Panels in Furniture: Observations and Conservation Issues

Paul van Duin

Abstract

This paper is intended as an introduction to furniture and its conservation issues for professionals dealing with panel paintings. It discusses the construction of oak doors of cabinets in the Netherlands in the sixteenth and seventeenth centuries, and by systematic observation, it explores their relation to damage caused by changes in humidity. In particular, the influence of wooden boards attached cross-grain onto panels is considered. This issue relates to the construction and condition of a poplar panel of the Tabernacolo di Linaioli *by Fra Angelico, created in Florence in 1433. Clearly, cross-grain supports may cause damage when panels shrink, but there is also evidence that when wooden auxiliary supports cover a substantial area of the panel and are well glued, the panel can absorb the tensions that would lead to shrinkage. Further research on old panels is required, to which a collaborative project by the Rijksmuseum, the Instituut Collectie Nederland (ICN), and University of Amsterdam will contribute. The second part of the article is devoted to the conservation treatment of two doors of a cabinet with floral marquetry, dated to 1690, by the Dutch master cabinetmaker Jan van Mekeren. A plea is made for preserving instead of trying to improve original constructions, because their quality should not be underestimated, and the authenticity of panels as well as of furniture is of paramount importance.*

Introduction

This article is an introduction to issues in furniture conservation for professionals dealing with panel paintings. The amazingly well-preserved central panel of the altarpiece by Fra Angelico known as the *Tabernacolo dei Linaioli* (1433), in the Museo San Marco in Florence, was the inspiration for comparing its condition to panels in furniture. By observing and comparing the condition of actual objects, this article attempts to find out more about the movement of wood in response to climate variations and construction. What sort of damage do we find—but also, what has withstood time well? A selection of paneled doors of oak cabinets from the sixteenth and seventeenth centuries in the Netherlands is discussed. To give an insight into the conservation approach and ethical considerations, the second half of this article is devoted to the treatment of two marquetry doors from a cabinet of the late seventeenth century.

Paneled Doors

The construction of panels and furniture starts with the selection of a tree with good-quality timber. After the tree is cut down, wood has to be transported, seasoned well, and dried, and great care must be taken to cut boards from a trunk in such a way that in time they do not deform or warp (Gérard and Glatigny 1997; Piena 2000). The Fra Angelico panel is made of poplar, and the cabinets discussed in this article are constructed of oak. Both woods have excellent properties and were therefore commonly used by craftsmen, poplar being favored in Italy and oak in the Netherlands. Oak came from old forests with slowly grown and straight trees. Because of oak's popularity for furniture as well as for houses and ships, trees from these forests were harvested extensively. The oak used for the cabinets discussed below is so-called quartered oak, with growth rings perpendicular to the surface. The rays, which run from the center of the trunk toward the bark, are clearly visible as shiny spots. Quartered, or radial, oak is therefore not only very durable but also decorative.

In furniture and larger panel paintings such as the *Tabernacolo dei Linaioli*, wooden components are fixed to each other at 90° angles. The purpose is to make stronger constructions and to keep panels in the correct, usually flat, shape. In response to fluctuations in humidity, unrestricted wood moves in radial and tangential directions but moves to only a negligible extent in the longitudinal direction. As a result of lower levels of humidity, wood wants to shrink. If a crossbar or stretcher is attached to a panel, it prevents the wood from shrinking freely. The forces that lead to shrinkage are very large and often cause damage in the form of cracks and/or warping of the panel. One could say that when exposed to lower levels of humidity, the panels may become their own enemies.

This knowledge—mostly passed on orally and a product of the immense experience of the craftsmen who worked with timber—was often underestimated in later centuries when people thought they knew better. A good example of what can go wrong in this respect are the many panels that have been thinned down and cradled and that now exhibit many more problems than panels that were left untreated. We, modern people from the age of technology, can only learn from that by being more considerate and avoiding "improvements" in construction.

Tabernacolo dei Linaioli, 1433

The central panel of the very large *Tabernacolo dei Linaioli* is 289 cm high, 177 cm wide, and 19.5 cm deep (113.8 × 69.7 × 7.7 in.), including the frame, which forms an integral part of the panel (fig. 1). The panel is made entirely of poplar and consists of five vertical boards that run the full height of the central panel. They are 3 cm (1.2 in.) thick and 25–40 cm (9.8–15.7 in.) wide, butt-joined and glued together. Four horizontal boards, also 3 cm (1.2 in.) thick and 33–45 cm (13.0–17.7 in.) wide are firmly attached to the back with glue and wrought iron nails; in this way about 60% of the panel is covered with cross-grain wood. Along the edges, narrower, vertical pieces, as well as triangular blocks, are fixed (fig. 2). At the front of the panel, a heavy 13.5 cm (5.3 in.) thick arched molding is applied with glue and nails. The base of the structure is a wooden plank (3 × 26 × 177 cm; 1.2 × 10.2 × 69.7 in.) that sustains the weight of the whole construction.

The construction is original, apart from the hinges, which have been replaced in the past. There is some evidence of previous conservation: along the cracks, some retouchings have become visible, and the back shows evidence of glue blocks along the cracks and many whitish spots. There is no indication of structural treatments. The damage in the

Figure 1
The central panel of the *Tabernacolo dei Linaioli* by Fra Angelico (Florentine, ca. 1400–1455), 1433. Front and back. Poplar, 289 × 177 × 19.5 cm (113.8 × 69.7 × 7.7 in.) (including frame). Museo San Marco, Florence, inv. 1890 n. 879. Photos: Archivio Photografico, Opificio delle Pietre Dure, Florence.

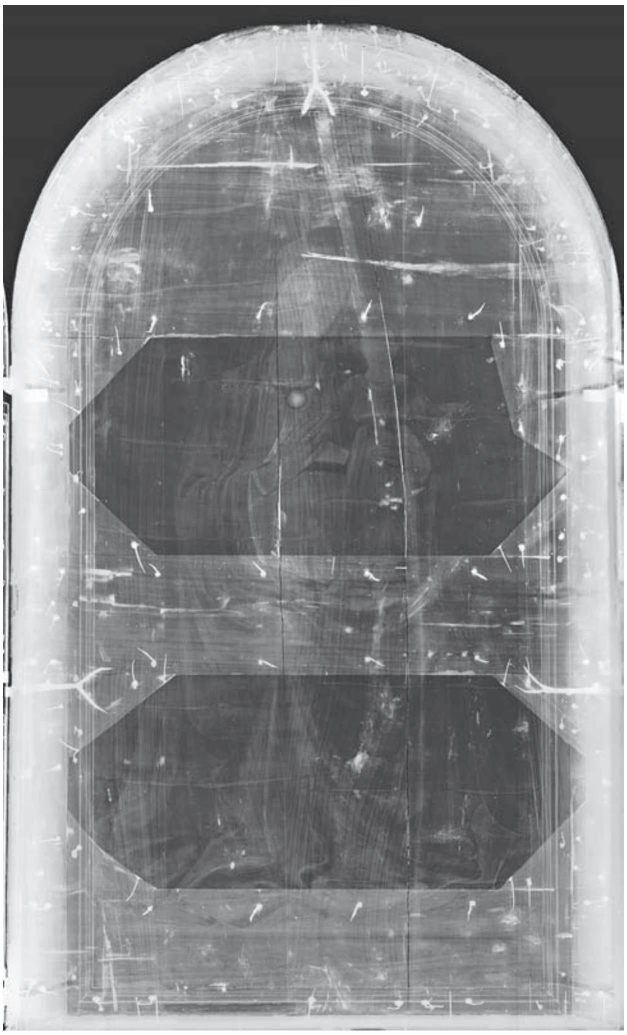

Figure 2
X-ray of the central panel of the *Tabernacolo dei Linaioli*. Image: Archivio Photografico, Opificio delle Pietre Dure, Florence.

form of shrinkage cracks is very limited—two cracks with a maximum total width of 0.4 cm (0.2 in.), equivalent to 0.25% shrinkage, are visible at the back and on the X-ray. They consist of two partly opened butt joints on either side of the middle board; one crack continues within that board. The cracks stop toward the top, where the panel is fully covered with cross-grain stretchers.

Archival Cabinet, 1500–1550

One of the earliest cabinets in the collection of the Rijksmuseum in Amsterdam is an archival cabinet made for the Dom church in Utrecht (Lunsingh Scheurleer 1952). It is very large, 224 cm high, 354 cm wide, and 91 cm deep (88.2 × 139.4 × 35.8 in.), with four doors, and it is entirely made of good-quality quartered oak. The doors are 185 cm high, 83 cm wide, and 5 cm thick (72.8 × 32.7 × 2.0 in.) and consist of three vertical boards, 2.5 cm (1.0 in.) thick and 25–30 cm (9.8–11.8 in.) wide. A framework is applied to the front with wrought iron nails and consists of five 2.5 cm thick and 18.5 cm wide (1.0 × 7.3 in.) horizontal stretchers with vertical stiles on either side and in between (fig. 3). This means that almost 50% of each vertical board is covered with cross-grain bars. The decoration is simple; the framework has carved quatrefoil ornaments around the square recesses.

The doors are stable and have a very slight horizontal warp with 0.5 cm (0.2 in.) deflection. The damage is limited to the joints between the boards, which have opened up by 0.4 cm (0.2 in.), equivalent to almost 1% shrinkage. Also, the miters have opened by about 0.1 cm (0.04 in.). The open joints have been covered in the past with thin strips of plywood, probably to prevent dust from entering the interior. The

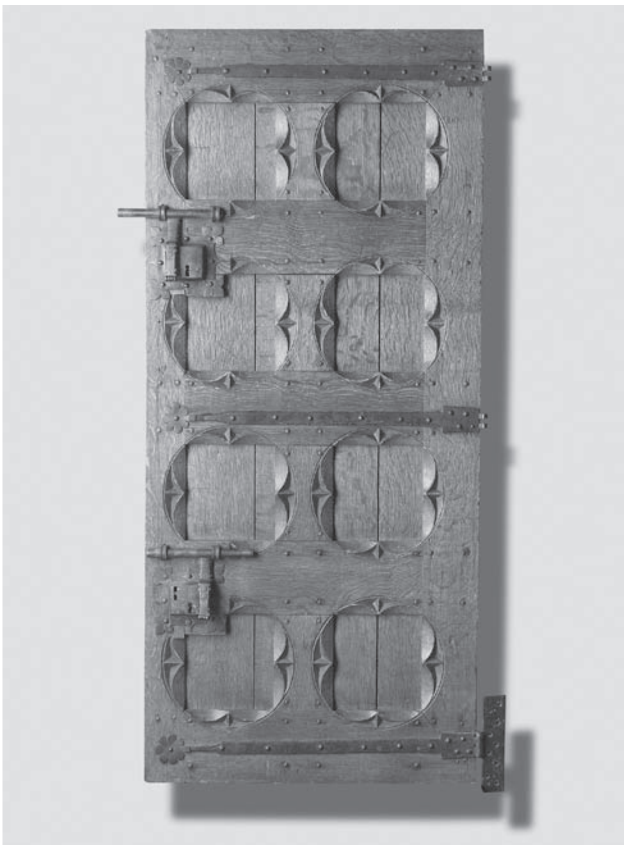

Figure 3
The right door of the archival cabinet made for the Dom church in Utrecht, 1500–1550. Oak, door: 185 × 83 × 5 cm (72.8 × 32.7 × 2.0 in.). Rijksmuseum, Amsterdam, BK-NM-125. Photo: Rijksmuseum, Amsterdam.

open joints are only visible in the recessed areas at the front. They are not disturbing and are not causing further damage. Conservation treatment is therefore not considered necessary.

