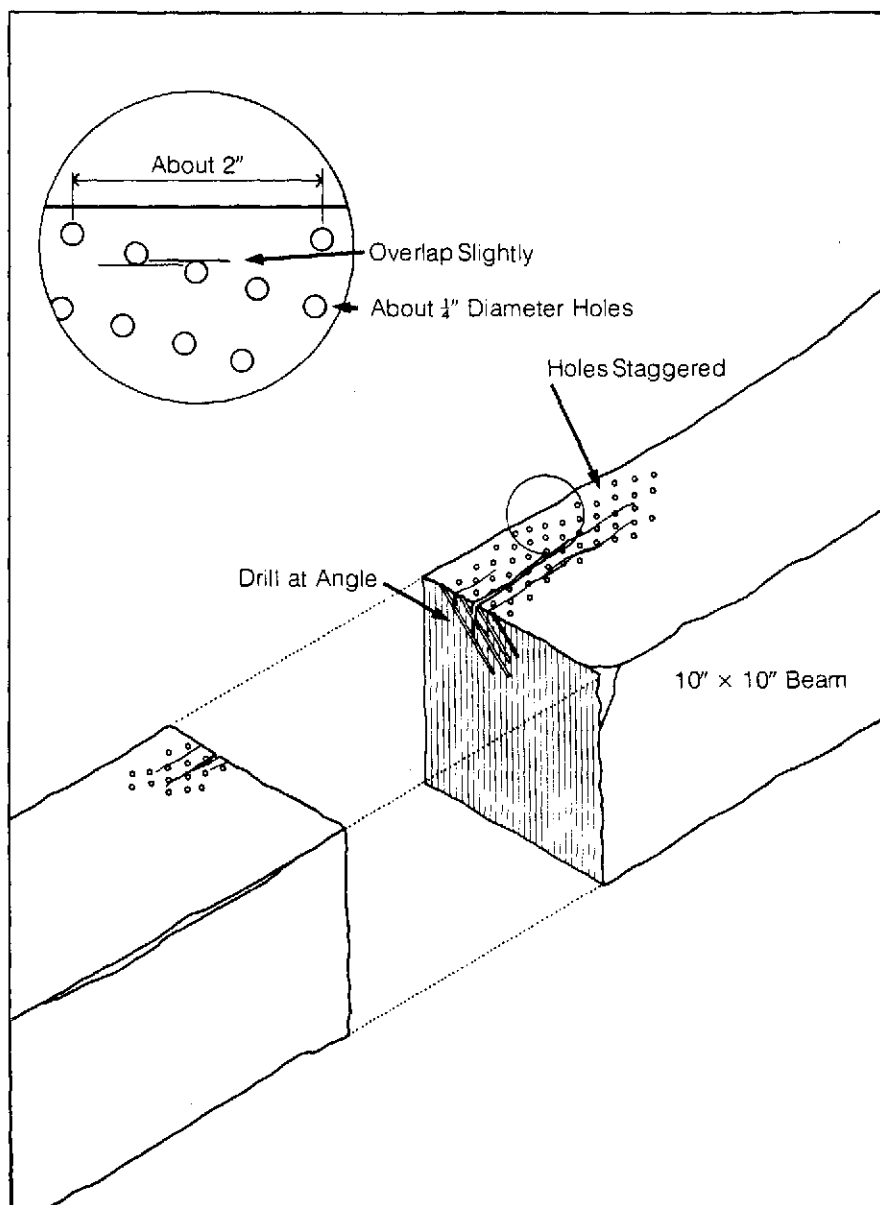


Figure 1. Pattern for holes drilled into rotted wood for the introduction of consolidant.

Semi-rigid patching compound No. 1:

| | Material | Manufacturer | Parts by Volume | Parts by Weight | Properties: viscosity—thick paste potlife—20 minutes cure time—sets to workability overnight at 70°F physical characteristics—semiflexible, may be carved, planed, sanded. Typical Uses: all applications now served by conventional wood pastes and putties, restoration of carved and turned trim elements. |
|--------------------|-----------------------------|--|--------------------|--------------------|--|
| PART A | DER 331 (epoxy resin) | Dow Chemical Midland, Michigan | 8 | 100 | |
| PART B | LP-3 (polysulfide polymer) | Thiokol Chemical 930 Lower Ferry Road Trenton, New Jersey | 7 | 96 | |
| | EH 330 (amine curing agent) | | 1 | 10 | |
| PART C (Filler) | Cabosil M5 | Cabot Corporation 125 High Street Boston, Massachusetts | 1 | 12 | |
| | Phenolic Microballoons | Union Carbide 270 Park Avenue New York, New York | 2 | 36 | Total weight filler = 24% of total weight parts A & B |

Preparation and Application

For the semi-rigid patching compound, both weight and volume mixing proportions have been listed for parts A, B, and C. Mixing by weight is preferred for the fillers as the density of these materials is strongly a factor of packing. An inexpensive triple beam balance weighing to 0.1 gram, such as the Ohaus 710T with weight attachment set (available from Fisher Scientific and others), is adequate for this purpose. It is best to prepare large batches of part C and put it aside for later use. (Recall that it is necessary to wear a respirator mask when measuring or mixing in the fillers.)

Part B should be carefully measured, well-mixed, labeled, and stored. The corresponding amount of part A should be measured and labeled.

Part C represents the fillers that are responsible for giving the patching material its desirable working qualities. It

is blended into both parts A and B to produce two pastes. Ideally, the amount of part C used should be 24 percent of the weight of the parts A and B combined. Thus, for a batch containing 100 grams of DER 331, 96 grams of LP-3 and 10 grams of EH 330 approximately 48 grams of part C filler are required. Half, or 24 grams, is blended into the 100 grams of part A to produce a paste-like part A with filler. Similarly, 24 grams of part C filler is added to the liquid part B to produce a paste. Mixing in the filler is best accomplished in a shallow bowl or enamel pan using a small spatula or putty knife.

If scales are not readily available, an alternate approach may be adopted. This would involve preparing parts A and B by using the volume proportions listed in the formulation. Part C may also be prepared using the volume ratio or preferably can be premeasured by weight before delivery to the workmen in the field. Again the materials should be placed in labeled containers. Then the following system may be used to add equal volumes of part C to the liquids. The amount of part C to be added

will be limited by the amount that part A will accept. Part A will wet *very slowly* and must be mixed *very thoroughly* to accept the filler. After part A appears to accept no more material and an equal quantity of part C has been added to part B, the materials should be permitted to stand overnight. Part A may accept more of part C after standing. An equal amount of part C must, of course, be added to part B. The thorough mixing of the liquids and filler must be stressed. Part A should be rather stiff after it receives the filler.

Parts A and B (containing fillers) may be stored as pastes for several months. They are then ready for use as patching

jobs arise. Thus, only two containers need be taken to the job. It should be noted that part A tends to get stiff and unworkable at temperatures much below 70°F. It is best to store and use the materials at approximately this temperature. To use the patching compound, equal quantities of both parts A and B (containing fillers) must be *thoroughly mixed*. Small quantities may be measured with spoons and mixed in a paper cup with a palate knife. Larger quantities may be blended on a plywood slab with the aid of a spatula or paddle. Mechanical mixing is not particularly helpful because of the viscosity of the pastes.³ *Failure to adequately mix the components will prevent the material*

from curing. The patching compound is a workable paste that may be applied thickly. Although, it shrinks little, it is best to slightly overfill a hole and then sand or plane it level. Surfaces for patching should be clean, solid or solidified (that is consolidated) wood. Surfaces should be prepared bearing in mind that regularly shaped holes are easier to fill. Wood need not be roughened prior to filling as the adhesive properties of the material are chemical as opposed to mechanical. It is usually unnecessary to remove well-adhered paint layers prior to application of patching compound.

Although the shrinkage associated with the setting of the patching compound is minimal, it is not suggested that this material be used for large holes. As a rule of thumb, areas to be filled should be less than 1" in two of

its dimensions. Long narrow cracks as well as small holes may be filled. Larger holes should be filled with new wood. Holes should be slightly overfilled with the patching compound and then tooled to the desired contour.

The cured patching compound can be painted with ordinary paints. Because wood is ordinarily painted for general weather protection in outdoor locations, this offers no complication.

-
3. An alternative approach has been adopted successfully by one craftsman. He takes three containers to the job; namely, liquid part A (no filler), part B (no filler) and filler. He thoroughly mixes equal volumes of the two liquid parts, then works in the filler to produce a stiff working paste.

Repairs to Historic Wooden Framing Members

Several repairs to important structural members of the Longfellow House, Cambridge, Massachusetts (1759), made during the summer of 1976 will be described. These framing repairs, as well as trim areas that were restored, are indicated on a photograph of the Longfellow House (figure 2). Insects and dry rot had partially damaged the structural integrity of the corner post near the juncture with the sill at the southeast corner of the building. Failure of the roof valleys of the central dormer caused damage to a main roof tie beam and adjoining roof rafter. Also, rafters near the chimney girt were damaged.

Figure 2. Longfellow House in Cambridge, Massachusetts, built in 1759, indicating areas where epoxy repairs were used.

