

Some Experiences with Flexible Gap-Filling Adhesives for the Conservation of Wood Objects

Donald C. Williams

Abstract

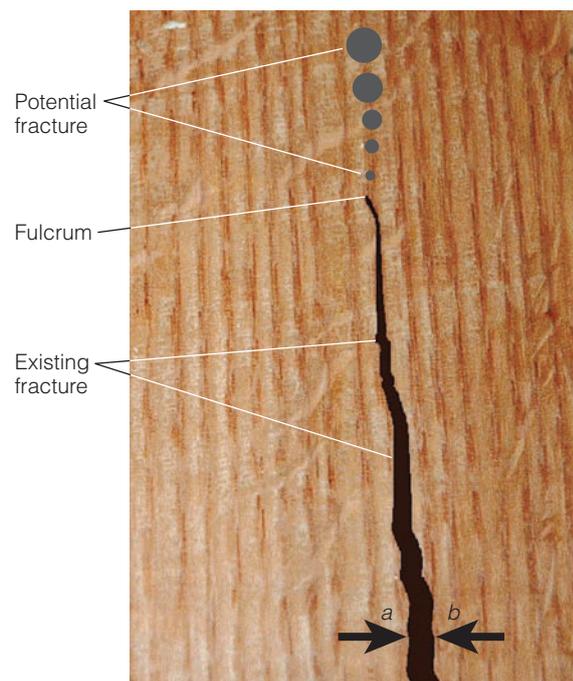
The functional requirements of gap-filling adhesives for use in the structural conservation of panel paintings impose considerable constraints on the choice of materials for this purpose. Some degree of flexibility in the adhesive is considered an important material characteristic. The paper presents an evaluation, based on accumulated personal experience from the practice of furniture conservation, of the properties and performance of a range of adhesive systems for gap-filling applications. Adhesive types considered include natural and synthetic water-based materials: animal-hide glue and acrylic and polyvinyl acetate polymer emulsion products—the latter group comprising both regular white PVA glues and aliphatic resin glues (yellow carpenter’s glues), which have improved water resistance and setting properties. Other adhesive systems evaluated include hot melt products, such as ethylene vinyl acetate (EVA) and multiple-component reactive systems of several types: rigid epoxies, flexible epoxies, and room temperature vulcanization (RTV) silicones. The use of isolating layers, to aid reversibility or to prevent penetration of the gap-filling adhesive into the porous structure of the wood, is discussed in connection with specific adhesive types.

Introduction

At the first Getty symposium on panel paintings conservation in 1995, I surveyed adhesives commonly employed within conservation for the treatment of wooden objects (Williams 1998). In that discussion, a distinction was made between “simple” fractures in the wood (which require only the introduction of an appropriate adhesive into the disjoin, alignment of the gluing surfaces, and application of moderate compression to achieve a successful repair) and “complex” fractures that presented greater technical challenges to the conservator. Complex fractures were defined to include those in which the gluing surfaces are distorted or involve a void or gap, for example, because of shrinkage or damage to the wood adjacent to the fracture. Joining of complex, open (gapped) fractures is usually achieved by adhering a (shaped) wood fillet into the gap or by filling the gap with a bodied, low-shrinkage adhesive, or sometimes by a combination of these approaches. The functional requirements of gap-filling adhesives impose considerable constraints on the choice of materials for this purpose (Grattan and Barclay 1988; Young et al. 2002; see also Christina Young, Britta New, and Ray Marchant, “Experimental Evaluation of Adhesive-Filler Combinations for Joining Panel Paintings,” in this volume).