Cabinet, 1607

Made some hundred years later than the Dom cabinet, this cabinet is 232 cm high, 229 cm wide, and 85 cm deep (91.3 × 90.2 × 33.5 in.) (Baarsen 1993; 2007). The date is part of the ornamentation in the architrave. All woodwork is of high quality and made of quartered oak. The cabinet has two large doors, 175 cm high, 69 and 81 cm wide, and 3.5 cm thick (68.9 × 27.2/31.9 × 1.4 in.) (fig. 4a). In contrast to the doors of the archival cabinet, these doors consist of a frame containing two panels of 70 by 49 cm (27.6 × 19.3 in.). The panels have a beveled edge and are set into a groove. The panels themselves are constructed in a way similar to that of the previous doors; they consist of two 0.9 cm thick and 24 cm wide (0.4 × 9.4 in.) boards onto which thin oak moldings are glued. The boards are tongue-and-groove joined, the joints being exposed along the beveled edges. The moldings are thin and vary from 1.0 to 0.1 cm (0.4–0.04 in.) in thickness and are glued onto the boards, covering 33% of them with cross-grain wood.

The doors are straight, stable, and very well preserved. They show no damage, except for some short cracks, approximately 0.1 cm (0.04 in.) wide, along the edges of the interior of some of the panels. The mitered joints are all firmly closed, but in some cases the vertical moldings have moved slightly inward. As the panels are set into a frame, they can expand and contract more freely, and closer inspection reveals that the panels have shrunk by 0.3 cm (0.1 in.), which is equivalent to 0.6%. This shrinkage is evident along the edge of the panels, where the wood that was previously inside the groove is now exposed and has a slightly darker color. The cabinet has recently received conservation treatment in which the moldings were checked and if (partly) loose were reglued. This was only necessary in a few cases; most moldings were still firmly stuck. In the past, some nails were used to enhance the fixing of moldings and central ornaments. These have not caused further damage and were preserved.

Cabinet, Northern Netherlands, 1650–70

Typical for the mid-seventeenth century is a cabinet with two large doors crowned by carved arches above tall flat panels (Baarsen 1993; 2007). This cabinet is decorated with ebony veneered fields in the architrave, pilasters, and door frames (fig. 4b). The cabinet is 200 cm high, 173 cm wide, and 74 cm deep (78.7 × 68.1 × 29.1 in.); the doors, which are 140 cm high and 55 and 70 cm wide (55.1 × 21.7/27.6 in.), have panels set into a frame. The frame is up to 3 cm (1.2 in.) thick. The doors have large panels, 128.5 cm high and 43 cm wide (50.6 × 16.9 in.), consisting of two boards, 21 cm wide and 0.9 cm thick (8.3 × 0.4 in.). They are tongue-and-groove joined and fit into a rebate of the frame, and they are secured with a beading, possibly of later date. The boards have nearly identical grain patterns, indicating that they were positioned in the trunk next to each other.

The doors are stable and straight. Shrinkage is not apparent at first sight, but darker wood along the edges of the panels shows that they have shrunk up to 0.45 cm (0.2 in.), equivalent to 1%. Apart from


a


b

Figures 4a and 4b
Cabinet doors. The right door of a cabinet, Netherlands, 1607 (a). Oak, 175 × 81 × 3.5 cm (68.9 × 31.9 × 1.4 in.). Rijksmuseum, BK-16071; the right door of a cabinet, Netherlands, 1650–70 (b). Rijksmuseum, Amsterdam, BK-1959-47. Photos: Rijksmuseum, Amsterdam.

a replaced ornament hiding the keyhole, the exterior of the doors is unchanged, but on the inside, previous conservation treatment is evident. Cross-grain stretchers have been slightly recessed and glued onto the boards and frame. The right door has a repaired crack in the top of the right board. Further conservation treatment is not considered since the doors are stable, and although we do not much like the new stretchers, they are not visible to the public, as the cabinet is displayed with closed doors.

Comparison of the Condition of the Panels

It is hypothesized that the good condition of the *Tabernacolo dei Linaioli* and the 1607 door panels is due to the high amount of cross-grain wood that is still firmly glued to the vertical boards. The 1% shrinkage of the doors of the other cabinets is considerably more. The later stretchers applied to the back of the panels of the cabinet dated to 1650–70 have caused no further damage, indicating that the shrinkage had taken place before they were applied. When did this shrinkage take place? This is not easy to answer, as we do not know the conditions in which the cabinets were kept, how often they were moved, and how carefully this was done. The doors with panels set into frames are still straight, whereas the doors consisting of backboards onto which moldings have been applied are slightly warped. This has occurred because the front of the boards was constrained by the horizontal moldings and could not shrink as much as the back of the boards. The construction of the *Tabernacolo* differs in that respect, as it has stretchers on the back as well as the engaged arched frame on the front—meaning that the vertical boards are constrained on two sides. If the assumption that a large percentage of cross-grain applications can help to prevent shrinkage is correct, this will, of course, only work for as long as the glue does not fail.

Conservation of the Van Mekeren Cabinet

The Van Mekeren cabinet is dated by dendrochronology to ca. 1695 and has floral marquetry on the front and sides very much like the popular still lifes that were painted by artists such as Van Huysum, De Heem, and many others in the seventeenth and eighteenth centuries (Baarsen 1993; 2007). The cabinet is constructed of oak and veneered with ebony, kingwood, and indigenous and tropical veneers for the marquetry (fig. 5) (Van Loosdrecht 2002). It is 205 cm high, 173 cm wide, and 61 cm deep (80.7 × 68.1 × 24.0 in.). Jan van Mekeren (1658–1733) became a master cabinetmaker in Amsterdam in 1687 and produced many cabinets and tables in this fashion (Lunsingh Scheurleer 1941). The cabinet conforms to a very popular type of furniture in the Netherlands in the late seventeenth century: a stand supporting a cabinet with flat surfaces between small moldings at the top and bottom. Variation in appearance was achieved by applying different types of decoration: painted surfaces, marquetry of many kinds of veneer, and materials like tortoiseshell, ivory, pewter, Asian and European lacquerwork, and even embroidery. Flat doors appear like panels, but their construction is much more complicated, as they are not contained by a frame. Cabinetmakers experimented

Figure 5
Right door of the Van Mekeren cabinet, Netherlands, ca. 1695. Oak veneered with ebony, kingwood, and marquetry of indigenous and tropical veneers, door: 110 × 80 × 3.5 cm (43.3 × 31.5 × 1.4 in.). Rijksmuseum, Amsterdam, BK-1964-12. The detail on the right shows the condition before conservation. Photos: Rijksmuseum, Amsterdam.

with construction methods to obtain durable flat doors that could be decorated on both sides. To prevent warping, the construction of doors always consists of horizontal and vertical boards. For a flat door, the joints between the boards have to be concealed underneath the decorative material. Cabinetmakers used various construction methods to achieve this (De Vlam 1993; Baarsen and Folkers 1992). Most commonly, cleated ends were used, where cross-grain stretchers are fixed against either end of the vertical boards. The cleats can vary considerably in width. Compared to the panels of the oak cabinets discussed earlier in this article, the surface area of the joints between the vertical boards and the cross-grain wood is much smaller. Often the boards have moved in relation to the cleats, and this movement is shown along their joint. The joints between the vertical boards have opened up because of shrinkage and failure of glue. The gap between the vertical boards is always wider toward the middle of the boards; near the cleats the boards have shrunk less (Van Duin 1993a; 1993b). This implies that to a certain extent they can absorb the forces that lead to shrinkage.

The doors of the Van Mekeren cabinet are 110 cm high, 80 cm wide, and 3.5 cm thick (43.3 × 31.5 × 1.4 in.). They are not constructed with cleated ends but consist of a sandwich construction of two thin oak panels with a frame, stretchers, and glue blocks in between the panels (Breebaart and van Duin, forthcoming). The front and interior panel of each door consist of three butt-joined boards onto which the marquetry is applied. The frame has miter joints and contains five cross-grain members. In the remaining spaces, thirty rectangular glue blocks are used, placed parallel to the grain direction across the joints of the wooden boards and placed cross-grain in the middle of the boards. In this way a light door was constructed in which the boards are kept flat and joints are reinforced by cross-grain members and glue blocks.

The condition before conservation showed that the joints of the boards had opened, and glue joints between the boards and most of the members had come apart. Total shrinkage was 0.3–0.5 cm (0.1–0.2 in.), equivalent to 0.6%. Interestingly, cracks did not continue through the marquetry tabletop where the veneer has been applied cross-grain. The cracks had been filled and retouched during a previous conservation treatment, and four nails were inserted through the boards into the stretchers. The cracks had since opened a little more, and the filling material had discolored. As the cracks run straight through the floral marquetry, conservation treatment was considered for aesthetic reasons, as well as to avoid the risk of further damage to the marquetry alongside the cracks. Various options were discussed, and eventually, after investigating the construction with X-ray, we decided to dismantle the doors in order to close the gap between the boards, and to reglue the original joints between the boards, stretchers, and glue blocks. Although dismantling the construction can be regarded as invasive, it made it possible to stabilize the door while maintaining the original construction.

Treatment started by swelling the glue underneath the veneer on the sides of the doors with moist tissue on top of the veneer, and by subsequently lifting the veneer with a thin knife. With methylated spirits and a thin knife, the remaining glue bonds between the three front boards and the stretchers were separated (fig. 6). The backboards were originally glued and also nailed with square wrought iron nails onto the stretchers. The tips of the nails just penetrated through the stretchers

Figure 6
Detail of the right door of the Van Mekeren cabinet during conservation. One of the front boards has been removed, and the interior of the door with stretchers and glue blocks is visible. Photo: Rijksmuseum, Amsterdam.