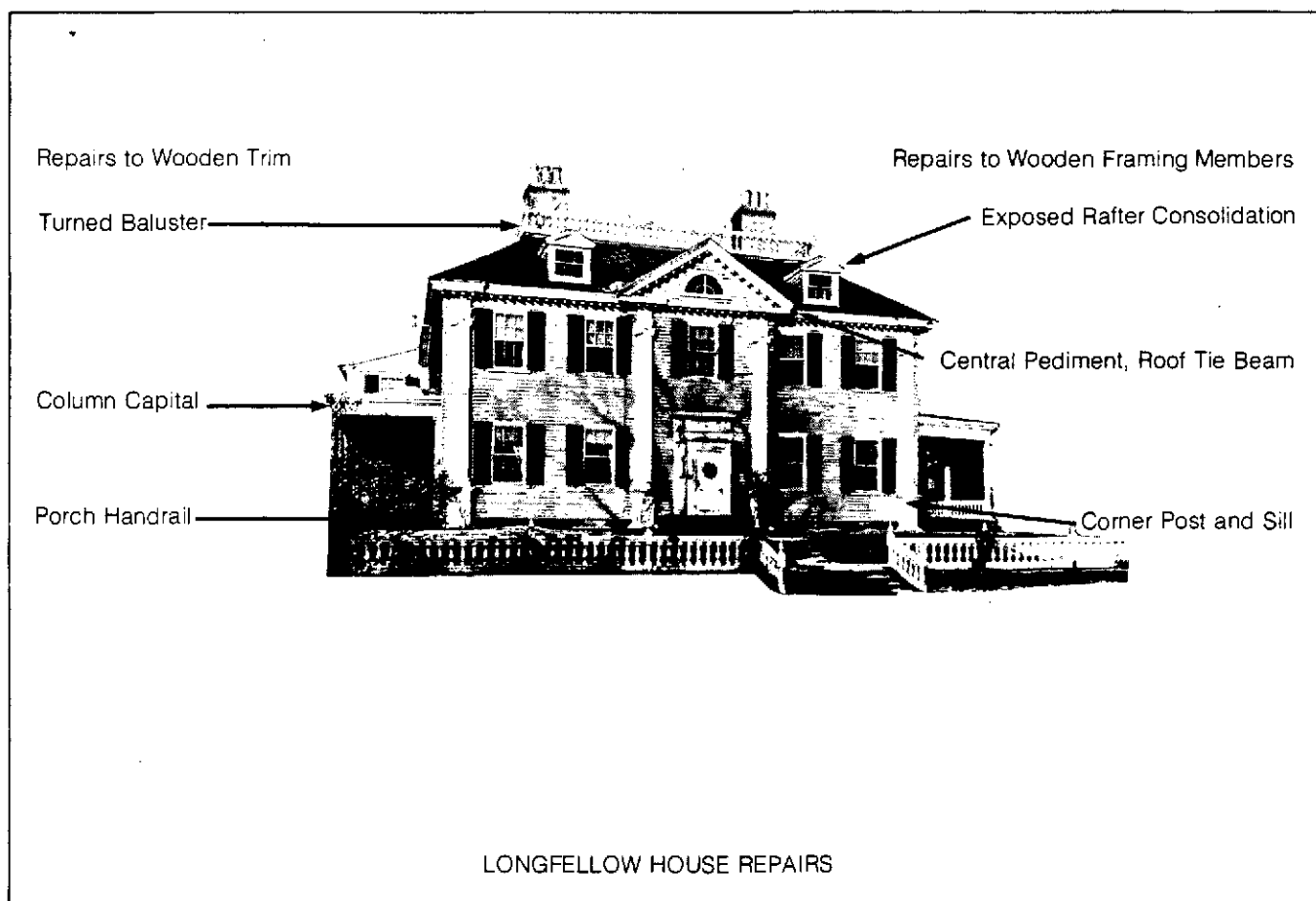
For each repair the existing conditions, repair criteria, and preservation treatment will be outlined. A self-critical approach evaluating the success of the treatment and alternative methods will also be presented.

LONGFELLOW HOUSE, CORNER POST AND SILL

Existing conditions

Removal of the clapboarding revealed that the corner framing consists of a 10" by 10" oak corner post set on 8" by 10" oak sills. Corner braces connect the sills and post. The cavity between the interior plaster and the exterior sheathing is filled with nogging that consists of soft, underburnt pink bricks set in lime mortar. Figure 3 is a diagram showing not only the framing, but also the damaged areas. A previous repair, namely a Portland cement patch in the sill under the post, probably made

in the 20th century, was noted. Unfortunately, this repair did not halt the deterioration of the members. In fact, the cement may have acted as a water-conducting wick fostering increased rotting of the framing. The weakened wood seems to have provided an entry point for powder post beetles. The lower 2 feet of the post and 6-7 feet of the adjoining sill on the southeast side of the house evidenced some degree of insect/water damage. In one area of the sill, as noted in figure 3, and further illustrated in figure 4, the wood deteriorated to the extent of being soft and crumbly. This area involved the lower 4-5 inches of the sill for a distance of approximately 2.5 feet. For the remainder of the sill only the lower inch or so was decayed. It should be noted that the deterioration of the framing was not extensive enough to cause obvious structural deformation or failure.



Case Studies: Repairs to Historic Wooden Framing Members

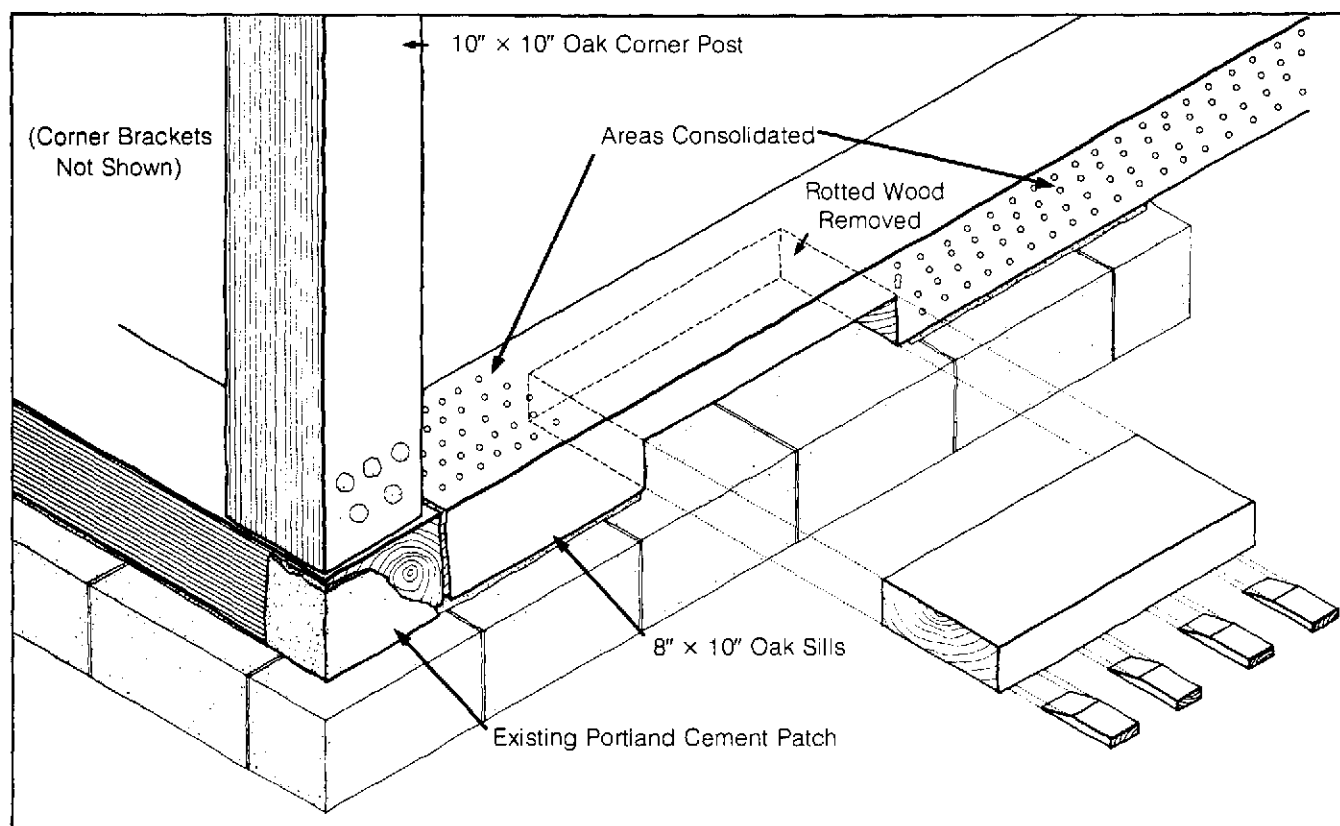


Figure 3. Longfellow House, Corner Post and Sill SE corner, framing isometric indicating decayed areas and areas drilled for consolidation.

Repair criteria

The purpose of the repair was to strengthen framing members subject to compressive forces, namely the sill and corner post, and to establish a framing configuration less prone to deterioration. Consolidation (rather than replacement) of the post was judged a desirable course of action as only a small portion of the bottom of the post was in poor condition. It was decided that the epoxy repair would be less difficult and less expensive than procuring and installing infill wood of the correct dimension and supporting the corner of the house to permit this process. Although a small portion of the sill obviously had to be removed and replaced, the consolidation of other portions was tried. Thus, it was concluded that the epoxy approach would be a good way to conserve the massive, historically significant, original framing timbers.

It should be noted that the epoxy also

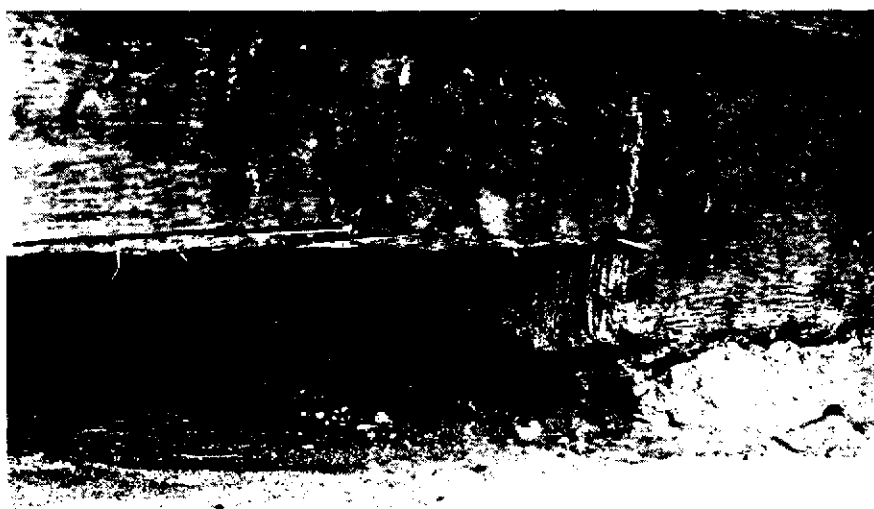


Figure 4. Longfellow House, Corner Post and Sill. The conditions near the most seriously deteriorated area, after removal of siding and part of the decayed wood, are shown. (Photo: Author)

could effectively coat and consolidate the portland cement previously applied to the corner post. This would have the effect of waterproofing the cement and providing a dampproof base for the post. Since water is prevented from migrating through the cement, it would not be necessary to remove this material. It was hoped that this treatment of the post and sill would have the long term effect of alleviating the chronic problem of water collection and subsequent damage to this area of the building frame.