In the reintegration of damaged wood panels, especially when the void is of a significant dimension, the adhesive must serve not only to “stick” the disjointed parts together, often while occupying more space than might be optimal for purely adhesive functions, but also to provide a sound base for subsequent visual reintegration (i.e., restoration). Successful repair or reassembly of sometimes delicate and deteriorated artifacts requires special consideration of the characteristics of adhesives, particularly from the points of view of flexibility, stability, deterioration, reversibility, and/or retreatability. Furthermore, the process of reintegration must not increase stresses inherent in the system nor introduce new stresses. For example, in a tapered crack such as that illustrated in figure 1, the two sides of the terminus of the crack might be in intimate contact, but at the other end, there could be an opening of 10 or 20 mm. Any attempt to pull the larger open end of the crack into proximity (i.e., bringing points *a* and *b* together) is almost certain to translate into a levered fracture on the far side of the terminus/fulcrum, creating new and potentially catastrophic damage. In such instances, it is not solely adhesive reintegration that is really called for; rather, what is needed is a well-adhering, flexible fill material. Wood preservation specialists have observed countless examples in which an inappropriate fill has actually compounded the damage it was employed to alleviate. When stresses occur, often something has to give; preferably, this should be either the adhesive or the adhesive-substrate interface and not the fabric of the artifact itself. If a hard, stiff fill or adhesive material is used and humidity fluctuations generate stress beyond the elastic capacity of the wood, and if the hardness or dimensions of the fill are enough to exert adequate stress on the substrate, the wood fibers may be crushed or split by the hard, comparatively rheologically inert fill. To ensure that the fill/adhesive material itself does not inflict further damage to the artifact, it is therefore preferable to select a gap-filling adhesive that is more flexible than the wood, softer than the wood, or more inclined to fail along the adhesive-adherend interface (Young et al. 2002).

Figure 1
Tapered open crack. If the fracture is closed at points *a* and *b*, it is likely that the stress will be transferred beyond the terminus, and a new fracture may open opposite the earlier void. Image: Courtesy of the Museum Conservation Institute, Smithsonian Institution.



Adhesives for the Conservation of Fractured Wood Panels

The general scope of adhesives for conservation of wooden artifacts has been presented elsewhere, and those fields need not be replowed here (Williams 1998). Instead, let us focus on the role of flexible gap-filling adhesives in the conservation of fractured wood panels. Reviewing the properties and uses of adhesives for wood conservation falls within the larger question of the goals and strategies for any particular conservation treatment. A structured problem-solving framework is an extremely useful and effective tool for determining an efficient, sequential path of activities. Over the course of the past two decades of my own practice, I have developed a model in which, in essence, any question of artifact care—including selection of materials and methods for joining wood—can be resolved by weighing three competing pairs of considerations:

1. the nature and needs of the object versus the nature and needs of the user;
2. the “perfect” desired outcome versus the limits of technology (and reality);
3. the desire for ethical treatments versus resource limitations.

Given the variable nature of objects and their condition, of users, and of situations, it is possible—likely, even—that for any conservation problem there exist a number of valid, viable treatment options and materials—rather than there being a single “ideal” treatment path. To take an example from furniture conservation, consider two identical historic chairs: one serves purely for display in a gallery and merely need support its own weight, and yet an identical chair serves a utilitarian function and thus must support not only its own weight but that of an occupant as well. In these two examples, it is probable that dramatically different approaches to conservation would be considered acceptable, since they would necessarily take into account the different functions of the objects.

The ideal adhesive for conservation gluing is one that would be perfectly stable over time, be easily applied and manipulated, be readily removable if further treatment were later required, and be able to form an adhesive bond strong enough to allow the object to fulfill its function yet weak enough to be the sacrificial boundary in case of applied stress. Obviously, no single material fulfills all of these requirements, and thus there is no ideal wood conservation adhesive. Instead, the conservator uses a range of adhesives with generally known characteristics.

When a gap filler is applied to any cavity within wooden artifacts, an isolating barrier coating on the surface of the void is almost always used. This is done in order to insulate the original material from penetration or contamination, provide greater latitude in the choices of new materials introduced into the artifact, and supply a margin at which removal of the new material can be safely accomplished, if necessary. If the proper barrier coating is chosen, a thermosetting filling material can be employed.