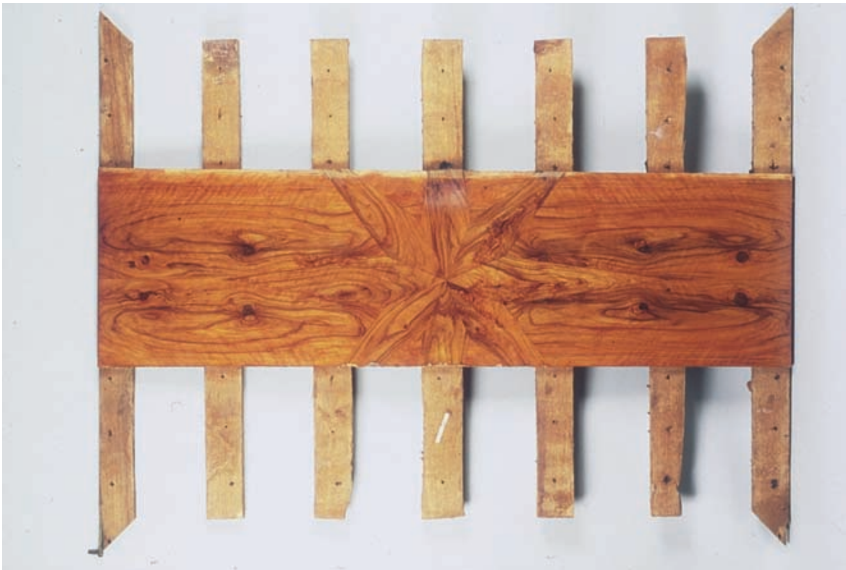

Figure 7
The stretchers and the middle backboard of the right door of the Van Mekeren cabinet. Photo: Rijksmuseum, Amsterdam.

and were heated by us with a soldering iron in an attempt to loosen the bond with the wood. The two outer backboards were then lifted; the middle backboard was not removed (fig. 7). All joints were cleaned by removing the old glue and fillings with a damp cloth and a heated spatula. No wood was removed. The nail holes in the stretchers were elongated in order to accommodate the original nails. This allowed us to move the boards sideways by some millimeters in order to close the joints with the middle board and to reglue them onto the stretchers. We used animal glue, the same kind of glue that was used originally. In contrast to PVA or other synthetic glues, animal glue is easily reversible and removable. It was unavoidable to shorten the miter joints of the frame by approximately 0.2 cm (0.08 in.) on either side, as the doors had become narrower by closing the joints between the boards. Subsequently, the joints between the three front boards were cleaned and reglued. Loose pieces of marquetry along the joints were fitted into place and reglued at the same time—a procedure that took advantage of the animal glue, which becomes fluid again with a little heat. In this way, the pieces of

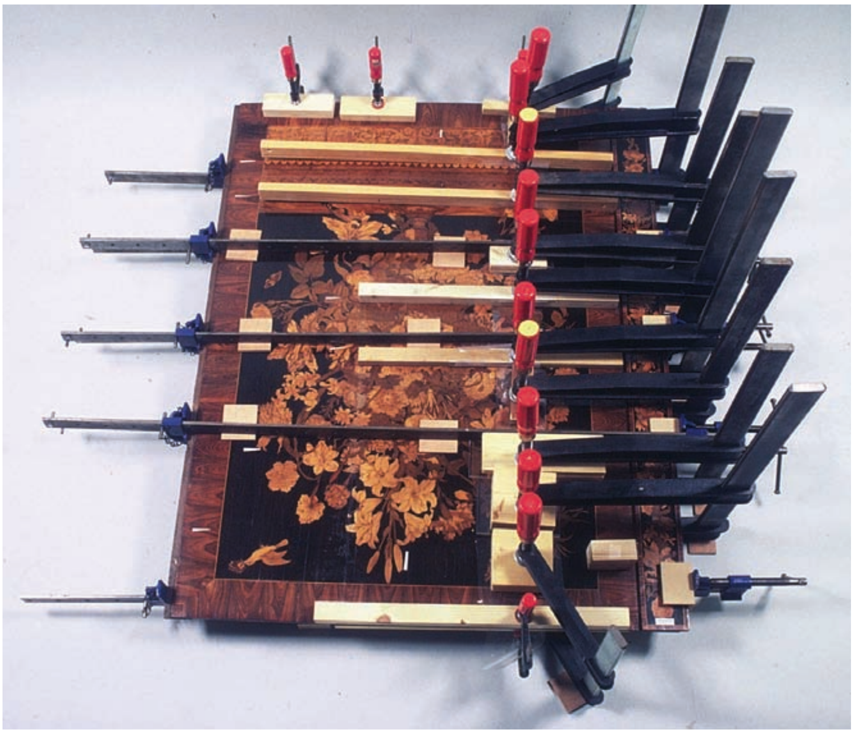

Figure 8
The front boards of the right door of the Van Mekeren cabinet in the process of being reassembled and reglued. Photo: Rijksmuseum, Amsterdam.

marquetry could be pressed into the right position (fig. 8). The glue blocks were reglued into their original position, and finally the front panel was reglued to the other half of the door. This was complicated because the surface area that had to be glued was large, and everything had to fit well together. Before gluing, the front panel had a slight warp, but this was easily pressed flat during gluing. Missing pieces of marquetry were cut and replaced. The cabinet had been french-polished during a previous treatment. This polish was removed with a cloth moistened with methylated spirits. The earliest remaining finish was preserved, and the surface was sealed with glue size. On top of this, several thin layers of beeswax were applied and polished to a silk gloss. The old cracks are hardly visible. Hairline cracks within the ebony veneer remain but are not disturbing.

The treatment was finished in 1999, and the cabinet has since been on display in the Rijksmuseum. The cabinet is now part of a long-term research project of the Netherlands Institute for Cultural Heritage, the Rijksmuseum, and the University of Amsterdam to monitor the influence of fluctuations in the museum climate on wooden objects such as furniture and panel paintings. So far the cabinet's condition has been very stable. Privately owned cabinets with a similar construction have been recently restored in the Netherlands, where sliding mechanisms were introduced to prevent new damage by movement of the wood (Greebe 1994). Whether these mechanisms function better than the reglued original construction is open to discussion. The original authentic construction is, of course, preferable in a museum setting.

Conclusion

Finding a definite explanation for the good condition of the *Tabernacolo dei Linaioli* is not easy. The oak cabinet dated to 1607 is in comparable condition and shows less shrinkage damage than the other cabinets discussed. The assumption is that a sufficient amount of well-glued cross-grain timber helps to prevent shrinkage cracks. This question needs further research. As conservators, we tend to focus too much on damage. It is easier to explain damage than to explain why no damage has occurred. In fact, all the cabinets discussed have survived very well. For example, although the construction of the Van Mekeren doors had become unstable, the marquetry was still firmly adhered to the oak boards. The animal glue easily survived the past three hundred years. These objects were evidently made with carefully selected, high-quality materials and with great skill and care. Therefore, the author would like to conclude with a plea for preserving the authenticity not just of the decorative layers but also of the wood, nails, and frames. We can see from the many thinned and cradled panel paintings that people had little confidence in the wooden support. The problems that do arise from these alterations prove that relatively intact, original panels have survived much better, as have the Dürer panels of *Adam* and *Eve* from the Prado show (see George Bisacca and José de la Fuente Martínez, "The Treatment of Dürer's *Adam* and *Eve* Panels at the Prado Museum," in this volume).

More research is needed to understand how old wooden objects such as panels and furniture react to changes in humidity. Research should also include the systematic comparison of the conditions of greater numbers of panels and furniture. The joint research program of the Rijksmuseum, the Instituut Collectie Nederland (ICN), and the University of Amsterdam, all housed in the new Atelierbuilding, aims to contribute to this.

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Materials and Suppliers

Sheppy Scotch Glue (animal glue), John Myland Ltd., 26–34 Rothschild St., London SE27 0HQ, UK.

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Restoration—A Sound Practice

Jonathan Woolston

Abstract

Violins might appear to have little in common with panel paintings, as their function is to produce sound. Rosined horsehair rubbed against a string can produce a sound of extraordinary tonal range and volume. Similar to panel paintings, instruments are made of wood and decorated on one side—not usually with paint but with fine varnish, which not only enhances the aesthetic quality of the material used but offers protection in everyday use. The thinly carved panels have to resist enormous pressure from the strings as well as adjust to climatic conditions. They have done this in some cases for nearly five centuries: the earliest violin with a dated label, by Andrea Amati, bears the date of 1564.

This paper will examine from the perspective of a violin maker and restorer the following concerns: tools and methods for repairing cracks, causes of cracks, procedures for gluing cracks in perfect alignment, crack reinforcements, and methods to ensure that the repair will not cause future problems.

The violin is a perfected and economic solution to an engineering problem, and no part is without its function. In order to maintain these instruments as both working tools and aesthetic creations, it is crucial to understand the methods and sequence of construction, the effects of humidity, and the movement of the wood.

I am a violin maker, and in this essay I will discuss some of the tools and methods required to repair cracks that occur most frequently in violins. The function of a violin is to produce sound; rosined horsehair rubbed against a string can produce a sound of extraordinary tonal range and volume. Similar to panel paintings, instruments are made of wood and decorated on one side—not usually with paint but with fine varnish, which not only enhances the aesthetic quality of the material used but offers protection in everyday use. The thinly carved parts, in places as thin as 1 mm (0.04 in.), have to resist enormous pressure from the strings as well as adjust to climatic conditions.

History and Construction

The violin has changed little in 450 years, apart from modification to the neck and fingerboard in response to string technology and adjustments to facilitate ever-increasing virtuosic repertoire. The violin was first created in Italy in the mid-1500s, and Andrea Amati of Cremona (born ca. 1505) is credited with the earliest instrument bearing a dated label. This

Figure 1
Andrea Amati, "Piccolo" violin, 1564. The instrument was commissioned for France's Charles IX. Tuille House Museum and Art Gallery. Photos: Tuille House Museum and Art Gallery.

violin was part of a commission of thirty-eight instruments for Charles IX of France and was most likely inspired by his mother, Catherine de Médicis, who would have been well aware of the musical scene in Italy at this time. Amati would have already been well established as a maker of this type of instrument. At this point, the violin was already quite highly evolved, and it can be assumed that many instruments of inferior quality or early prototypes have not survived (fig. 1).

The violin owes its longevity to the careful choice of materials, the construction methods, the quality of varnish, and the choice of animal glue. The ideal woods—spruce for the front and maple for the backsides and scroll—are still used because of their strength and tonal performance. A hot-melt animal glue, heated to about 60°C (145°F) in a double boiler, just below the strength of the wood itself, is flexible, reversible, and reactivated with water.

Quite remarkably, the instruments made today use the same materials and construction methods as in Amati's time, and they are made to basically the same specifications. Each string is able to be bowed individually while the musician comfortably supports the instrument with the left hand and stops the string to sound appropriate notes.

The sound holes, often referred to as f holes, are positioned precisely and allow movement of the bridge. These f holes are shaped in such a way as to allow for this flexure without risk of cracks occurring

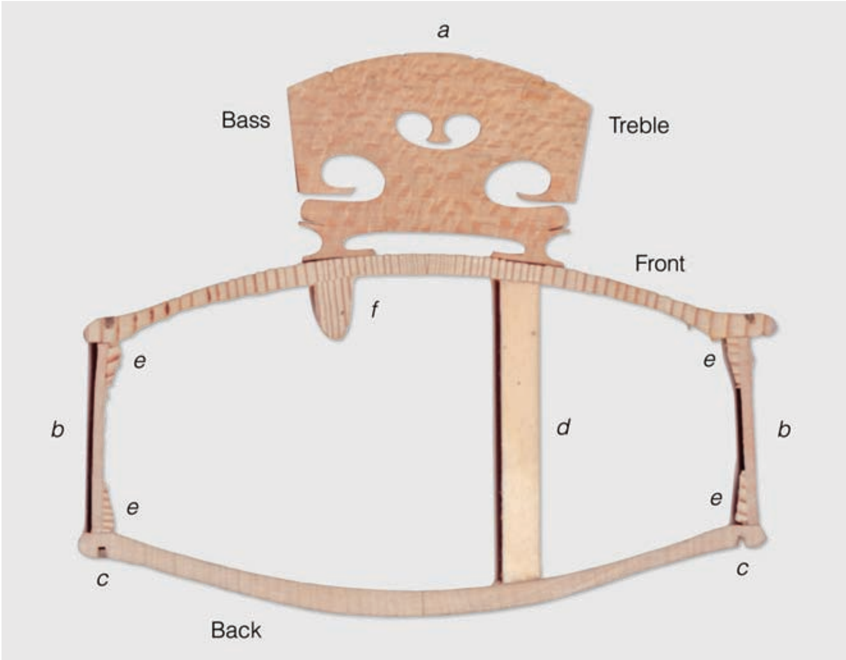


Figure 2
Cross section of a violin, with various parts labeled: (a) bridge, (b) rib (1 mm, or 0.04 in. thick), (c) purfling, (d) sound post (6.5 mm, or 0.26 in. diameter), (e) lining, and (f) bass bar. The front is made of spruce, *Picea excelsa*, and the back is made of maple, *Acer pseudoplatanus*. Photo: Jonathan Woolston.

at the extreme edges. The f holes also conveniently allow for the fitting of the soundpost, which couples the front to the back acoustically and mechanically (fig. 2).