Preservation treatment

After the siding was removed, chemical treatment to eliminate any remaining insect problems was the necessary first step in the conservation process.⁴ Severe deterioration necessitated the removal of a portion of the sill. Next, a series of $\frac{1}{4}$ " holes spaced approximately 3" on centers were drilled at a downward angle through the wooden sill to the right of the void (figure 5). Strong consolidant No. 1 was introduced into the holes using a plastic squeeze bottle. Each of the holes was filled with the liquid epoxy until the holes appeared to hold no more liquid (figure 6). A total of $\frac{1}{2}$ pint of consolidant was needed to saturate the right side of the sill. The small amount of consolidant used indicates that the wood was reasonably non-absorbant and sound. As the face of the wood was reasonably sound, it was not necessary to seal the surface.

Large holes had been drilled into the corner post in the course of the insect control work. These were subsequently used to introduce approximately $\frac{1}{2}$ gallon of the strong consolidant No. 1. As the larger holes were not filled with epoxy, wood dowels were placed in the holes.

The sill immediately to the right of the post (figure 3) was consolidated using the slightly less strong, that is, more flexible, formulation, than the preceding one. Approximately $\frac{1}{2}$ gallon of the strong consolidant No. 2 was absorbed.

4. Terminex 3A3B, a powder post beetle and termite control material, was applied by the local distributor.

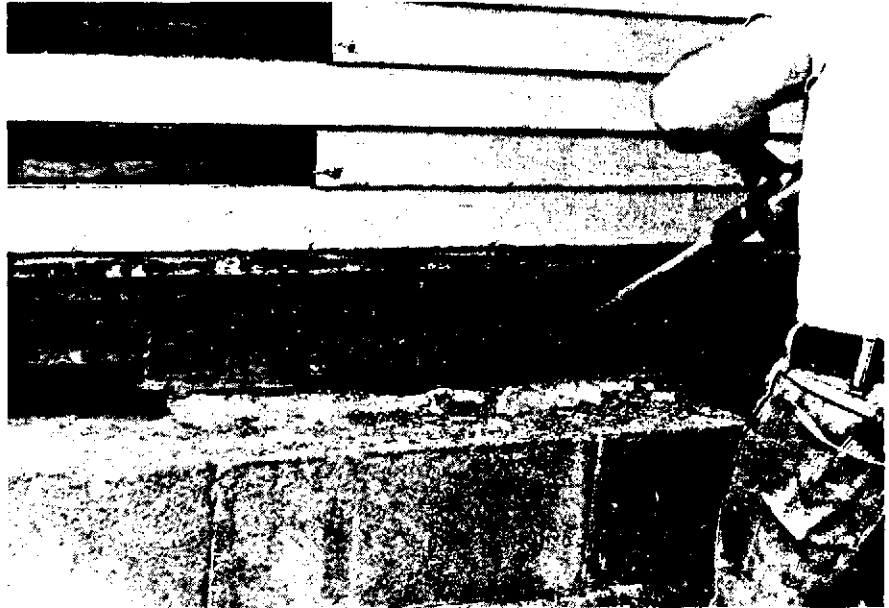


Figure 5. Longfellow House, Corner Post and Sill. Siding has been removed and chemical fumigation completed. In the area to the right of the removed portion of the sill, a series of staggered $\frac{1}{4}$ " holes approximately 3" on centers were drilled downward into the sill. Ideally, holes should have been made only in the lower third of the sill and more closely spaced. (Photo: Author)

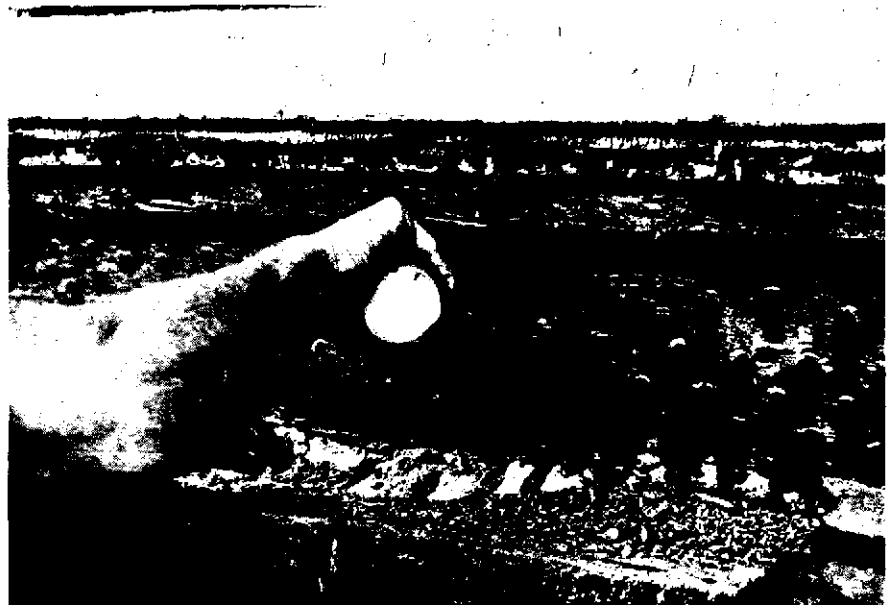


Figure 6. Longfellow House, Corner Post and Sill. Epoxy consolidant is introduced into holes using a plastic squeeze bottle. In this case it was not necessary to seal the surface to prevent run-off because the wood was reasonably sound. Dark areas on the face of the beam are the result of surface absorption of consolidant and slight dripping during the filling process. (Photo: Author)

This section of the repair area proved to be the most absorbant. Figure 7 shows the application of epoxy using the squeeze bottle. Strong consolidant No. 2 was used in this instance, although no clear rationale for its choice can be given. However, since the sill rests on a granite foundation, the fact that this formulation has more flexibility probably will not lead to any problems. Both consolidants have more than sufficient strength for the job. In fact, since the deteriorated structural members were, at least for the short run, holding up the house, little additional strength was needed. Observation of the *in situ* aging of the two different epoxy materials in this instance may enable us to better understand how to formulate the most suitable materials for future use.

The final phase in the process of conservation of this area of the framing involved filling the void created in the sill. A block of oak shimmed by a series of four oak wedges front and back was inserted into the opening. These wedges assured the tight fit of the oak block patch (figure 8).

Critique of treatment

In overview, the pattern of holes drilled into the sill for the introduction of the consolidant was probably less than optimum. If a similar process is to be repeated, it would be advised that the holes be made much closer together in the areas where the wood is soft. (See figure 1.) This closely spaced hole pattern should not be extended into areas of sound wood. Thus, the holes shown in figure 5 should be much more closely spaced in the bottom third of the timber and probably no holes at all should be made in the sound upper two-thirds.

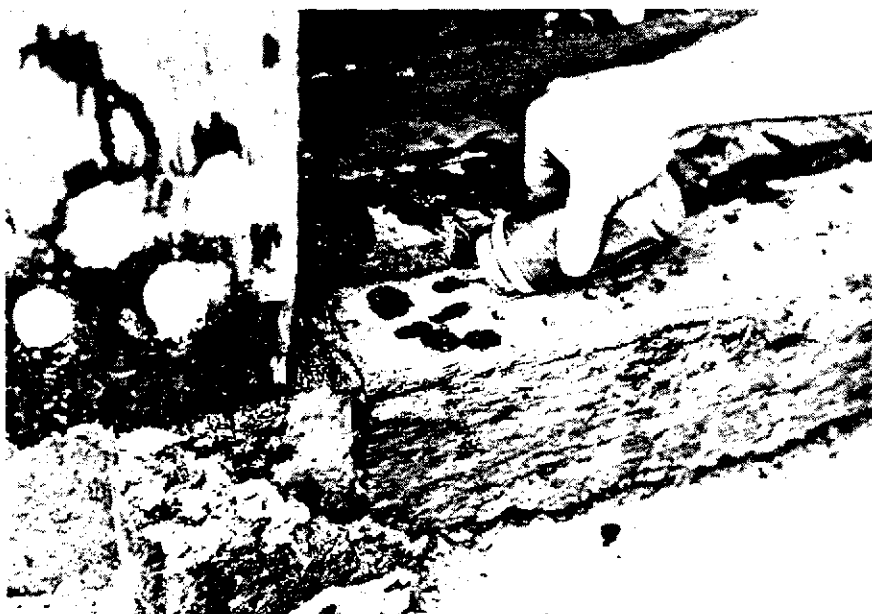


Figure 7. Longfellow House Corner Post and Sill. Epoxy consolidant is introduced into holes in the left end of the sill using a squeeze bottle applicator. (Photo: Author)



Figure 8. Longfellow House Corner Post and Sill. In the most deteriorated portion of the sill, new wood infill was used. Oak was used to match the material of the original. Wedges front and back were used to tightly position the wood in place. No adhesive was used as the compressive forces really allow no movement of the block once positioned. (Photo: Author)

LONGFELLOW HOUSE, CENTRAL PEDIMENT, ROOF TIE BEAM

Existing conditions

Prior to reslating the roof, it was discovered that major structural timbers in the roof of the east side of the central