The choices for a material to perform simultaneously as an adhesive and as a suitably flexible gap-filling material for fractured wood are fairly well defined, and what follows is a summary of the theoretical and practical benefits and drawbacks of several options, from an experiential point of view:

1. hot animal-hide glue without isolating layer
2. synthetic emulsion adhesive (polyvinyl acetate, PVA) with Paraloid B-72 isolating layer
3. rigid reactive (epoxy) with hide glue isolating layer
4. flexible reactive (epoxy) with hide glue isolating layer
5. flexible reactive (room temperature vulcanization silicone, or RTV silicone) with paste wax isolating layer
6. phase change (molten ethylene vinyl acetate, EVA) with hydroxypropylmethyl cellulose (HPMC), or similar, isolating layer

Hide Glue

For generations, the reflexive default for adhesive selection for wood repair has been hot animal-hide glue. Its beneficial properties are manifold: it is nontoxic; it can be modified for almost any set of working properties desired; it is extremely strong; it is stable under reasonable environmental conditions (intact glue lines of several centuries' duration are not uncommon); and it is easily reversible. Details of the production of glues and of their preparation, manipulation, and use are widely available elsewhere (De Beukelaer, Powell, and Bahlmann 1930; Fernbach 1907; Rose and von Endt 1984).

Hide glue comes in a variety of numbered grades, based on the molecular weight of the protein chains composing the gelatin matrix; the higher the grade number, the higher the average molecular weight. Longer protein chains (higher "gram strength" grades) absorb significantly more water per given mass than do those of shorter length (lower gram strength). Accordingly, shrinkage on drying is greater for higher gram strength grades. When fully dry, most hide glues used by wood artisans form an extremely hard material. This hardness renders the glue resistant to creep, but if it is thick enough, it may become very brittle, especially at low moisture contents. The flexibility of a dried glue mass depends upon the molecular weight—i.e., upon the grade. Lower grades remain more pliable when dry than do the higher grades, and the latter are very susceptible to fracture when the glue deposit exceeds ~1 mm.

Hide glue is easily plasticized, most commonly with glycerine at a ~10:1 w/w ratio of dried glue granules to glycerine. Glycerine is an efficient and inexpensive means of accomplishing the goal, and it actually enhances the specific adhesion—the "stickiness"—of the glue. Unfortunately, the migration and slight volatility of glycerine eventually render the glue line hard and brittle. Another excellent option is to incorporate, as a plasticizer, low-molecular-weight polyvinyl alcohol, rather than glycerine, into the aqueous glue solution.

The hardening of the hot animal-hide glue from the wet state is a two-step process: initial gelation on cooling, followed by loss of solvent (water). However, as with all solvent-release processes, the glue mass will shrink during drying in an amount equal to the solvent-loss volume. This shrinkage behavior effectively renders hot animal-hide glue, used alone without any additives, an unacceptable gap-filling adhesive for treatment of splits with voids in wood panels. To compensate partially for this volume loss, hide glue can be bulked with a variety of inert materials. Even then, I do not usually find the performance adequate to the task of gap filling, as the resulting material may still be too brittle, hard, or powdery.

Another shortcoming of hide glue as a gap-filling adhesive is its hygroscopic nature: its stability and properties vary significantly in rela-

tion to changes in environmental moisture. Desiccation may lead to the glue becoming extremely brittle and prone to fracture, even with very little applied strain; raised humidity levels may lead to the glue softening and becoming susceptible to plastic deformation.

PVA and Acrylic Emulsions

Today's most widely used general-purpose wood glues are based on aqueous emulsions of polyvinyl acetate or similar formulations (acrylics) commonly known as white glues. Emulsion glues, whether PVA or acrylic, consist of spherical polymer droplets suspended in an aqueous phase with the aid of surfactants. They solidify through the loss of water, which causes the polymer spheres to fuse into a larger continuous mass. These glues are widely available in different forms and for different applications from the major craft adhesives manufacturers, such as the North American brands Elmers and Titebond and the British Evo-Stik Resin W, as well as many others; they are easily obtained, require essentially no preparation, provide a moderate work time and easy cleanup with water, and generally have good shelf and functional lives. As with other glues, the best bond line for emulsion glues is very thin. Due to their thermo-plastic tendencies, they may deform or fracture if the glue line is too thick and if the stresses are sufficiently great.