The purfling, the black-white-black wooden inlay around the perimeter of the violin, is placed directly above the rib line and serves partly as an acoustic hinge; it is, of course, decorative, but it is also functional, since it reduces the likelihood of cracks propagating from the outer edges, the places where the instrument is most vulnerable to getting knocked.

The arching of the front and back plates offers strong but flexible support for the string tension, which is of the order of 25 kg (55 lb.) with a bridge loading of about 10 kg (22 lb.). There are quite a few instruments that have withstood these forces as well as the rigors of a performing life, including being transported in historical conveyances through various geographical zones and under varying climatic conditions.

Causes of Cracks

Cracks occur for several reasons: accidental, climatic, internal weakness of material, or previous restorer error. Changes in humidity give rise not only to dimensional changes but to changes in the properties of the material. Increases in moisture make wood more flexible, and in the case of the violin, this will affect the sound to a degree. The arching and thinness of the plates also gives some tolerance to changes in humidity. The greatest changes happen to the front of the violin, and it is for this reason that the front is usually glued in place with a weaker solution of glue, so that, in extremes, the top will become unglued at points if under stress. A side that becomes open is quite easily glued back together with animal glue of the appropriate strength.

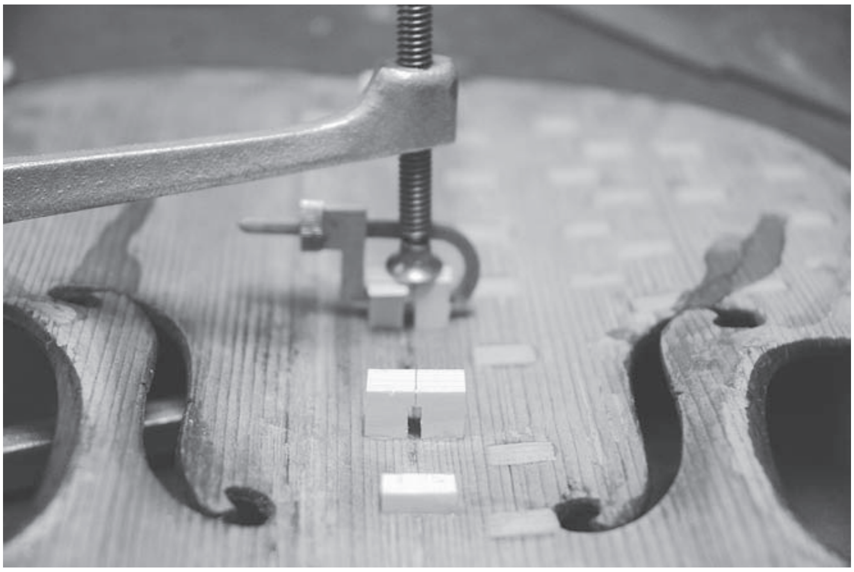
The changes that occur are not necessarily uniform and are dependent on many factors, including the dryness of the material when it was used. Other variables are the choice of tree, the timing of its felling, and how it was dried. These aspects were more carefully considered when trees were felled and cut by hand. Great care is taken by violin makers to source the best material for their instruments, and restorers must also use similar high-quality material for repairs.

Shrinkage cracks in instruments are caused by decreases in humidity and usually start at the edge of the instrument. In order for these to be glued back together, first of all one has to release any tension there might be in the plate, which usually means releasing the rib-front seam in the general area of the crack. This is usually done with a thin stainless steel spatula and a thin application of industrial methylated spirits (IMS or denatured alcohol) positioned to run into this juncture. This has the effect of making the glue very brittle, and the seam will usually open quite easily. Usually a shrinkage crack will close up once the side is released; however, it is prudent to have a stretcher clamp adjusted and ready, just in case it is required. Stretcher clamps are ideal for repairing cracks from the outside (fig. 3). By shaping the stretcher bar to the contour of the plate, one can direct the force from the side by use of the screw. It is possible to control the level at which the crack is brought together by using wedges pushed in under the stretcher bar and a Perspex protector, which is placed above the varnished surface of the plate.

For more serious repairs requiring internal access, the top is removed by use of a thin stainless steel spatula, IMS, and patience. Before this is done, detailed measurements are taken for future reference. For clean fresh cracks, special care must be taken to not contaminate the crack with dirt from the surrounding area. The same care needs to be taken with old cracks. Before any work takes place on the crack site, the

Figure 3
Stretcher clamps (top) and aluminum double-swivel clamps (bottom) in use. Photos: Jonathan Woolston.

Figure 4
Crack repair with a stud positioned at the end of the crack (foreground). A single block with a small cutout above the crack is placed behind the stud; it will be cut through for wedge insertion. Photo: Jonathan Woolston.

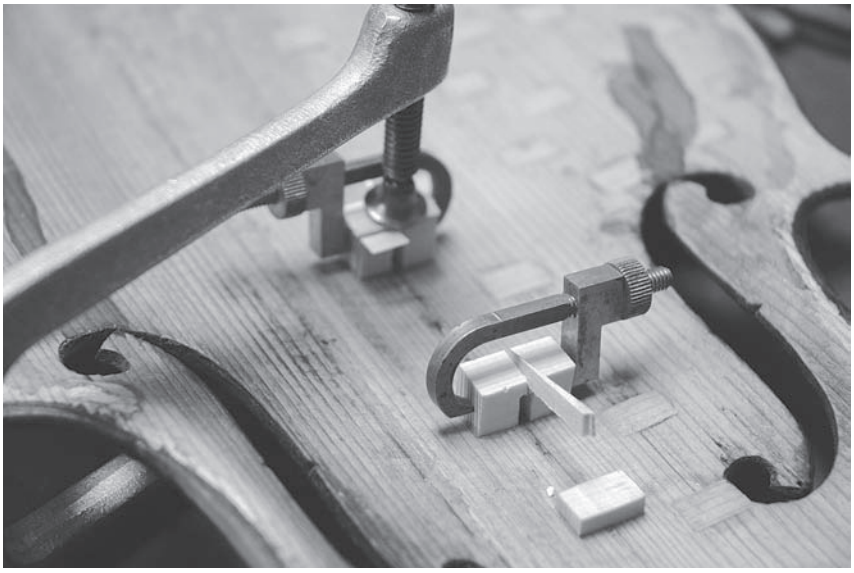


repairer might consider gluing a stud at the end of the crack, which will help stop the crack from propagating while the crack is being flexed. (fig. 4). Old glue needs to be lightly soaked with a small piece of damp paper towel and gently stroked with a soft, short-bristled brush. Care should be taken not to completely saturate the area, as the wood will soften. Likewise, brushing too vigorously will remove fibers and damage edges. If there are many unsupported cracks to deal with, gluing support tabs (light studs) placed strategically can be beneficial. Specialist lightweight clamps can be used to help keep the crack in register. For this purpose, a lightweight aluminum double-swivel clamp is used; this tool is different from most clamps purchased commercially, which only have one foot that swivels (fig. 3).

Block-and-Wedge Clamping System

With the block-and-wedge clamping system, full control over the angle at which these cracks are brought together can be achieved (fig. 5). Even cracks that do not appear to join together and that may have been out of

Figure 5
Control of gluing angle with block-and-wedge clamping system, with J clamp (foreground); cap over block-and-wedge repair using J clamp and double-swivel clamps (behind). Photo: Jonathan Woolston.



register for years can often be coaxed back into alignment. This is very difficult to achieve unless one can have full control over the clamping pressure. It is crucial that the crack be glued in perfect alignment for the integrity of the vibrating system. Misaligned cracks are weak; they are prestressed; and they can also cause stresses to be focused elsewhere on the surface of the plate. Cracks that occur in the vicinity of, or as a result of, a misaligned crack can be problematic to repair successfully. Undoing the old repair and then regluing is sometimes the only solution.

This system of clamping can only be used when the front or the back has been removed, as it requires access to the inside surface of the instrument. Quite simply, two blocks are glued on either side of the crack; these can be chalk-fitted to the inside surface and then glued (fig. 6). Chalk fitting is a process in which one surface, in this case the top plate, is used as a reference, and chalk is applied. When the block is in contact, the chalk leaves a print, which is then removed with a scraper or edge tool. The process is repeated until the entire surface contacts. I tend to use quarter-cut spruce approximately 5 mm (0.2 in.) square (but it depends on the size of the job). The block is placed perpendicular to the grain of the front. Alternatively, one can use a single block with a small cutout positioned where the crack falls (fig. 4). The goal is to not have any glue fall into the crack. Several blocks can be strategically placed and glued. The top portion can be cut through when required with a fine Japanese pull saw, the curf of which designates the width of the aperture.

The J clamp can now be fitted in place. The J clamps are designed so that the screw is furthermost from the clamp foot—as

Figure 6
Chalk fitting a cleat below an f hole.
Photo: Jonathan Woolston.

opposed to a G clamp, where the screw is in line with the clamp foot. A wedge can now be made to fit between the aperture made by the saw cut to control the angle at which the crack is brought together. The J clamp is positioned close to the surface of the plate for maximum effect. Each wedge needs to be numbered to correspond to the correct block and also marked so it can be quickly positioned at the correct depth. With a wedge in place and by lining up the crack at the correct angle, one can "cap" the two blocks with a single thin piece of wood (fig. 5). This procedure now makes the wedge redundant and might be helpful on one or two blocks; however, the angle cannot be altered except by removal of the cap. This system can be used in combination with stretcher clamps, if required.

With the crack lined up and wedges in place, it is possible to do a "wet run" with a little warm water brushed into the crack, which will line up all the wood fibers. The crack is then left to dry overnight. A straightedge (a piece of dark plastic with a perfectly straight edge) is used to check the levels of the outside and varnished surface of the crack—assuming that this is a good reference point. It might be that adjustments could be necessary, in which case another wet run might be required. It can be useful to glue strips of veneer between each set of posts, a step that will help to keep everything in register during gluing. The lightweight double-swivel clamps can also be used for this purpose. These, however, must be removed within the hour, as they can create depressions in the outside surface. This happens because the clamps don't allow the wood fibers to swell; so instead, they sink when the moisture leaves.