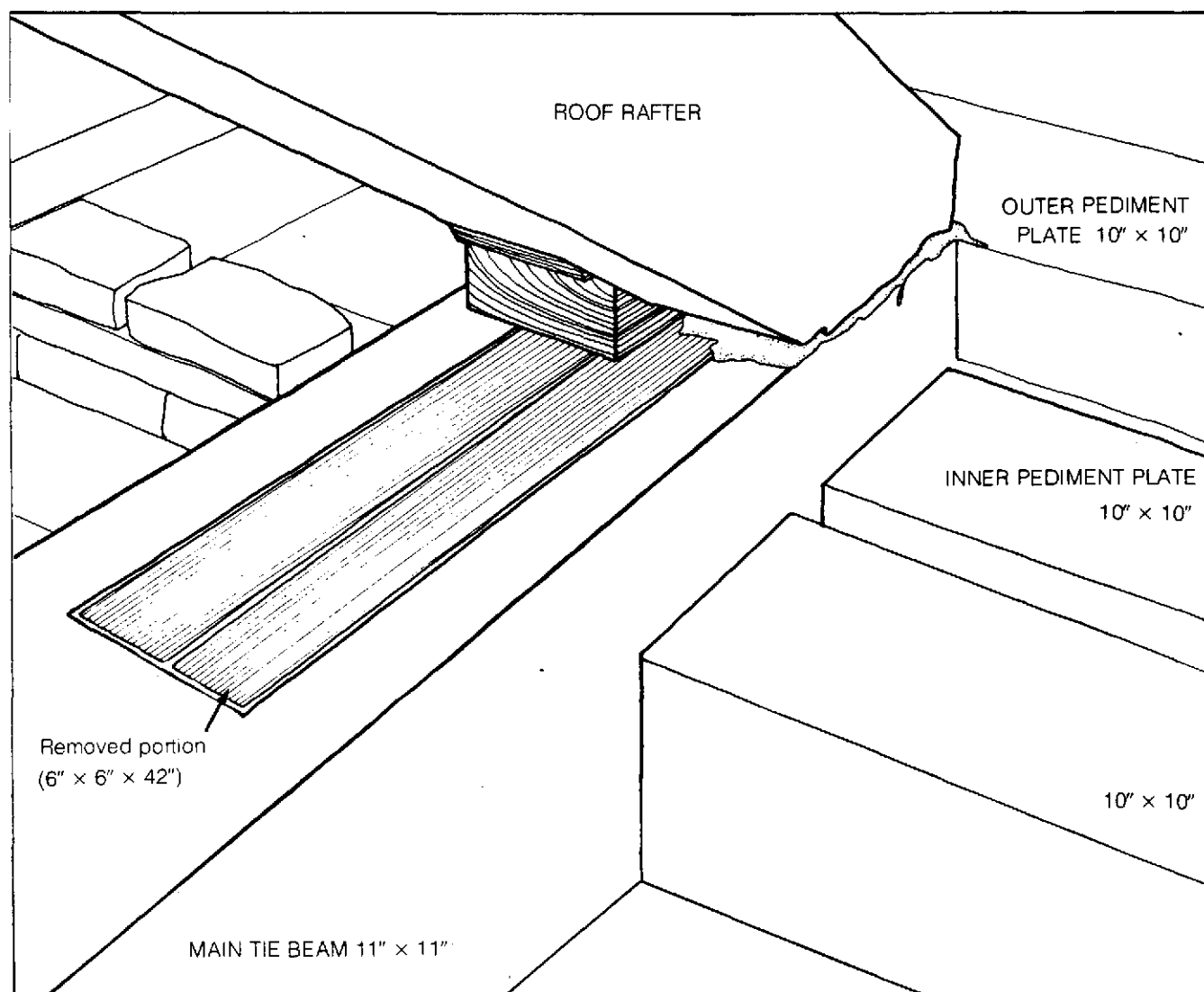
pediment were rotted. It appeared as though water had penetrated through deteriorated valley flashings and funneled its way via the roof rafter into the main tie beam. This completely destroyed the tenon of the rafter and the upper portion of the pine tie beam, starting at the outer end and extending in 42 inches. The rotted area measured approximately 6" by 6" at the outer end and narrowed down to a much smaller section 2 feet into the beam. Figure 9 diagrams a portion of the pediment framing. It should be noted that the outer plate for the pediment is completely supported by the cantilevered end of the deteriorated tie beam and

the corresponding one at the other end of the pediment. The rot (that is wood practically reduced to powder) occurred directly over the point where the cantilevered end of the tie beam is supported.

Repair criteria

A repair was effected without the need for obtaining new large members and with minimum dismemberment of the sound parts of the structure. New wood was introduced into a cavity that was partly consolidated and partly sound old wood. Epoxy adhesive allowed laminated small wood infill members to be installed.

Figure 9. Framing isometric of the Longfellow House central pediment. Note that the damaged area includes the tenon that formerly connected the rafter to the tie beam. The outer pediment plate is supported by the cantilevered end of the rotted tie beam. Thus, before the repair, the support for the outer pediment plate was very poor.



Preservation treatment

The initial phase of the repair entailed removal of a section 6" by 6" by 42" of the tie beam (figure 10). The cavity was reinforced with Allied Resin Seep-N-Seal®, a strong two-part epoxy consolidant. Seep-N-Seal® was chosen because it sets rapidly, thus enabling the roofers to proceed without undue delay. Checks along the side of the beam were caulked prior to this application to prevent the epoxy from flowing out through the channels in the wood, then the consolidant was poured into the cavity.

Two pieces 3" by 6" by 42" of long-leaf yellow pine were laminated together with Allied Resin E 152 Marine Epoxy Adhesive. These were then dated and inserted into the cavity that had been lined with the same adhesive (figure 11). An epoxy adhesive shrinks very

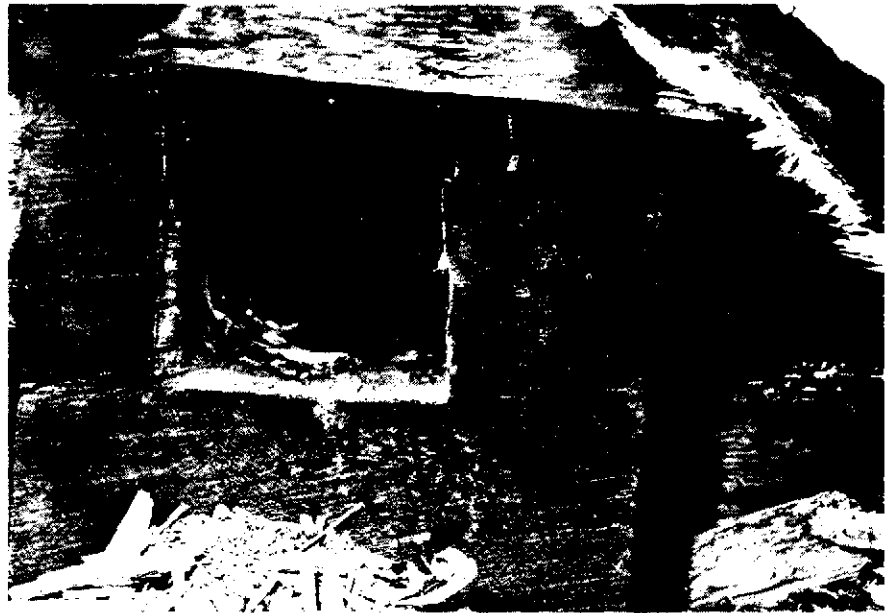


Figure 10. Longfellow House, Central Pediment, Roof Tie Beam. The pediment siding, as well as a portion of the roofing, were removed to allow access to the rafter and tie beam. Here we see the outer end of the very soft area on the top of the beam. The cavity (6" x 6" x 42" long) was made as regular as possible, avoiding the removal of too much reasonably sound wood, to best receive the new wood. (Photo: Author)

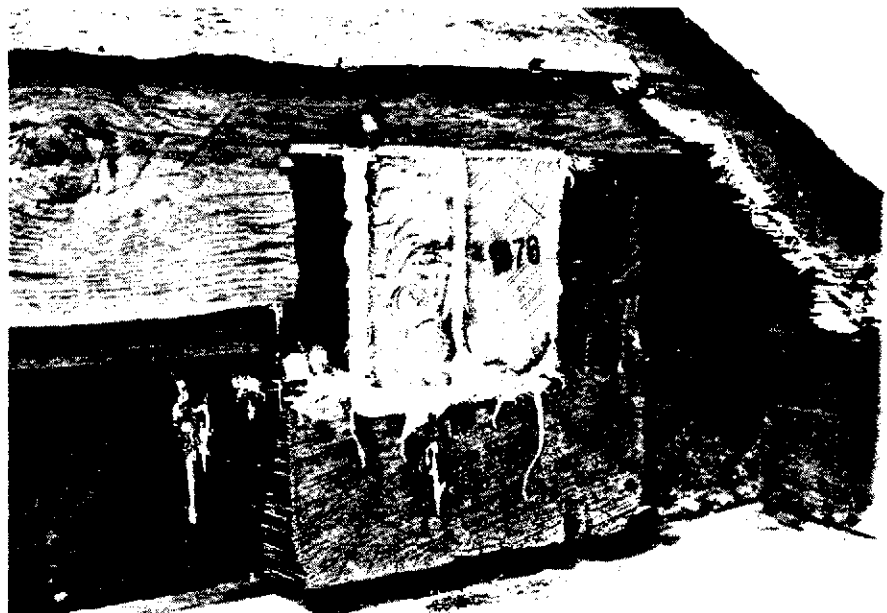


Figure 11. Longfellow House, Central Pediment, Roof Tie Beam. Two 3" x 6" x 42" sections of long-leaf pine yellow pine, laminated with Allied Resin E 152 epoxy adhesive, were placed into the rafter cavity which was lined with the same adhesive. Care was taken to identify the new wood with the year of insertion. (Photo: Author)

little. This enables a good bond to be made even when a thick bed is spread over a somewhat irregular surface as in the present instance. The bottom of the roof rafter was then shimmed with pine to replace the rotted lower section. Figure 12, photographed from inside the pediment, illustrates not only the tie beam infill, but also the new rafter base.

Originally the beam and rafter were secured together by a mortise and tenon joint. As this connection no longer exists, a steel plate, secured with lag screws, was made to connect the members. The plate has the effect of helping to prevent any tendency of the rafter to thrust outward, although other framing members in the area also tend to restrain it. In this case the steel plate was

not installed in the manner characteristic of the other roof repairs made during this project. The preferred technique should have been used here, namely, steel plates on both sides and one inch through-bolts connecting them.