In some PVA emulsion glues, sometimes called aliphatic resin glue or yellow carpenter's glue (e.g., Titebond II Premium Wood Glue, Elmers Carpenter's Wood Glue Max), the formulations are modified to promote cross-linking, increase viscosity, and confer water resistance. They are primarily beneficial as waterproof products suited to exterior use and quicker set times—in some cases, minutes versus hours. The two types of PVA adhesives have different grip characteristics before initial set, with "white" PVAs generally exhibiting more slip during assembly and "yellow" glues having more initial grip. The greater viscosity of yellow glues leads to their use as gap-filling adhesives. One widespread practice in the restoration trade is to mix PVA emulsion, whether white or yellow, with wood flour to create a filling putty.

My observations suggest that emulsion glues shrink more than is commonly acknowledged. In addition, fully cured PVA emulsion masses are considerably harder than low-density wood. These glues remain, to a low degree, soluble and reversible (depending on the degree of intercellular penetration). White glues can usually be softened with a water-surfactant solution and are generally removable with a variety of organic solvents. Yellow glues usually require an organic solvent to soften and swell them, but they are generally considered to be partially reversible.

In many respects, acrylic emulsion adhesives (Rhoplex/Primal grades, Jade 403N) are much like PVA emulsions in appearance, use, and drying process. The advantage of acrylic emulsions is that they can be obtained in a wider variety of formulations with specific properties, including mechanical properties and solubility characteristics of the dried film.

Multiple-Component Reactive Adhesives

Classes of adhesives in this category include urea-formaldehyde (e.g., DAP Weldwood Plastic Resin Glue), phenol formaldehyde (DAP Weldwood Marine Resorcinol), epoxy (e.g., West System epoxy),

polyester (most commercial “fiberglass” resins), polyurethane (Gorilla Glue is the most widely known commercial product), and other formulations. Multicomponent adhesives possess great strength in a wide variety of circumstances. They can be less susceptible to thermal, physical, or chemically induced failure. Because of their mechanism for hardening, epoxies show negligible shrinkage, while urea formulations shrink only very slightly. As such, these adhesives may be good gap fillers, especially when modified with bulking agents. Despite these qualities, the use of these polymers as conservation adhesives is not widely accepted in wood conservation circles because of their intractable, irreversible nature (Rivers and Umney 2003, 159–60, 442; Williams 1998). Some of these cross-linked network polymers can be swelled with solvents, but usually they must be removed mechanically, potentially causing severe damage to the substrate or to adjacent surfaces. In addition, while strong and robust when relatively new, they may begin to break down in a short period of time (a few years), especially when exposed to strong light. My experience indicates that if they are protected from light exposure or modified with light-blocking additives, they can last for many decades.

Rigid Epoxy

Epoxy systems have the benefit of being readily available and moderately priced for even high-performance applications. When first prepared, most rigid epoxies are relatively low-viscosity, easily absorbed liquids that cross-link and harden in place. In my experience, the most common epoxy resin used by American conservators for wood conservation is the West System epoxy (Gougeon Brothers Inc.). As a practical matter, products of this type are irreversible once they have penetrated into a porous substrate via wicking, which is a common occurrence with this type of adhesive. The wicking problem is preventable by the application of an easily reversible barrier coating to the wood substrate, allowing for reasonably nondamaging removal of the cured adhesive/fill. Furthermore, rigid epoxies are much harder than wood, and if they are used as gap-filling components, they are bound to eventually exacerbate any fractures. Even bulked carvable epoxy demonstrates this tendency. These and other functionally related systems are adequate—but generally not flexible—gap-filling adhesives used widely in the lower, less-sophisticated rungs of the furniture restoration ladder, where cross-linked polyester auto body filler is also used sometimes as a fill for fractures. Over time, the result is more widespread damage. Better overall results should be possible with the addition of lightweight bulking agents, such as glass or phenolic microballoons or fumed silica, but that does not necessarily overcome the hardness or brittleness inherent in fully cured thermoset formulations. Bulked formulations tend to have an exceedingly high viscosity and are not particularly useful as regular adhesives; they are, rather, useful solely as gap fillers.