With everything in place and ready to go, it is time to glue. Glue is applied from the outside, the varnished side, as this avoids the problem of unnecessary glue on the inside, which in turn will swell the wood on the inside. For long cracks it might be necessary to glue in two stages. As can be seen in figure 7, inserting a wedge into the throat of the blocks in order to open the crack might be useful if one needs to flex the crack in order to create capillary action to get the glue into the fissure. After the glue is allowed to dry, the clamps and blocks are carefully removed. Since the blocks are made of quartered spruce with the

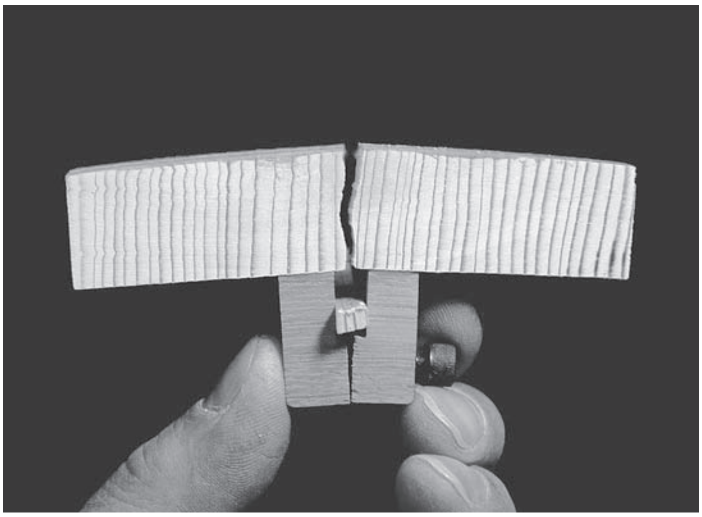


Figure 7
A crack being opened with a wedge in the throat of the block. Photo: Jonathan Woolston.

grain perpendicular to the front, it should be possible to split most of a block away, removing the rest with a gouge or thumb plane. The final wood layer is removed with a little moist paper towel left on the area for twenty minutes.

Crack Reinforcements

It is normal practice to cleat the crack with thin (approximately 0.6 mm, or 0.02 in.) blocks of wood. Spruce is used for the front, and spruce or willow for the back. The size and shape of these blocks depends on several factors, such as thickness of the plate, wood loss in the crack, and quality of bond. In general, cleats are kept as small as possible. Cleats should be chalk-fitted only when the violin plate has had plenty of time to reach equilibrium. The grain is placed perpendicular to the grain of the front and split from a block; it is important to ensure that the gluing surface follows this split line so as to offer maximum strength. The cleats are approximately 2–3 mm (about 0.1 in.) thick, with the grain line running from the gluing surface up; they are chalk-fitted with the use of a knife and scraper. When you get a good chalk reading, you can glue them swiftly into the exact place using the double-swivel clamp, removing excess jelled glue with a stick and minimal water. When the glue is dry, the clamps are removed, and the cleats are trimmed to a feather edge at the ends (fig. 8). It is fairly important that the end of the cleat does not form an excessively stiff area at the edge; it is also important that the cleats do not line up or follow one specific grain line, as a crack could form should the instrument be knocked.

Once the crack is cleated and trimmed, the crack is then sealed with a varnish made of dewaxed white shellac, sandarac, and mastic or copal that will also act as a filler varnish for small varnish losses. The dry resins in a 4:1:1 ratio are dissolved in alcohol in a warm bath. This varnish is laid on using the point (not too sharp) of a stick; the flow is controlled with the speed of the stroke. The repairer can trim with a scraper laid as flat as possible, using gentle stroking action.

The violin is a perfect ergonomic and economic solution to an engineering problem, each part having a function that contributes to the

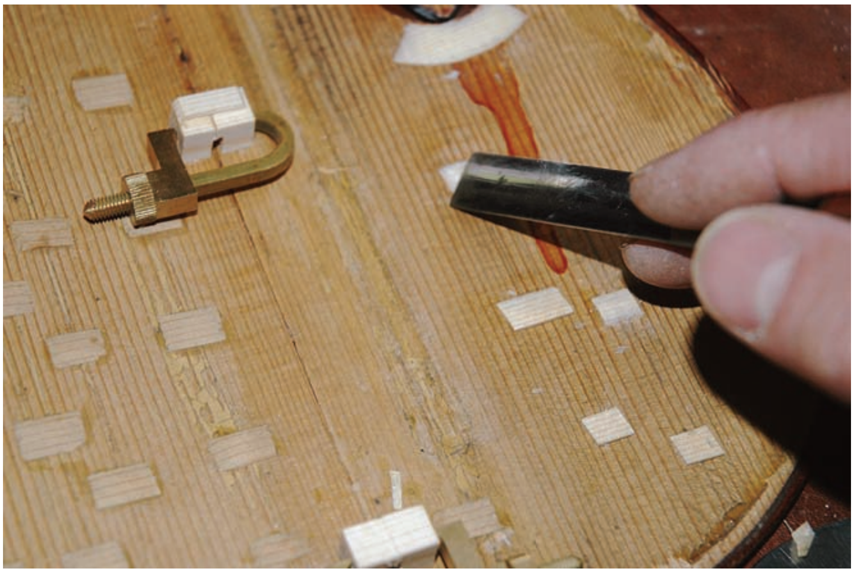


Figure 8
Feathering the edges of the cleats with a gouge. (Note the old cleats on the left.) Photo: Jonathan Woolston.

sound the instrument is designed to produce. It is crucial to understand the methods and sequence of construction, the effects of humidity, and the movement of wood in order to maintain these instruments as both working tools and artistic creations. Well-repaired cracks not only protect the structural integrity of the violin but also allow the instrument to retain its tonal character. Because the materials used are worked so thinly, it would not be prudent to leave a crack in an open state for too long, as the adjacent sides would be free to move, and that movement might cause the crack to elongate and the edges of the crack to curl.

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 disjoined 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).

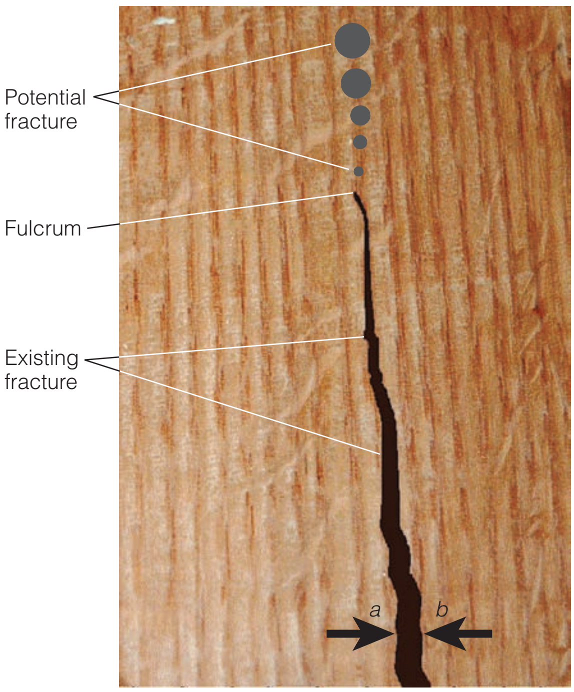


Figure 1
Tapered open crack. If the fracture is closed at points *a* and *b*, it is likely that the stress will be transferred beyond the terminus, and a new fracture may open opposite the earlier void. Image: Courtesy of the Museum Conservation Institute, Smithsonian Institution.

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 relation 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 thermoplastic 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.

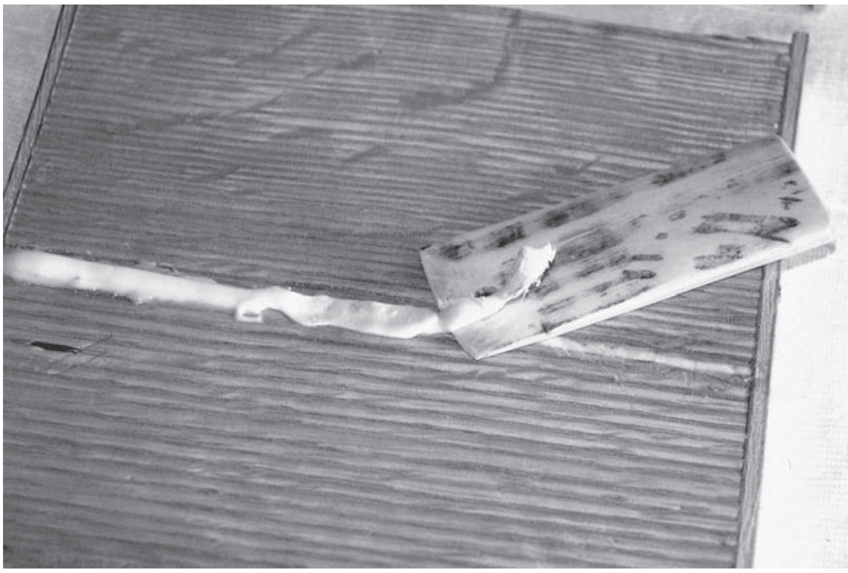
The flexible epoxy product I have employed is Marine-Tex FlexSet, intended, as the name suggests, for the boat building and repair market. This product has a much higher initial viscosity than regular (liquid) rigid epoxy, and it works more like a flowing putty than a wicking liquid. In order to use 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.

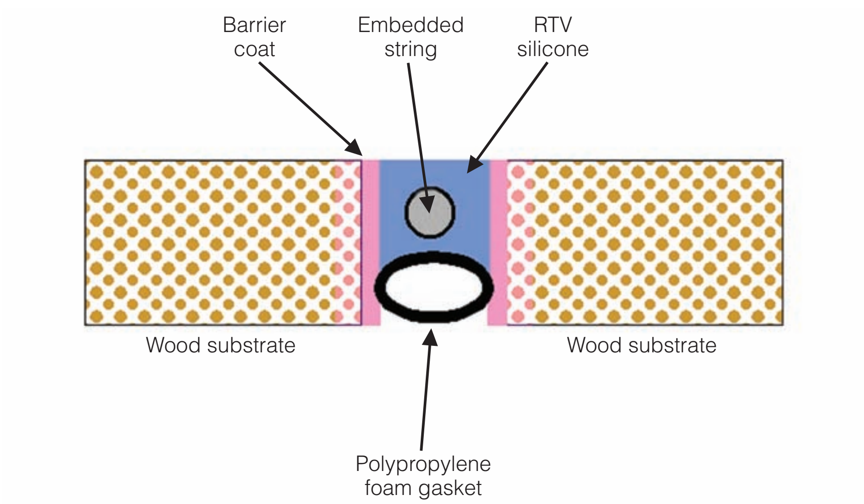
Figure 3
A sharp-edged tool—the shaped outer sheath of an ivory tusk—used to shave off excess flexible epoxy once the surface tack has gone. Photo: Courtesy of the Museum Conservation Institute, Smithsonian Institution.



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.

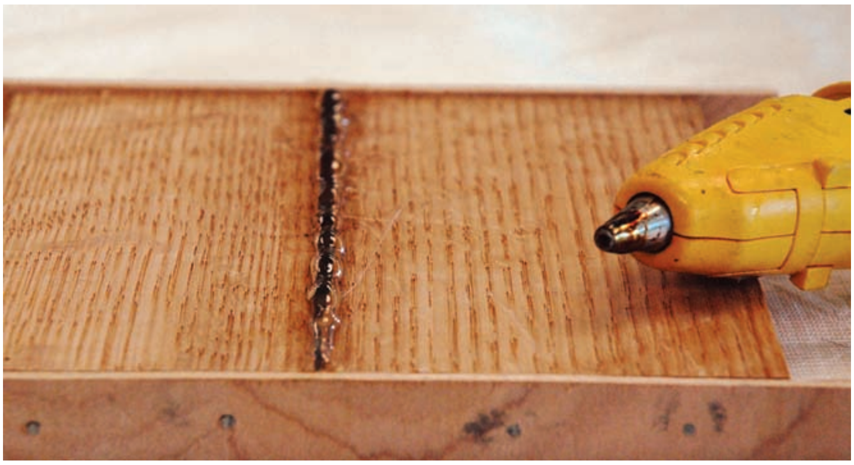


Figure 6
Hot melt EVA adhesive injected into a void. The gap is filled so that the EVA is slightly proud of the adjacent surface; it is then allowed to cool. Photo: Courtesy of the Museum Conservation Institute, Smithsonian Institution.