Critique of treatment

In retrospect, an improved technique would involve drilling the sides of the cavity and using a squeeze bottle to inject the holes with epoxy consolidant. Ideally the glue should have also been thickly spread onto the infill wood. It should be sufficiently thick that some becomes forced out of the top of the joint when the new wood is fitted into place. This forces out trapped air and helps to insure a long and continuous bond.

Again, it should be emphasized, that in this application the primary bending and shear stresses are borne by the new wood. The epoxy is merely an adhesive used to laminate the infill and consolidate the useful parts of the old wood.

Figure 12. Longfellow House, Central Pediment, Roof Tie Beam. This interior view shows not only tie beam infill, but also the piece used to shim the rafter base. These have been glued in place with epoxy adhesive. It should be noted that the framing elements have lost the mortise and tenon joint that formerly connected them. (Photo: Author)



LONGFELLOW HOUSE, EXPOSED RAFTER CONSOLIDATION

Existing conditions

Yet another badly deteriorated roofing member was exposed after roof sheathing was removed in order to inspect the framing in preparation for reslating. A roof rafter framed into the chimney girt showed an area of extensive water and insect damage. Only the shell of the rafter remained for 4 feet of its length. Fortunately, from below, the exposed rafter still maintained an excellent visual appearance in the finished room. In fact, the rafter was painted to resemble wood graining.

Repair criteria

One excellent rationale for the use of epoxy consolidants is to preserve the appearance of structural timbers that are exposed on the interior of the building, as occurs in this case. The rafter was judged not to be subject to significant stress; it had to support only the weight of the roofing material directly above. Thus, although the member was badly damaged by water and insects, epoxy consolidation and infill with new wood was deemed practical because little structural strength was necessary.

Preservation treatment

Removal of the rotted section resulted in a key-shaped cutout in the rafter (figure 13). The depression was prepared for strong consolidant No. 1 by using plywood and caulking compound to prevent liquid epoxy from flowing freely out of the cavity (figure 14). Since insects had effectively drilled channels through the remaining wood, no further preparation for consolidation was necessary. The consolidant was applied



Figure 13. Longfellow House Exposed Rafter Consolidation. View from above after removal of roof slates and sheathing. Deteriorated section of rafter has been removed producing a key-shaped cavity. A purlin is shown framed into the rafter. (Photo: Author)



Figure 14. Longfellow House, Exposed Rafter Consolidation. Rafter cavity shown prepared for consolidation by using plywood and caulking to close cavity. (Photo: Author)

with a brush. Care was taken to coat the wood repeatedly until further absorption appeared to cease and the surface appeared wetted. Overnight setting was required prior to application of the non-shrinking Allied Resin E 152 adhesive. Again, this material permits a thick glue line on the uneven surface assuring a good bond. New wood was also adhesive coated and fitted into the cavity. The completed repair, illustrated in figure 15, retains all the integrity of the interior appearance.

Critique of treatment

This approach should be considered the method of choice for the conservation of exposed interior framing. If space had permitted, bolts, and perhaps a longer bottom section of the "keyhole," could be added to increase the amount of loading acceptable on this sort of patch.

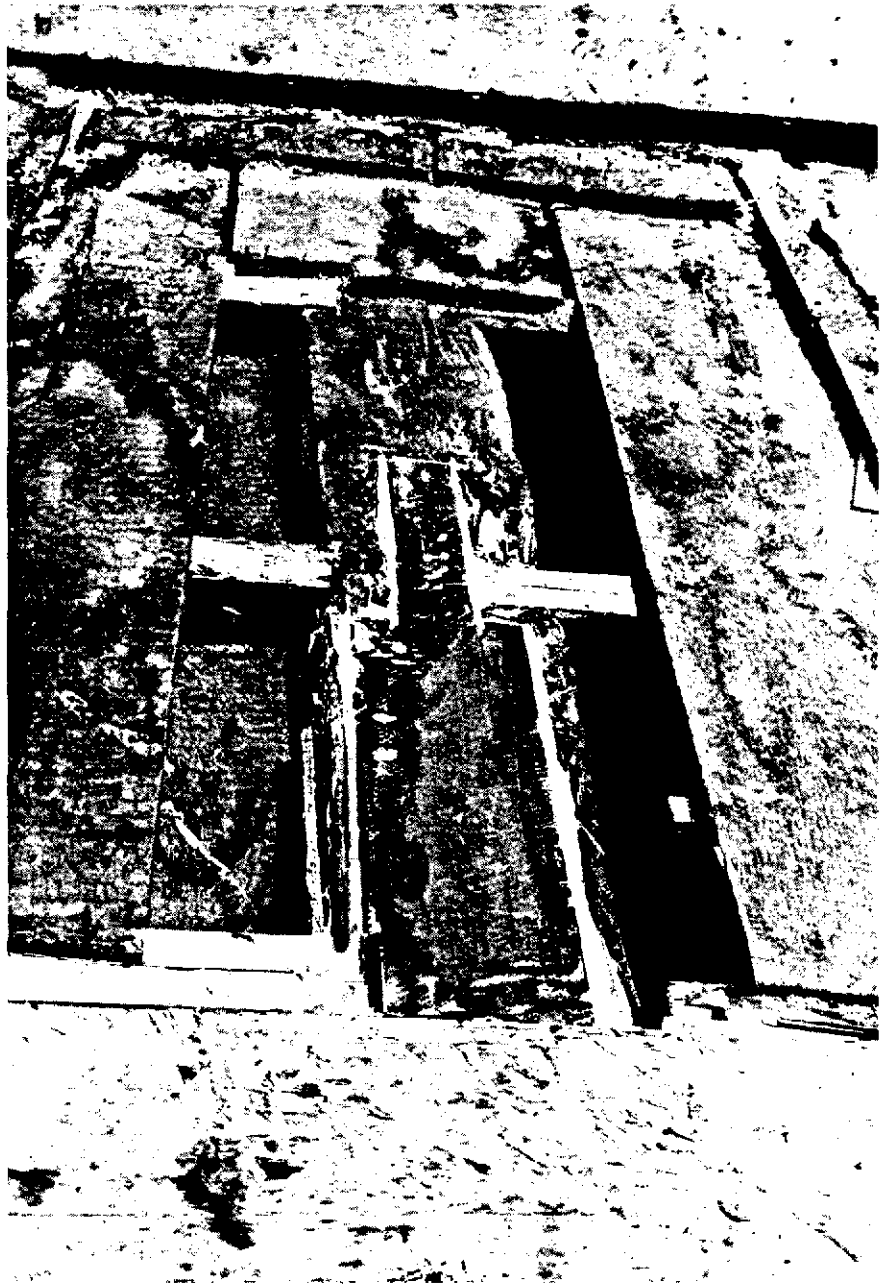


Figure 15. Longfellow House, Exposed Rafter Consolidation. Consolidant was brushed on the sides of the cavity so as to saturate it. After this cured, the cavity was thickly lined with Allied Resin E 152 epoxy adhesive. The bottom and sides of the new wood were adhesive coated and fitted into place to complete the repair. (Photo: Author)

Repairs to Historic Wooden Trim

The semi-rigid wood patching compound used either alone or in combination with wood consolidation offers an outstanding method for repairing hand-carved or turned trim elements. In addition, the patching compound simplifies all conventional wood repairs. Typical uses of the patching compound will be detailed using examples drawn not only from the Longfellow House, but also from work done to restore the fire-damaged Hyde Mansion in Bath, Maine. Figure 2 highlights the areas at the Longfellow House where the nonstructural repairs involving epoxy materials to be described were made.

LONGFELLOW HOUSE, TURNED BALUSTER**Existing conditions**

The east and west piazzas as well as the roof of the Longfellow House have hand-turned wooden balusters. Many elements of these balustrades were

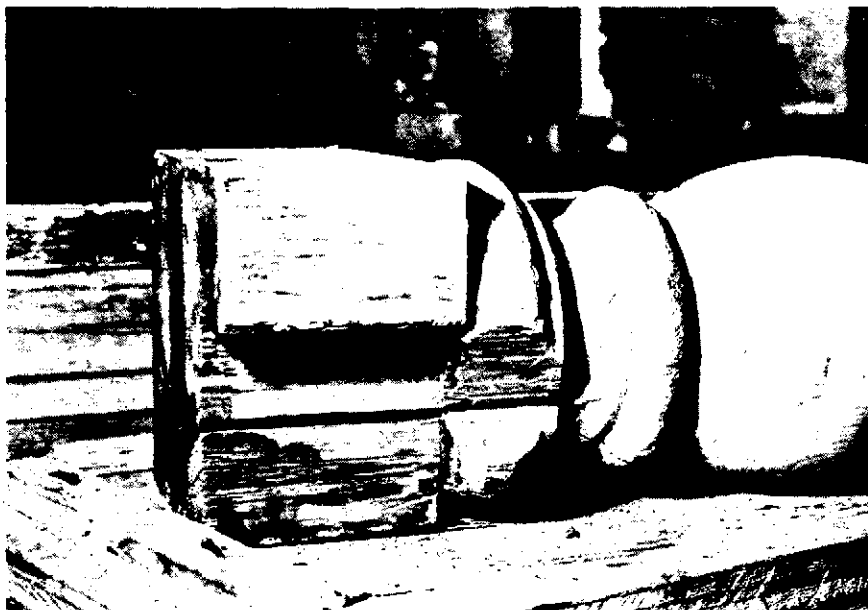


Figure 16. Longfellow House, Turned Baluster. A typical unit shown after paint removal prior to repair. There are cracks along the grain as well as missing pieces. It should be noted that very well-bonded paint need not always be removed prior to application of epoxy patching compound.



Figure 17. Longfellow House Turned Baluster. Semi-rigid patching compound No. 1 is applied to fill the smaller holes using a putty knife. Care must be taken to prevent air from becoming trapped behind the patch as this will weaken the bond. (Photo: Author)

split, cracked, rotted, or missing altogether. Figure 16 shows the "before" condition of a typical baluster after initial paint removal.