Flexible Epoxy

One new material with growing impact in many industrial applications is formulated “flexible” epoxy. Provided the flexibility remains integral to the formulation over a long working life span, this material seems an excellent option for flexible gap-filling applications in conservation, under the right conditions of use.

Figure 2

Delivery of the viscous flexible epoxy. Injection of this epoxy requires a robust delivery system, in this case an equine syringe without needle. Photo: Courtesy of the Museum Conservation Institute, Smithsonian Institution.



The flexible epoxy product I have employed is Marine-Tex FlexSet, intended, as the name suggests, for the boat building and repair market. This product has a much higher initial viscosity than regular (liquid) rigid epoxy, and it works more like a flowing putty than a wicking liquid. In order to use this gap filler, it must be forced into the void rather than allowed to flow into it. To introduce flexible epoxy into the void, an equine or spinal-tap syringe works well to force the viscous liquid into the cavity (fig. 2). An excess of the filler material can be applied initially and the excess removed mechanically, once the flexible epoxy has started to cure. At the appropriate time (typically after about two hours), when the epoxy is firm but not yet fully stiff, the excess material can be shaved off; I use a sharpened ivory blade for this purpose (fig. 3).

As with the previously described use of regular epoxy, the gluing interfaces must be generously coated with hot animal-hide glue or another similar, easily reversible barrier coating to prevent the epoxy from soaking into the wood (Anderson and Podmaniczky 1990).

RTV Silicone Rubber

Simply put, room temperature vulcanization (RTV) silicone rubbers excel as flexible gap fillers for split panels and the like. Products of this type will be familiar to most conservators and include those from Polytek, Dow Corning, Smooth-On, and many other companies. In addition to being flexible and maintaining this property in the long term, RTV silicone conforms absolutely to whatever it contacts, assuring a “perfect fit” (and thus adhesion) for the fill. Used carefully and appropriately, silicones (especially the softer grades of the product) can form a functionally inert, flexible fill with sometimes astonishing tenacity and extensibility.

Figure 3

A sharp-edged tool—the shaped outer sheath of an ivory tusk—used to shave off excess flexible epoxy once the surface tack has gone. Photo: Courtesy of the Museum Conservation Institute, Smithsonian Institution.

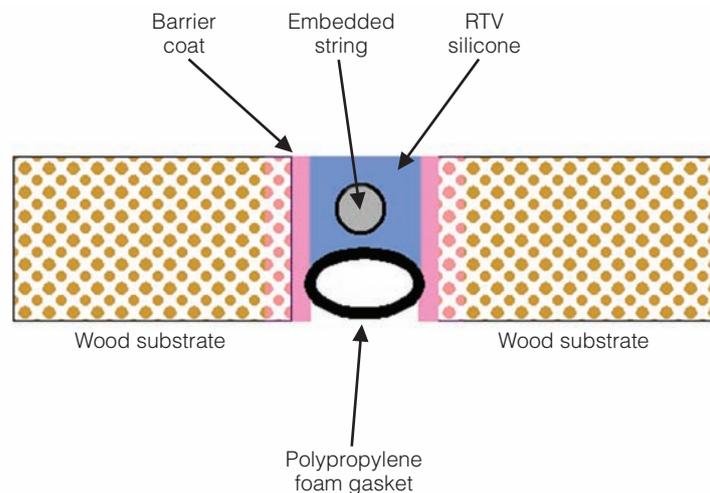


On the negative side, silicones are rightly notorious as sources of contamination, and great care must be used in preparing, handling, and applying them. A generous application of a removable barrier coating of beeswax/paraffin/Stoddard solvent paste to the gluing margins and the adjoining surfaces is a way of circumventing this problem. Also, the “slickness,” or hydrophobicity, of some RTV silicones can make for difficulties with subsequent applications of inpainting materials. This problem can be overcome during the application by pouncing pigment into the surface before the silicone fully cures, or mitigated after the fact by a thin application of shellac in ethanol or propanol prior to inpainting. When fractures with wide voids are addressed, the “problem” of reactive silicone flowing until it cross-links (often measured in hours) is addressed by inserting a semi-rigid gasket/dam, usually polypropylene foam, into the void to dam the silicone, as shown in figure 4.