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.gorillaglue.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.henkelna.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.

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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.

Experimental Evaluation of Adhesive-Filler Combinations for Joining Panel Paintings

Christina Young, Britta New, and Ray Marchant

Abstract

This paper reports on an experimental evaluation of adhesive-filler combinations for joining panel paintings. The samples and tests were chosen on the basis that the gap to be rejoined was not suitable for a wood fillet, or it was too large to join without the addition of filler to the adhesive. In the present tests, the most mechanically suitable combinations from the previous tests have been subjected to thermal aging, and their properties are compared. Additionally, new combinations have been tested; they are based on materials used by conservators but not included in the original tests, and some combinations are ones that the authors consider to be suitable alternatives. Also investigated are the effect of priming the wood with a dilute adhesive and the influence of contaminants from residues of previous adhesives. The main criteria chosen to assess the suitability of the adhesive-filler combinations were strength of join, mode of join failure, workability, and mechanical stability.

Introduction and Context

This paper evaluates the use of adhesive fillers, which provide structural integrity to a panel painting. It builds on previous research undertaken on this subject (Young et al. 2002). There is an adequate range of adhesives that meet many requirements for the structural conservation of works of art. However, to the authors' knowledge, proprietary adhesive fillers, approved for conservation, do not exist for wooden objects. Rather than use commercial fillers, one option is to choose a familiar adhesive, modifying it by adding fillers for the specific application. However, adding fillers to these materials changes their mechanical properties, and therefore, their suitability needs to be assessed for specific types of treatment. Fillers are often needed if the panel requires a rejoin of two boards that do not butt closely together, or a rejoin of two boards that have an irregular gap. For large gaps, wood fillets can be used, but for irregular gaps above 0.5 mm (0.02 in.), an adhesive filler is usually suitable because it both adheres the panel sections and provides bulk where sections are missing. The filler must allow some deformation without failing, even if the panel has an auxiliary structure restraining movement. The deformation is usually convex or concave warping of the panel under fluctuating relative humidity (RH). Since most panels are subject to some restraint, this will induce bending.

European panels of the Renaissance and Baroque periods were constructed of boards that were simply glued and butt-jointed, sometimes reinforced with dowels, fabric strips, or battens (Wadum 1998).

The bonding edges have small surface area relative to the size and weight of the planks, and hence the joint will be highly stressed.

The quality of an adhesive joint will be affected by: surface contamination, porosity, coherence of surface, bonding pressure, moisture content, ambient temperature on cure, and ambient RH on cure (Adams, Wake, and Comyn 1986, 218). For partial disjoins, surface preparation is almost impossible. Frass from woodworm, failed adhesive, adhesive added during a prior treatment, varnish, and filler material all introduce contaminants that may compromise the joint. Even for complete disjoins, contaminant material is hard to remove without damaging ground and paint layers. Thus, a realistic prediction of joint behavior must take into account all the above factors.

The practical problems of rejoining panel paintings and the equipment devised to assist in the processes have been outlined in the conservation literature (Kozlowski 1962; Reeve 1989; Brewer 1998). Other studies have highlighted the problems of irreversibility and the lack of long-term stability of most classes of adhesives (Bradley 1984; Howells et al. 1984; Down 1984; Down et al. 1996; Williams 1998). The continuing study at the Canadian Conservation Institute into the properties of adhesives used in conservation provides invaluable information (Down 2009). However, there is little information on the mechanical performance for adhesives and fillers employed on panels. Research into fillers for wooden artifacts is pertinent to materials for treating paintings, even if the aims are not directly applicable (Grattan and Barclay 1988). Information on wood adhesives is available from the timber industry, but this material tends to concentrate on the fabrication applications; it is only relevant to conservation for understanding the general behavior of adhesives (Davis 1997). Other research into structural adhesives and treatments has taken a different approach. It has focused on "developing effective joining techniques that do not rely solely on the development of new adhesives" or the "assumption of an 'eternal bond.'" This includes designing joints that may require future disassembly (Podany, Risser, and Sanchez 2009).

The required structural and, hence, mechanical properties of the filler mixture are essentially the same as for the adhesive. The properties required for panel paintings will vary from case to case. However, for the scenario stated in this paper, the following criteria, discussed in detail elsewhere (Young et al. 2002), are suggested:

1. good handling and curing characteristics; resistance to slumping during application or curing
2. good wetting of the joint surfaces
3. gap-filler strength commensurate with the wood surrounding the joint, reducing the risk of failures within the original wood
4. sufficient flexibility to accommodate hygroscopic movement in the original wood
5. ability to fail in a ductile manner and be resistant to rapid crack growth
6. stable mechanical properties over time
7. inert to humidity and temperature changes, in terms of stiffness, strength, and resistance to fracture
8. minimal creep
9. removable
10. resistant to fungal and bacterial attack

11. nontoxic
12. once cured, capable of being sanded or carved and providing a surface that will accept either a surface filling or a coating (varnish or retouching media)

Methodology

The experiments reported here were based on the experience gained by the authors from monitoring the curvature of panels in response to fluctuations in RH, using both traced profiles and 3-D electronic speckle pattern interferometry (ESPI) (Young and Hibberd 2000). These profiles are used to indicate the allowances required for anticipated dimensional response.

Figure 1 illustrates a typical instance of the kind of treatment in which this approach is adopted; here the painting undergoing repair of a recent split is a sixteenth-century English panel from a UK National Trust property, Trerice in Cornwall, which has a semicontrolled environment.[1] Observation of the panel as part of the conservation treatment showed that it exhibited a change in depth of curvature of 16 mm (0.6 in.) in response to a change in RH from 55% to 62%. This type of data has informed the parameters of the testing for the present research study, as will be shown later. The experiments reported here were designed to test the fillers under realistic loading conditions; thus, a four-point bend test was chosen to replicate the forces on a panel subjected to environment-induced deformations.

The tests measured the stiffness (measure of flexibility) and strength of the gap filler subjected to bending forces. The changes in these properties with time (stability) were also assessed after periods of natural and thermal aging. As both the joint itself and the wood on either side experience the same bending moment, it is possible to ascertain whether the filler or the wood fails first. The test allows visual inspection of the failure process. The load at which the joint fails demonstrates the "practical" properties that might be expected for each adhesive and type of filler in a real situation. Additional tests were undertaken to determine how contaminants affected the strength of the gap filler in this application.

Surface wetting is important for partial disjoins, where glue penetration is difficult. Priming with dilute adhesive aids penetration and provides a good bonding surface. Priming agents were tested in this

Figure 1
Sixteenth-century English panel painting during rejoining of the boards. Attributed to William Segar (English, active by 1589, d. 1633), *Portrait of a Lady*, inscribed "Elizabeth I 1588." Oil on panel, 60 × 49.5 cm (23.6 × 19.5 in.). Trerice (National Trust property), Cornwall, UK. Photo: Christina Young.

ongoing research but are beyond the scope of this paper (Tellier 2002; Young 2009 [Getty podcast]).

Samples

The panel samples were constructed from 5 × 50 × 50 mm (0.2 × 2.0 × 2.0 in.) naturally aged oak blocks, approximately radially cut from two pieces of oak; the samples are considered representative of some Netherlandish panel paintings. Samples for mechanical testing were prepared by adhering two blocks together, with the growth rings approximately parallel to the join, as described in more detail below.

In these tests, the most suitable adhesive-filler combinations from the previous research have been subjected to thermal aging and their properties compared (Young et al. 2002). Additionally, new combinations have been tested; they are based on materials used by conservators but not included in the original research, plus some combinations that the authors considered suitable alternatives. The adhesives to which fillers were added were Evo-Stik Resin W interior wood adhesive, Mowilith DMC427, and Jade 403N. Various samples of Lascaux BEVA 371 and Paraloid B-72 with filler were prepared. However, cohesive and adhesive failure occurred at the curing stage. Araldite 1253, a proprietary wood filler that can be carved and sanded, was also tested, as it is used in conservation (tables 1 and 2).

Adhesives were used in standard concentrations, and each filler mixture was added to 5 mL (0.17 oz) of adhesive. Sufficient filler was added to produce the handling properties of a workable paste with some degree of flow. Good results had previously been obtained using a 1:1 mixture of coconut shell flour and phenolic resin microballoons as the filler (Young et al. 2002). This mixture was used as the standard for all the adhesives. Natural and thermal aging at 60°C of the joined blocks was carried out at 55% RH for different time periods.

Table 1 Materials used in the adhesive-filler combinations and their glass transition temperatures (T_g).

Material	Code	Composition	T_g (approx.) °C
Adhesive			
Evo-Stik Resin W interior wood glue	RW	Poly(vinyl acetate)	29–34*
Mowilith DMC427	DMC427	Vinyl acetate/dibutyl maleate copolymer	27–35*
Jade 403N	JA	Poly(vinyl acetate)	10.9*
Araldite 1253	EA1253	Epoxy	63 †
Hide glue	Hg	Collagen-derived proteinaceous glue	—
Filler			
Phenolic microballoons	Mi	Spherical balloons of 50 μm diameter	—
Coconut shell flour	Co	Ground and sieved coconut husks	—
Filler in EA1253	—	Silica/titanium dioxide/iron oxide/phenolic resin	—

* By dynamic mechanical analysis (DMA) (personal communication, Alan Phenix, 2009).

† Manufacturer's stated value.

Table 2 Adhesive-filler combinations.

Adhesive	Filler 1	Filler 2	Code	Preparation
Evo-Stik Resin W interior wood glue	phenolic microballoons	coconut shell flour	RWCoMi	Fillers 1:1 (w/w) 1 g in 5 mL adhesive
Mowilith DMC427	phenolic microballoons	coconut shell flour	DM427CoMi	Fillers 1:1 (w/w) 1 g in 5 mL adhesive
Jade 403N	phenolic microballoons	coconut shell flour	JACoMi	Fillers 1:1 (w/w) 1 g in 5 mL adhesive
Araldite 1253	—	—	EA1253	2-part applied 1:1 as per instructions

Contaminants

Filled Resin W and Araldite 1253 were tested with contaminants representative of glue residues from an original or treated join, consolidant, or varnish. Resin W was also tested as a hairline join (no filler) with the contaminants (table 3). The contaminants were Paraloid B-72, dammar, BEVA 371, and hide glue.

Sample Preparation

Low-tack adhesive tape was applied to the top and bottom faces of each wooden block to prevent penetration of the filler mixture into these faces. An additional strip of tape was attached between a pair of blocks on the underside faces to align them 2 mm (0.08 in.) apart. This operation also prevented loss of mixtures with low viscosity. The mixture was first brushed along the edges to be adhered. The blocks were then clamped in a polytetrafluoroethylene (PTFE) jig to maintain alignment, and the gap was overfilled with the mixture. After twenty-four hours, the blocks were released and the tape across each pair removed. They were then inverted and left to ensure complete curing. Finally, the excess filler was pared away, and the protective tape was removed. Samples with contaminants had the contaminant brushed onto the edges first; it was then left to dry for twenty-four hours before the adhesive mixture was applied.