Repair criteria

Using epoxy patching compounds and epoxy adhesives it was possible to recondition the balusters without incurring the high expense of having new hand-turned units fabricated, while at the same time preserving the valuable historical fabric.

Preservation treatment

Surfaces were prepared by paint removal and smoothing out the more irregular gaps. Allied Resin E 152 adhesive, with a small amount of phenolic microballoons added, was used to fill the areas where the wood was split along the grain. Although the quantity of microballoons added was not specifically measured, the amount was governed by the goal of obtaining a stiff, but still workable, paste. The adhesive was needed to prevent further splitting of the wood. The microballoons were added to make the cured epoxy easier to work, although this was at the expense of some degree of bond strength. Semi-rigid patching compound No. 1 was used to fill small holes and surface irregularities.

This material is less strong, but more workable than the E 152 adhesive. In figure 17 this material is applied to fill surface irregularities. The E 152 adhesive was used to glue new wood into the larger cracks. Available wood scraps were used for this purpose. Smaller pieces of wood were laminated with adhesive to provide larger blocks. Infill pieces were oversized as final sizing was accomplished after curing of the epoxies. Figure 18 shows the repair ready to be clamped for drying. A day of drying is required before the final planing, carving, and sanding is undertaken. The repaired baluster is shown ready for repainting in figure 19.

Critique of treatment

This procedure has proved an excellent method to preserve historic fabric with readily applied conservation techniques.

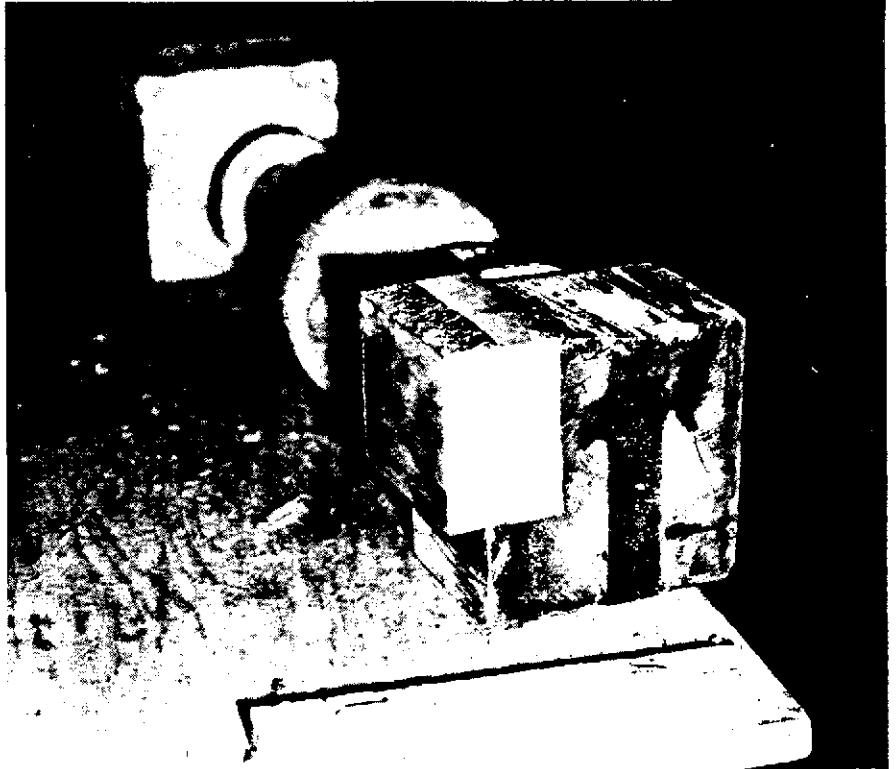


Figure 18. Longfellow House. Turned Baluster. Larger gaps were filled with new wood attached with epoxy adhesive. Oversized infill are to be shaped after epoxies have cured. The larger block was clamped for drying. (Photo: Author)



Figure 19. Longfellow House, Turned Baluster. Baluster has been sanded, planed and carved to obtain correct contours. The completed baluster is now ready for repainting. (Photo: Author)

**LONGFELLOW HOUSE, PORCH
HANDRAIL****Existing conditions**

Epoxy procedures have been applied to fill narrow cracks and holes in balustrade handrails and porch steps at the Longfellow House. We will illustrate the technique in the instance of the handrail. Although basically sound, the railings were in need of attention to smooth the surfaces.

Repair criteria

Patching with epoxy patching compounds was the method chosen to preserve historic fabric.

Preservation treatment

The handrail was removed from the balustrade and the paint stripped with the aid of heat. Some of the surface irregularities were slightly enlarged to give larger and more regular surfaces for adhesion of the epoxy filler (figure 20). More regular voids are easier to completely fill with semi-rigid patching compound No. 1. The material was forced into the hole with care taken to prevent trapping air behind the filler (figure 21). Obviously, a maximum contact area between the patch and old wood is desired. The workability of the dried filler is illustrated well by figure 22. The patching compound is flexible and easily chiselled or planed because of the inclusion of the spherical, non-bonded microballoons in the epoxy formulation.

It must be emphasized that in finishing woodwork that is to be exposed to the weather, care must be exercised in removing all excess patching compound from the surface. This is to prevent water from becoming trapped under the patch. Figure 23 shows a schematic section of the handrail illustrating the correct surface preparation for repainting.

Critique of treatment

Correct removal of excess epoxy material on the surface must be strongly stressed. Painting to prevent ultraviolet degradation must be done.

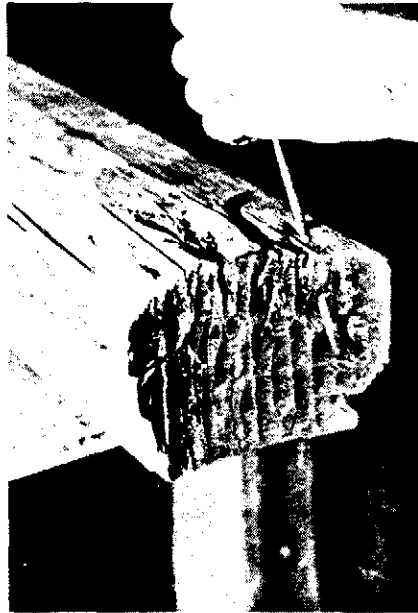


Figure 20. Longfellow House, Porch Handrail. Soft wood was removed from surface and cracks. Very narrow cracks were slightly enlarged to make filling with patching compound easier and to provide more area for bonding the patch. (Photo: Author)

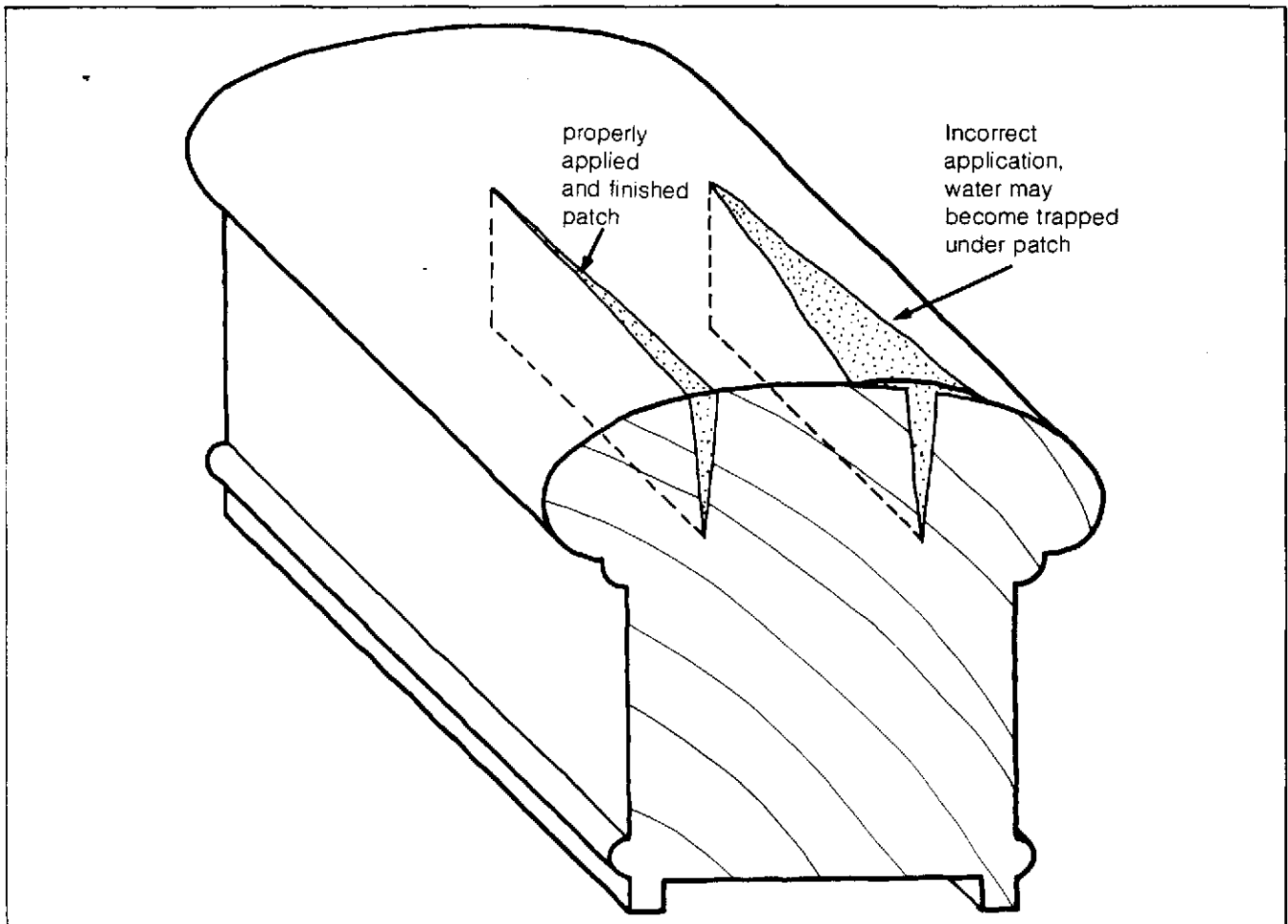


Figure 21. Longfellow House, Porch Handrail. Semi-rigid patching compound No. 1 was used to fill the cracks. A putty knife was employed to force the material into the openings.