Another advantage of a cured silicone fill is that it can simply be removed from the void if that becomes necessary for any reason; and while the cured silicone can be gently pulled out of the void like a rubber band, a piece of string embedded in the fill allows this to be done more easily, if necessary.

Figure 4

The gasket/silicone rubber fill system.



Hot Melt Synthetics

Hot melts flow well, do not shrink, and adhere to a wide variety of materials. They can be obtained in a number of different formulations, many of which are easily reversible with heat or organic solvents.

The formulation of these adhesives can be very specific regarding the properties of the adhesive, not only when solid but also when liquid. The temperature to which these adhesives must be heated to flow is well above room temperature in most cases, and since these materials solidify by cooling, their use is limited to the penetration that can be achieved in a brief time.

In the field of conservation, one particular polymeric material, ethylene vinyl acetate (EVA), has long been in use. This stable, archival-quality adhesive is very easy to use and manipulate, and it accepts subsequent solvent-based coatings very well. The two major configurations available are solid rods, which must be used/injected with a heated glue gun, and sheets, which can be used anywhere the gluing surfaces can be heated (BEVA 371 film, Loctite Hysol 1942 hot melt adhesives). Conveniently, however, hot melt adhesive sticks that bear the descriptors “low temperature” and “nontoxic,” and which are almost certainly solid EVA, are commercially available from craft and art stores (fig. 5). I have purchased and used several brands of “nontoxic low temp” and “dual temp” hot melt adhesive sticks. In each case, from a review of the product literature and safety data sheets, it was apparent that the sole or primary ingredient of the formulation was EVA, especially for those hot melt adhesives marketed specifically for assembling dried flower arrangements.

The ease and rapidity of this technique make it a strong favorite for most of my gap-filling adhesive needs. By definition, this method utilizes molten material in the proximity of the artifact, and accordingly, it requires that a heat-resistant but easily reversible isolating layer (methylcellulose) be applied to the adherend surfaces. Using an inexpensive (under \$10) glue gun and glue sticks, the conservator can inject the molten EVA into a void until the deposit is slightly proud of the surface

Figure 5
Hot melt EVA adhesive. Photo: Courtesy
of the Museum Conservation Institute,
Smithsonian Institution.



Figure 6

Hot melt EVA adhesive injected into a void. The gap is filled so that the EVA is slightly proud of the adjacent surface; it is then allowed to cool. Photo: Courtesy of the Museum Conservation Institute, Smithsonian Institution.

*Figure 7*

A void filled with hot melt EVA adhesive after the excess has been shaved off with a sharp-edged tool. Photo: Courtesy of the Museum Conservation Institute, Smithsonian Institution.



(fig. 6). Once the EVA becomes firm, the excess can be shaved off level with the surrounding surface (fig. 7). An alternative way to finish off the glue line could involve wiping the surface with toluene on swabs or felt blocks, in order to create a polished surface. An EVA fill can be easily inpainted after the application of ethanol-, acetone-, or toluene-based solutions as a first sealing coat.

Conclusion

When a wood conservation treatment requiring the use of a flexible gap-filling material is undertaken, it is vital that the artifact be protected and isolated from the added material to the greatest possible extent, and that the newly added fill material mimic the mechanical properties of the adjoining substrate and remain stable over time, retaining these properties. The adhesive/fill system must be safely removable after the fact, if necessary. Attempting a conservation treatment requiring adhesive/fill processes without first understanding every component of these

processes—wood, isolating layer/fill resin, and bulking agents—is a practice fraught with unnecessary risks.

Based on my experience in conserving wooden objects, I rank the options for flexible gap-filling adhesives in my own work as follows:

1. molten EVA
2. flexible epoxy (tentative: this material is promising, but I need more experience to be fully convinced)
3. RTV silicone
4. bulked plasticized animal-hide glue
5. bulked rigid epoxy
6. bulked PVA

This ranking comes from my own experiences, which derive inevitably from working on particular types of objects. Other conservators treating other object types and tackling different conservation problems might view the respective strengths and weaknesses of these materials differently and perhaps even consider different solutions; even so, I offer my experience of these materials in the hope that I might help other practitioners achieve successful outcomes.