Sample Names

In the following discussion, samples are coded with the first letters for the adhesives Araldite 1253 (EA1253), Evo-Stik Resin W (RW), Mowilith DMC427, and Jade 403N (JA). An added filler is identified as CoMi (coconut shell flour and microballoons filler), and a contaminant is identified as B72 (Paraloid B-72), Dam (dammar), Be (BEVA 371), or Hg (hide glue) (see tables 1–3). For example, RWCoMiHg is Resin W adhesive (RW)

Table 3 Contaminants applied to wood blocks.

Contaminant	Code	Preparation
Beva 371	Be	Thinly brushed on surface as provided by manufacturer (Lascaux)
Dammar	Dam	Thinly brushed on surface; 30% in Shellsol D40
Hide glue	Hg	Thinly brushed on surface; 20% w:v solution in water
Paraloid B-72	B72	Thinly brushed on surface; 10% w:v solution in Shellsol A100

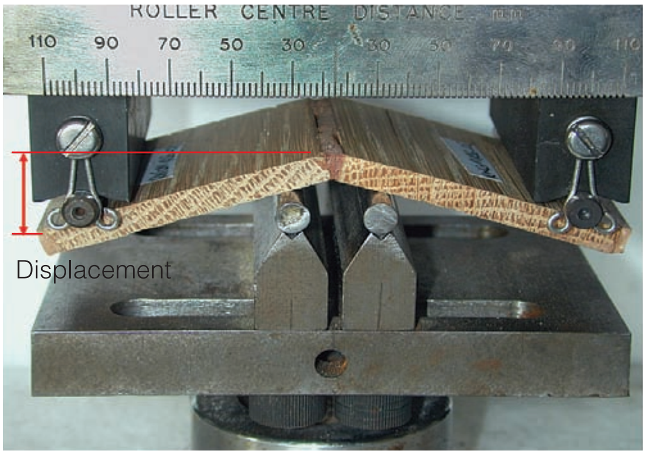


Figure 2
Wood block sample under four-point bend test. Photo: Christina Young.

with coconut shell flour and microballoons filler (CoMi), with a contaminant of hide glue (Hg) on the edges of the wooden block.

Experimental Procedure

The mechanical properties of the samples were investigated with a four-point bend test. Tests were performed on an Instron 4301 machine at 55% +/– 3% RH and 20°C +/– 2°C. The samples were supported on the lower rollers of the four-point bend jig. The moving crosshead was lowered at 5 mm/min (0.2 in./min), so that the upper rollers created a bending moment (fig. 2). The displacement of the top rollers, the compressive force, the temperature, and RH were all recorded. Samples were photographed after testing to confirm the mode of failure and aid in the failure analysis.

Depending on the ease with which good-quality joints could be achieved, between three and eight samples were tested for each adhesive-filler combination. The results also note the failure mode: whether the fracture was ductile or brittle, and whether wood was removed as the joint failed—such damage being indicated if any wood were visible on the fracture surfaces of the adhesive. Where failure occurred along the wood-adhesive interface (adhesive failure) or within the body of the adhesive (cohesive failure), the stiffness was calculated by taking the gradient of the initial linear section of load-displacement curves—i.e., tangent modulus at 20 N. The stiffness and peak load values were calculated and averaged for each type of joint. The peak load before bending failure was recorded and taken as a measure of the strength of the joint. This analysis is summarized in table 4.

In a number of tests, failure occurred in the wood at low load because of an inherent weakness in the block. Therefore, the measured stiffness did not represent the true stiffness of the wood or the adhesive; these results are not included in the present analysis.

Results

The maximum stiffness at 20 N for all samples was approximately 50 N/mm. This stiffness primarily derives from the wood, as the joint is only a small proportion of the loaded sample. Two types of behavior occur during the bend test, depending on the flexural stiffness and cohesive

Table 4 Tangent modulus and peak load for naturally and thermally aged samples.

Material	Aging	Days	Tangent modulus (N/mm)	Peak load (N)	Tangent modulus standard deviation	Peak load standard deviation
Gap filler						
RWCoMi	Natural					
		2	7.8	15.8	2.0	0.4
		15	23.3	54.0	4.6	7.3
		30	39.7	96.7	0.7	2.8
		122	39.9	90.7	3.5	0.6
		470	54.7	140.8	1.9	7.0
		11*	27.1	68.6	0.5	6.0
	Thermal					
		30	42.5	97.8	2.4	2.3
		60	48.9	131.7	1.1	8.7
		120	52.3	168.4	7.3	14.4
EA1253	Natural					
		2	56.7	135.7	6.7	24.4
		7	49.1	129.3	4.5	36.4
		15	41.9	138.1	6.0	16.6
		30	48.4	104.9	6.6	17.6
		59	49.2	114.4	6.9	30.4
		122	52.4	129.5	1.9	31.3
	Thermal					
		30	51.2	116.2	2.5	6.2
		60	41.1	101.0	8.9	3.7
DMC427	Natural					
		2	3.3	15.4	1.0	3.0
		15	10.4	29.2	1.5	2.7
		30	13.4	44.7	5.8	8.1
		56	27.5	58.8	8.4	5.7
JACoMi	Thermal					
		30	28.1	57.0	8.7	17.0
		60	32.2	70.7	0.6	6.1
	Natural					
		60	20.1	44.1		
	Thermal					
		30	23.8	44.8	7.9	7.17
		60	11.4	40.2	2.3	6.5
Contaminant						
RWCoMi	Natural	30	39.7	96.7	0.7	2.8
RWCoMiHg	Natural	32	41.8	96.6	11.7	5.9
RWCoMiBe	Natural	32	38.3	54.9	10.8	7.4
RWCoMiDam	Natural	32	47.0	61.7	10.9	7.7
RWCoMiB72	Natural	32	46.3	84.8	5.5	3.3
EA1253	Natural	30	48.4	104.9	6.6	17.6
EA1253Hg	Natural	32	48.2	124.3	4.5	10.6
EA1253Be	Natural	32	42.4	76.7	7.3	10.1
EA1253Dam	Natural	32	49.8	59.3	11.1	2.2
EA1253B72	Natural	32	44.8	129.7	5.1	10.0
Hairline						
RWBe	Natural	31	45.0	28.4	10.9	3.3
RWB72	Natural	31	53.5	108.6	15.6	11.9
RWDam	Natural	31	55.9	38.1	13.7	11.7
RWHg	Natural	31	56.9	139.7	3.2	5.4

*Data from Young et al. 2002.

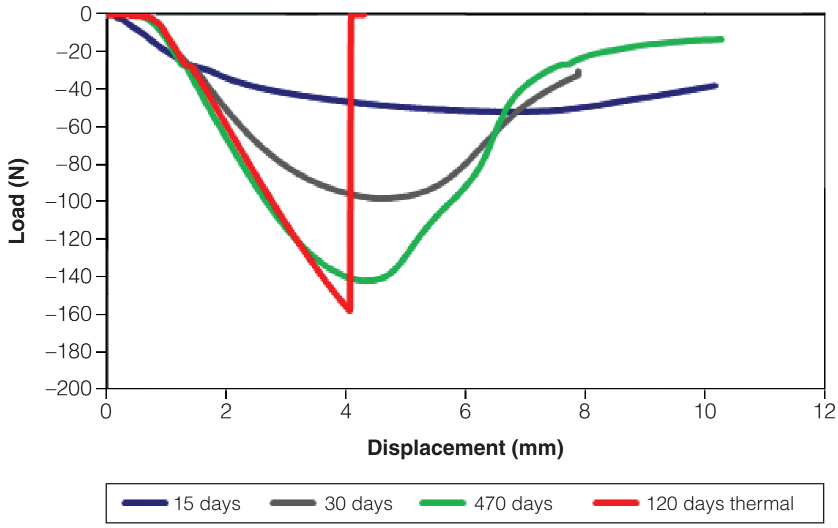


Figure 3
Load displacement versus aging for Resin W, coconut shell flour, and microballoons, showing ductile-brittle failure transition. The load values are negative because of the four-point bend test setup.

strength of the gap filler relative to the wood. First, when the stiffness of the adhesive alone is equal to or above that of the wood, the wood bends around the rollers during the test. In this case, it is not possible to ascertain conclusively the stiffness of the adhesive alone. Second, when the stiffness of the adhesive is less than that of the wood, the sample bends at the joint rather than across the points of contact at the rollers (fig. 2). The peak load of the wood had been found in previous tests to be in the range of 120–150 N (Tellier 2002, 15).

Data from the four-point bend tests are shown in figure 3, which illustrates the difference in load-displacement behavior for Resin W filled with coconut shell flour and microballoons, aged for different periods. In a four-point bend test, the bending force is created by the outer rollers pushing down on the sample, which is balanced on the two inner static rollers (fig. 2). Thus the load cell is in compression and returns a negative load value.

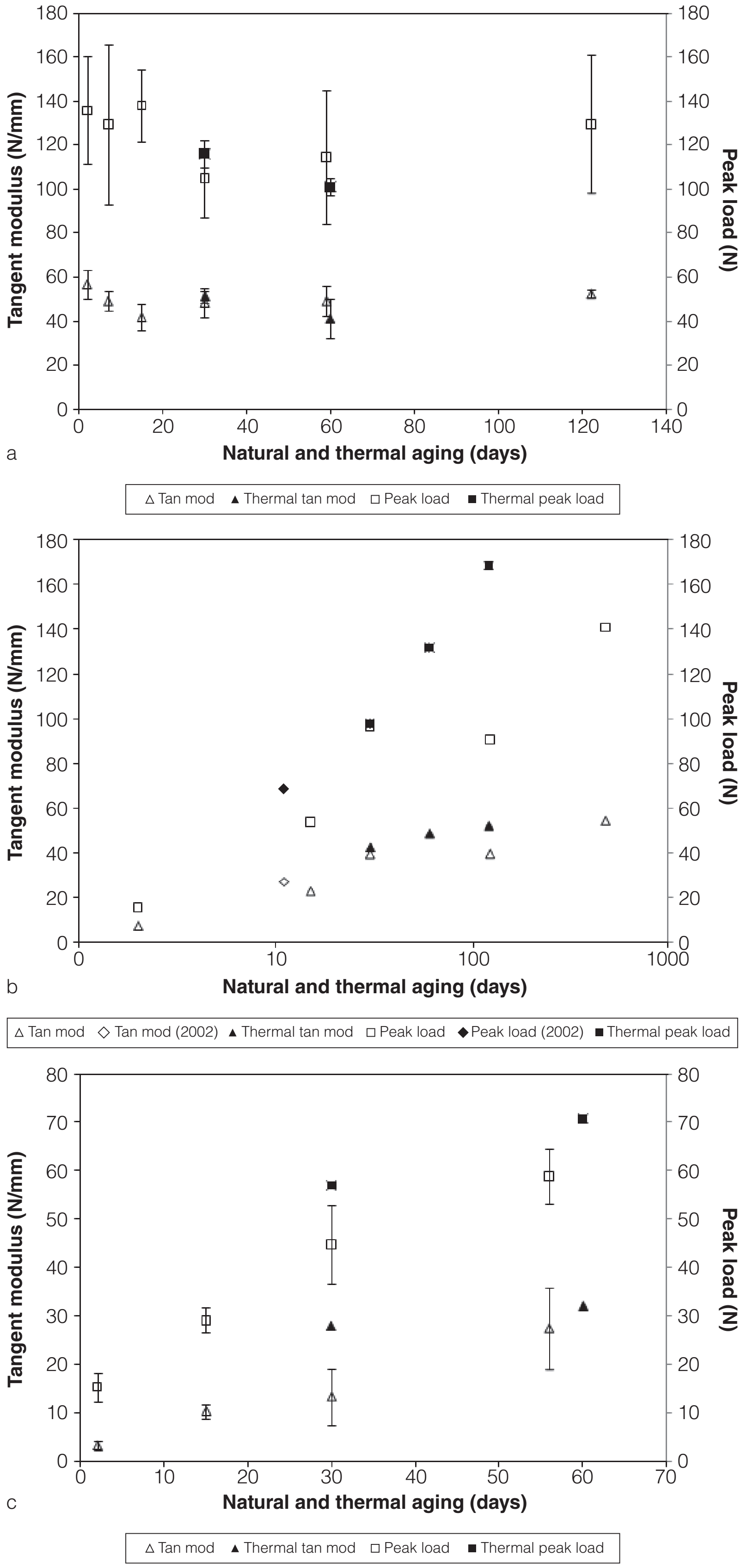
Fillers

Araldite 1253 (EA1253)