Figure 22. Longfellow House, Porch Hand-rail. The epoxy patching compound is easily planed as well as sanded. (Photo: Author)

Figure 23. Longfellow House, Porch Hand-rail. Filler on the surface must be thoroughly removed before painting to prevent water from becoming trapped below the patch.



**LONGFELLOW HOUSE, REPAIR
OF COLUMN CAPITAL****Existing conditions**

Several of the wooden column capitals from the Longfellow House piazzas had rotted due to the action of water. These capitals were, in fact, split into several sections. In some cases small pieces were missing.

Repair criteria

Epoxy repair was the preferred route based on both economic and preservation criteria.

Preservation treatment

The repair in this instance made use of not only an epoxy patching compound and an epoxy adhesive, but also strong consolidant No. 1. Each section was strengthened by applying the consolidant to the porous inner surface as shown in figure 24. The wood was too weak to allow paint removal prior to consolidation. This is a good example of a nonstructural application of the epoxy consolidant. The pieces of the capital were reassembled using the two part epoxy adhesive, Allied Resin E 152. The checks between the sections on the surface of the capital were then filled with the semi-rigid patching compound No. 1. The surface was sanded in preparation for painting.

Critique of treatment

This repair shows how the consolidant may be used to prepare trim elements for further piecing and patching resulting in the maintenance of original building fabric while effecting significant cost savings.

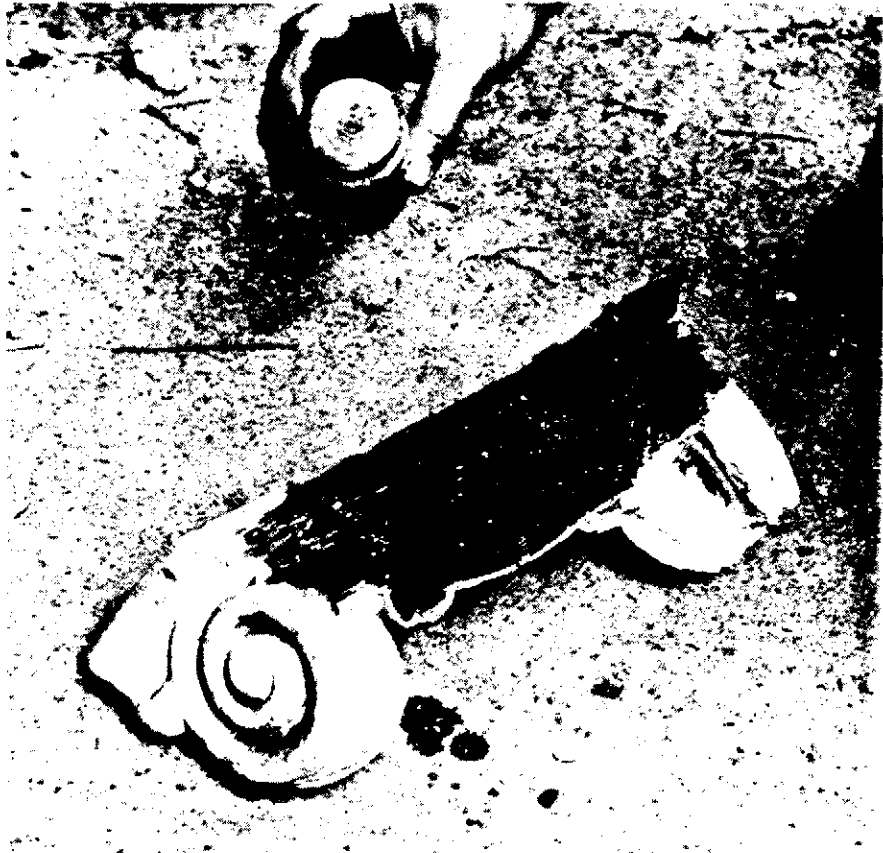


Figure 24. Longfellow House, Column Capital. Each part of a capital from the porch columns was treated with strong consolidant No. 1 along the inner surface. A squeeze bottle was used to apply the epoxy. The paint was left on the outer surface as it prevented the consolidant from running out at the other side. (Photo: Author)

HYDE SCHOOL, WOOD TRIM**Existing conditions**

Figure 25 shows a portion of the interior carved wood cornice from the Hyde Mansion in Bath, Maine. This building, an elaborate Georgian Colonial Revival home built in 1910, designed by John Calvin Stevens, is now the main administration building for the Hyde School. A fire in 1975 extensively damaged wood panelling, trim, and decorative plasterwork. Small sections of the elaborate cornice molding shown in figure 25 had lost detail. Carved brackets suffered similar loss of detail. Voids in door and window sills required filling.

Repair criteria

Epoxy repair was quicker and more economical because most of the damaged material was ornate and hand-carved. Sills and casings can be repaired more rapidly by patching than by cutting new wood to fill voids and then gluing in place.

Preservation treatment

Areas mentioned were carefully filled with semi-rigid patching compound No. 1. Care was taken to follow the hole size and filling guidelines specified in the section on "New Materials, Preparation and Application" of the patching compound.

Critique of treatment

Craftsmen were uniformly well-pleased with the workability of the cured epoxy. Figure 25 shows the material being worked to recreate the proper cornice profile. A filled hole is being chiseled level in figure 26. Window sills were readily filled with patching compound faster and at a lower cost than would be possible in the case of replacement. Since skilled craftsmen able to fabricate and carve various trims are rare and expensive, the value of this restoration procedure is great.



Figure 25. Hyde School, Wood Trim. An elaborately carved cornice had lost detail in a fire. Epoxy patching compound was applied in areas where wood was lost. An electric hand grinding tool was used to restore detail. (Photo: Author)



Figure 26. Hyde School, Wood Trim. Patching compound was used to fill a hole in a door casing. It was chiseled level after it set. (Photo: Author)

The preparation of two epoxy consolidants and an epoxy patching compound for wood have been detailed. Instructions for application of these materials have been provided. A study of these sections, coupled with the case study examples, is intended to provide the craftsman, conservator, or historic property administrator with a relatively complete working knowledge of the newly developed wood conservation techniques.

Criteria for application of these epoxy methods stress the convenience as well

as economic advantages of epoxy technique for retaining massive, historically significant original building timber as well as ornate trim. No special skills or equipment are required to repeat these procedures.

It must be stressed that these techniques are new. Other applications of the materials are still being documented. It is hoped that interested craftsmen who try these techniques will share their knowledge and experience so that epoxy wood repair will become a more standard and widely applied conservation technique.

Testing and research aimed at determining the long range durability of these materials is only beginning. Indeed, the repairs described in this paper represent a field test of these ma-

terials. The virtues and drawbacks of the materials still need further elucidation. This will only be possible after we can evaluate many epoxy repairs.

At present the chemicals necessary for making the materials are not widely available for purchase in small quantities. Certainly, as this technology becomes more widely applied this situation should be eased. Possibly, in the future, these or improved products suitable for wood repair will be available prepackaged.

Finally, comments and feedback on these techniques and materials are welcomed.

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This handy guide to product selection gives data in comparative tables on resins, modifiers, and hardeners made by U.S. manufacturers.

Gaylord, Norman G., ed. *High Polymers*. Vol. 13, part 3. Polyalkylene Sulfides and Other Polythioethers. New York: Wiley-Interscience, 1962.

This is a key book on polysulfide rubbers and their use as modifiers for epoxies.

Lee, Henry, and Neville, Kris. *Handbook of Epoxy Resins*. Rev. ed. New York: McGraw-Hill, 1967.

This is an outstanding text and handbook on epoxies.

Potter, W. G. *Epoxide Resins*. New York: Springer-Verlag, 1973.

Less detailed than the *Handbook of Epoxy Resins*, this book is valuable for its clarity and compactness.

Secondary Books

American Concrete Institute. *Epoxies with Concrete*. Detroit: American Concrete Institute, 1968.

Available as publication SP-21 from the ACI, P.O. Box 4754, Redford Station, Detroit, MI 48219. These symposium papers discuss flexible epoxy systems used in bonding new concrete to old and for patching old concrete, especially as in highway repair.

Cook, John P. *Construction Sealants and Adhesives*. New York: Wiley-Interscience, 1970.

Useful for its discussions of epoxies and polysulfides, and of design problems in filling spaces with polymeric materials.

Feller, Robert L.; Stolor, Nathan; and Jones, Elizabeth H. *On Picture Varnishes and Their Solvents*. Rev. ed. Cleveland and London: Press of Case Western Reserve University, 1971.

This work gives concise instruction in the basic chemistry of organic materials used in conservation, as well as detailed information on thermoplastic acrylic resins useful in wood consolidation.

Houwink, R., and Salomon, G. *Adhesion and Adhesives*. Vol. 1. 2nd. ed., rev. Amsterdam, London, and New York: Elsevier Publishing Co., 1965.

This excellent book discusses theories of adhesion and basic types of adhesives. Applications are treated in volume 2, Epoxies are one of the adhesive systems discussed.

Madison, Willard H., ed. *Epoxy Resins in Coatings*. Federation Series on Paint Technology. Unit 20. Philadelphia: Federation of So-

cieties for Coatings Technology, 1972.

A brief discussion of epoxies. Other units in the series treat other polymers of possible use in wood consolidation.

Stambolov, Todor, and van Asperen de Boer, J.R.J. *The Deterioration and Conservation of Porous Building Materials in Monuments, a Literature Review*. Rome: International Center for the Study of the Preservation and the Restoration of Cultural Property, 1972.

Pages 53-55 in this reference give a good outline of literature discussing impregnation of porous materials with polymers.

Articles and Abstracts

Boenig, H.V. "Polyesters, Unsaturated." *Kirk-Othmer Encyclopedia of Chemical Technology*. Vol. 11. 2nd ed. New York: Interscience Publishers, 1963, pp. 129-168.