Materials and Suppliers

Animal-hide glues, Milligan and Higgins Corp., Maple Avenue P.O. Box 506, Johnstown, NY 12095, USA. www.milligan1868.com.

BEVA 371 film adhesive, available from Conservation Resources, www.conservationresources.com; Talas, www.talasonline.com; Conservation Support Systems, conservationsupportsystems.com.

DAP Weldwood Plastic Resin Glue and DAP Weldwood Marine Resorcinol, www.dap.com.

Elmers white glue, Elmers Carpenter's Wood Glue Max, www.elmers.com.

Evo-Stik Resin W white glue, www.bostik.co.uk/diy/product/evo-stik/Resin-W-Extra-Fast-Interior-Wood-Adhesive/4.

Gorilla Glue, www.gorillaglu.com.

Jade 403N polyvinyl acetate adhesive, available from Conservation Resources, www.conservationresources.com; Talas, www.talasonline.com; Conservation Support Systems, conservationsupportsystems.com.

Loctite Hysol 1942 hot melt adhesive, www.henkeln.com/adhesives/.

Low-temperature hot melt adhesives and guns, available at Michaels craft stores (nationwide chain). www.michaels.com.

Marine-Tex FlexSet, www.marinetex.com/marinetexflexset.html.

Rhoplex/Primal acrylic polymer emulsions, available from most conservation materials suppliers: Conservation Resources, www.conservationresources.com; Talas, www.talasonline.com; Conservation Support Systems, conservationsupportsystems.com; Kremer Pigments, www.kremerpigments.com.

Silicone molding rubbers and casting resins, Polytek Corp., 55 Hilton Street, Easton, PA 18042, USA. www.polytek.com; Smooth-On Corp., 2000 Saint John Street, Easton, PA 18042, USA. www.smoothon.com.

Titebond White Glue, Titebond II Premium Wood Glue, www.titebond.com.

West System epoxy, www.westsystem.com.

A wide range of conservation-related supplies, Museum Services Corp., 385 Bridgepoint Way, South St. Paul, MN 55075, USA. www.museumservicescorporation.com.

References

- Anderson, Mark J., and Michael Sandor Podmaniczky. 1990. Preserving the artifact: Minimally intrusive conservation treatment at the Winterthur Museum. In *American Institute for Conservation Annual Meeting, Richmond, Virginia. Wooden Artifacts Group Specialty Session, June 2 & 3, 1990*, 14. Washington DC: American Institute for Conservation.
- De Beukelaer, Frank L., J. R. Powell, and E. F. Bahlmann. 1930. Standard methods (revised) for determining viscosity and jelly strength of glue. *Industrial and Engineering Chemistry* 2 (3): 348–51.
- Fernbach, R. Livingston. 1907. *Glues and Gelatine: A Practical Treatise on the Methods of Testing and Use*. New York: D. Van Nostrand Co.
- Grattan, David W., and Robert L. Barclay. 1988. A study of gap-fillers for wooden objects. *Studies in Conservation* 33:71–86.
- Rivers, Shayne, and Nick Umney. 2003. *Conservation of Furniture*. Oxford: Butterworth Heinemann.
- Rose, Carolyn L., and David W. von Endt. 1984. *Protein Chemistry for Conservators*. Washington DC: American Institute for Conservation.
- Williams, Donald C. 1998. A survey of adhesives for wood conservation. In *The Structural Conservation of Panel Paintings: Proceedings of a Symposium at the J. Paul Getty Museum, 24–28 April 1995*, ed. Kathleen Dardes and Andrea Rothe, 79–86. Los Angeles: Getty Conservation Institute.
- Young, Christina, Paul Ackroyd, Roger Hibberd, and Stephen Gritt. 2002. The mechanical behaviour of adhesives and gap fillers for re-joining panel paintings. *National Gallery Technical Bulletin* 23:83–96.