This is a good outline of polyester chemistry and technology.

International Institute for Conservation. *Art and Archaeology Technical Abstracts*. New York and London: New York University and the International Institute for Conservation, published semi-annually.

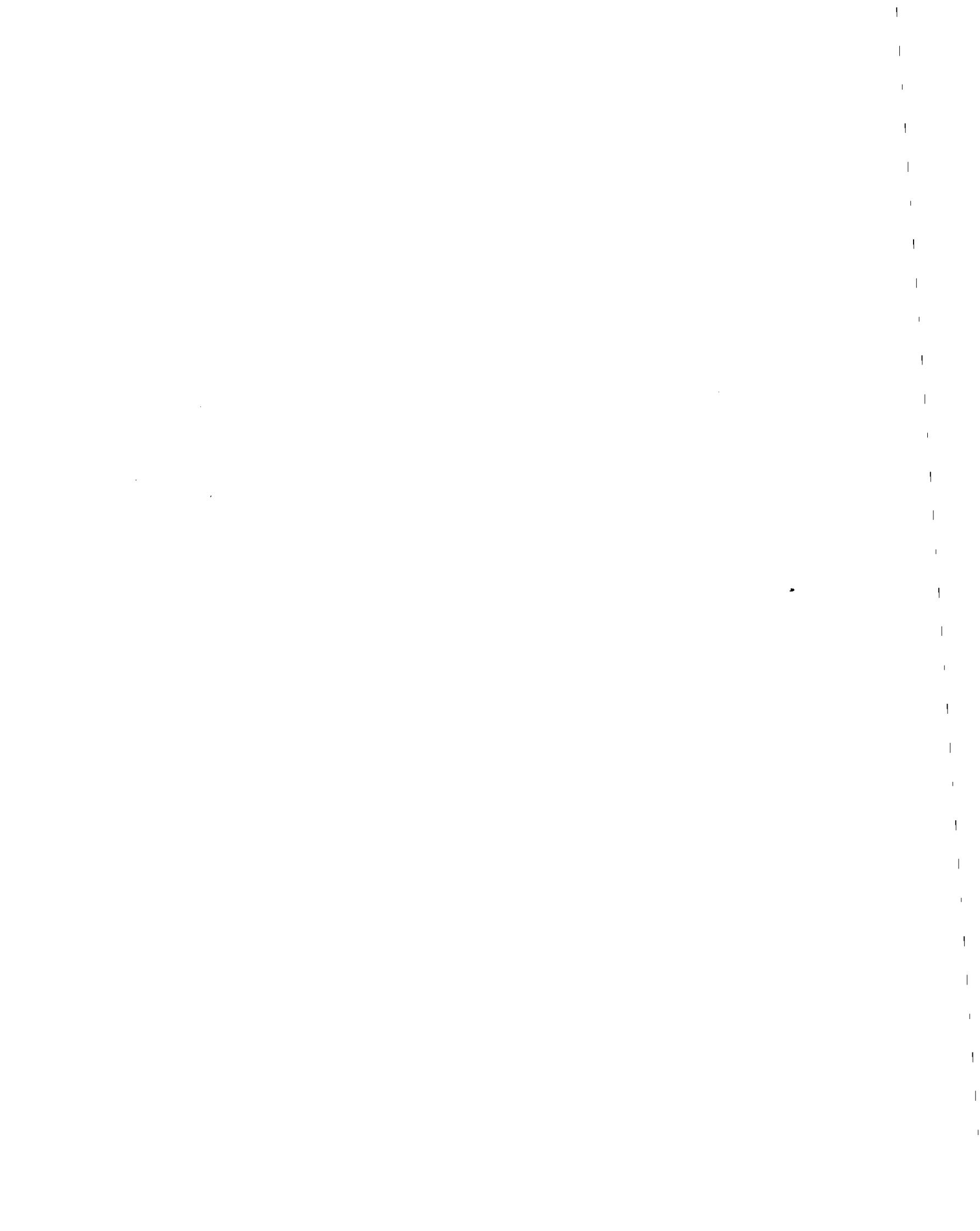
Abstracts of numerous articles on wood consolidation in many countries are found here.

Luoma, Eino J. "Syntactic Foam." *Modern Plastics Encyclopedia* 50. New York: McGraw Hill, 1973-1974, p. 146.

A brief discussion of several types of microballoons used as fillers with various resins.

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- This article, and the others listed below by Munnikendam, Schaffer, and Packard, give a good sense of the state of the art of consolidation procedures used for stone and wooden art objects.
- Munnikendam, R. A. "Preliminary Notes on the Consolidation of Porous Building Materials by Impregnation with Monomers." *Studies in Conservation* 12, no. 4 (Nov. 1967): 158-161.
- . "Low Molecular Weight Epoxy Resins for the Consolidation of Decayed Wooden Objects." *Studies in Conservation* 17, no. 4 (Nov. 1972): 202-204.
- . "A New System for the Consolidation of Fragile Stone." *Studies in Conservation* 18, no. 2 (May 1973): 95-97.
- . "The Conservation of Water-logged Wood with Glycol Methacrylate." *Studies in Conservation* 18, no. 2 (May 1973): 97-99.
- . "The Combination of Low Viscosity Epoxy Resins and Silicones for the Consolidation of Stone." In *The Treatment of Stone*. Edited by R. Rossi-Manaresi and G. Torracca. Proceedings of the Meeting of the Joint Committee for the Conservation of Stone, Bologna, Oct. 1-3, 1971 (ICOM, ICOMOS, International Center for Conservation—Working Group on the Treatment of Stone), pp. 197-200. Bologna, Centro per la Conservazione delle Sculture all'aperto, 1972.
- . "Acrylic Monomer Systems for Stone Impregnation." In *1970 New York Conference on Conservation of Stone and Wooden Objects*, 1: 15-18. 2nd ed. London: International Institute for Conservation, 1971.
- Packard, Elisabeth. "Consolidation of Decayed Wooden Sculpture." In *1970 New York Conference on Conservation of Stone and Wooden Objects*, 2: 13-22. 2nd ed. London: International Institute for Conservation, 1971.
- Plueddemann, Edwin P. "Catalytic Effects in Bonding Thermosetting Resins to Silane-Treated Fillers." *Advances in Chemistry Series*, no. 134, pp. 86-94. Washington, D.C.: American Chemical Society.
- Prudon, Theodore H. "Wooden Structural Members: Some Recent European Preservation Methods." *Bulletin of the Association for Preservation Technology* 7, no. 1 (1975): 5-11.
- This article describes current European uses of epoxy mortars to replace rotted wood in structural applications.
- Schaffer, Erika. "Consolidation of Softwood Artifacts." *Studies in Conservation* 16, no. 3 (Aug. 1971): 110-113.
- . "Consolidation of Painted Wooden Artifacts." *Studies in Conservation* 19, no. 4 (Nov. 1974): 212-221.
- Stumes, Paul. "The Application of Epoxy Resins for the Restoration of Historic Structures." *Bulletin of the Association for Preservation Technology*. Vol. 3, no. 1 (1971): 59-63.
- This article describes the use of epoxies in Canada as consolidants for historic architectural woodwork.
- . "Testing the Efficiency of Wood Epoxy Reinforcement Systems." *Bulletin of the Association for Preservation Technology*. Vol. 7, no. 3 (1975): 2-35.
- This article outlines the findings of a pioneering test program on the use of epoxies for structural reinforcement of beams in old buildings.
- U.S. Patent 3,389,037; June 18, 1968.
- This patent describes Git Rot, an epoxy consolidant mentioned repeatedly in the conservation literature. The patent indicates that Git Rot consists of a blend of materials discussed in the present paper.
- U.S. Patent 3,637,591;
- This patent describes Monsanto Mod-Epoxy (triphenyl phosphite), a common accelerator for epoxy systems.
- Werner, A. E. "The Conservation of Leather, Wood, Bone and Ivory, and Archival Materials." In *The Conservation of Cultural Property*, pp. 268-271. Paris: UNESCO, 1968.



Appendix

Manufacturers of Materials Discussed in this Study

Prepared by Morgan W. Phillips

ARCO Chemical Company, Division of
Atlantic Richfield Co., ARCO Ra-
diation Process Center, P. O. Box
115, Karthaus, Pennsylvania
16845.

B. F. Goodrich Chemical Company,
6100 Oak Tree Boulevard, Cleve-
land, Ohio 44131.

Cabot Corporation, 125 High Street,
Boston, Massachusetts 02110

CDI Dispersions, 27 Haynes Avenue,
Newark, New Jersey 07114. Sup-
pliers of dispersed color
pigments.

Ciba-Geigy Corporation, Ardsley, New
York 10502.

Daniel Products Company, 400 Clare-
mont Avenue, Jersey City, New
Jersey 07304. Suppliers of dis-
persed color pigments.

Dow Chemical Company, Midland,
Michigan 48640.

Dow Corning Corporation, Midland,
Michigan 48640. See especially
brochure on "Silane Coupling
Agents."

DuPont Company, Plastics Depart-
ment, Polymer Products Division,
Wilmington, Delaware 19898. See
brochure on "Methacrylated
Wood."

Emerson and Cuming, Inc., Canton,
Massachusetts 02021.

General Mills, Inc., Chemical Division,
4620 W. 77th Street, Minneapolis,
Minnesota 55435.

Jefferson Chemical Company, 3336
Richmond Avenue, P. O. Box
53300, Houston, Texas 77052.

Monsanto Industrial Chemical Co., 800
N. Lindbergh Boulevard, St. Louis,
Missouri 63166.

Shell Chemical Company, Polymers
Division, One Shell Plaza, Hous-
ton, Texas 77002.

Thiokol Corporation, Chemical Division,
930 Lower Ferry Road, P. O. Box
1296, Trenton, New Jersey 08607.

Union Carbide Corporation, 270 Park
Avenue, New York, New York
10017.

Wilmington Chemical Corporation, P. O.
Box 66, Wilmington, Delaware
19899.

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