During the tests, the wood started to bend about the rollers prior to failure because the stiffness of the EA1253 was equal to or greater than the wood. No change in stiffness or peak load occurred after natural or thermal aging (fig. 4a and table 4). The stiffness at 20 N is 49.6 +/– 4.9 N, and the peak load was 125.3 +/– 13 N. In one case the adhesive failed cohesively at 90 N. Brittle fracture occurred in all cases, often initiating in the wood and running into the wood-adhesive interface. The large variation in peak load is expected because failure initiates at points of weakness in the wood and the adhesive. Postfracture inspection showed that the EA1253 had produced an excellent bond with the wood, and the measured peak load is effectively that of the wood.

The research published in 2002 included a wider range of adhesives and mixtures, but no aging was undertaken (Young et al. 2002). Although the wood source differs in the current research, the general trend of the results is comparable. Therefore, it is appropriate to take both sets of data together to give a fuller understanding of gap-filler properties.

Figures 4a–c
Tangent modulus and peak load trends: for naturally aged Araldite 1253 (a); for naturally and thermally aged Resin W, coconut shell flour, and microballoons (b) (error bars removed for clarity); and for naturally and thermally aged Mowilith DMC427, coconut shell flour, and microballoons (c).



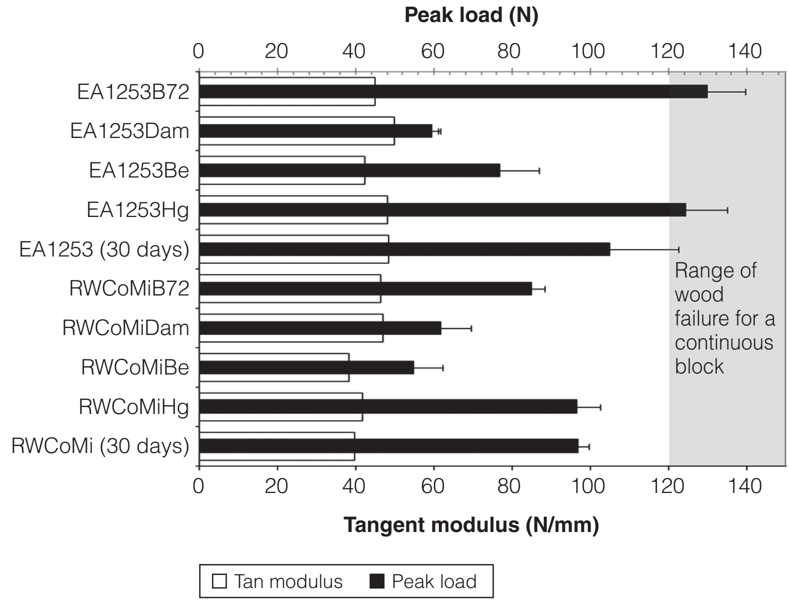
Resin W with Coconut Shell Flour and Microballoons Filler (RWCoMi)
Both stiffness and peak load increase with natural and thermal aging over a period of 470 and 122 days respectively (fig. 4b and table 4). In neither case can the exact relationship between these properties and time be established. The trend is approximately linear, with no obvious inflection of the curve for long exposure times (which would indicate that changes have stopped). However, the original load-displacement graph (fig. 3) shows the change from ductile to brittle fracture with time, indicated by the shorter displacement to complete loss of load and the more defined final fracture. This is confirmed by inspection of the fractured faces where failure had occurred at the interface of the wood (adherend) and adhesive, for the 470-day natural (peak load 140.8 N) and 120-day thermal (168.4 N) samples. Failure at these loads also occurs when the wood has split. Thus, it is possible that the adhesive would increase further in peak load and stiffness with aging, but for these wood samples, the values would exceed that of the wood. This could be confirmed for the aged adhesives by carrying out ASTM D2095-96 (2008). One can see in figure 3 that the displacement of 4–8 mm (0.16–0.31 in.) over 50 mm (2.0 in.) of the sample under test is commensurate with the displacement exhibited by the panel over the same distance shown in figure 1 for a 7% change in RH.

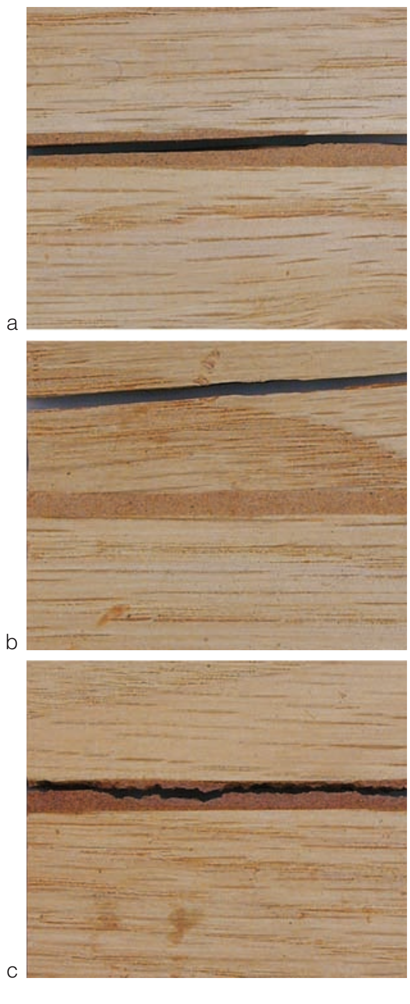
The stiffness values for the thermally aged and the 470-day naturally aged samples are comparable with the mean value for EA1253 (both stiffer than the wood). The peak load values for the 60- and 120-day thermally aged and the 470-day naturally aged samples are commensurate with the mean value for EA1253, as there is a brittle mode of fracture that runs along the interface and into the wood. Hence, aged RWCoMi behaves similarly to EA1253. Less damage to the wood occurs, as the bond with the wood is not as good as for EA1253, and thus, interfacial failure occurs preferentially.

Mowilith DMC427 with Coconut Shell Flour and Microballoons Filler (DMC427CoMi)
Both stiffness and peak load increase linearly with natural and thermal aging (fig. 4c and table 4). There is no obvious leveling off with time—a finding that suggests that further increases in properties would occur over longer periods. Interestingly, a comparison of thermal with natural aging, at 30 and 60 days, showed that stiffness and peak load increases are only slightly higher for thermal aging. In all cases, ductile, cohesive fracture occurs in the adhesive. However, the curves show a decrease in elastic deformation before fracture with increasing aging, which indicates a change to less ductile failure. Some adhesive failure at the interface occurs for a few samples, but there is no correlation with aging period. In one case, fractures also occurred within the wood along the boundary.

Jade 403N with Coconut Shell Flour and Microballoons Filler (JACoMi)
For sample JACoMi, there were insufficient data to establish trends in stiffness and peak load with respect to time. Unexpectedly, the results show a decrease in stiffness between 30 days (23.8 N/mm) and 60 days (11.4 N/mm) of thermal aging, respectively. In these tests, ductile, cohesive fracture occurred, resulting in a "tearing" of the adhesive. The adhesive was significantly weaker and less stiff than the wood. Sample

Figure 5
Tangent modulus and peak load for 32-day naturally aged adhesive fillers with contaminants. Samples are coded, with first letters indicating the adhesives Araldite 1253 (EA1253) and Evo-Stik Resin W (RW); added fillers and contaminants are also identified (see text under "Sample Names"). The range for the peak load (120–150 N) of wood tested as a continuous block is shown by the shaded area.





Figures 6a–c
Failure modes of wood samples: cohesive brittle fracture and bulk failure of the wood occurring in uncontaminated sample bonded with Araldite 1253 (a); bulk failure of the wood occurring in samples bonded with Araldite 1253 contaminated with hide glue or Paraloid B-72 (b); and cohesive ductile fracture occurring in sample bonded with Resin W, coconut shell flour and microballoons (RwCoMi) (c). Photos: Christina Young.

JACoMi is neither strong enough nor stiff enough for use as a gap filler, and it creeps at room temperature because it has a low glass transition temperature of 10.9°C (table 1).

Contaminants with Fillers

All contaminants were tested after 32 days of natural aging and compared to the gap-filler mixture without a contaminant for the same time period (fig. 5).

Araldite 1253 (EA1253)
The uncontaminated samples failed by cohesive brittle fracture and also failed at the wood-adhesive interface (fig. 6a), with a peak load of 104.9 N +/– 17.6 N. The high standard deviation indicates the variability of the initial point of failure. Inclusion of hide glue or Paraloid B-72 contaminant produced joints where failure occurred in the wood only with peak load values of 125.3 N +/– 10.6 N and 129.7 +/– 10.0 N, respectively (fig. 6b). Dammar-contaminated samples resulted in brittle fracture at the adhesive interface with a peak load of 59.3 N +/– 2.2 N. Samples contaminated with BEVA 371 had brittle fracture at the interface adhesive, within the wood, and, in one case, cohesively with a peak load of 76.7 N +/– 10.1 N. Thus, dammar and BEVA 371 weakened the joint, while Paraloid B-72 and hide glue strengthened the joint.

Resin W with Coconut Shell Flour and Microballoons Filler (RWCoMi)
The uncontaminated samples failed by cohesive ductile fracture (fig. 6c), in one case accompanied by a slight splitting at the wood interface, with a peak load of 96.7 N +/– 2.8 N. Both hide glue and Paraloid B-72 contaminant samples failed in a cohesive ductile manner. The hide glue–contaminated sample had a peak load of 96.6 N +/– 5.9 N, which was very close to that of the uncontaminated samples; thus, it does not compromise the joint. Paraloid B-72 gives a slight reduction in the strength to a peak load of 84.8 N +/– 5.5 N. Dammar and BEVA 371 contaminants

resulted in a mixture of cohesive ductile and brittle fracture with peak load values of 61.7 N +/–7.7 N and 54.9 N +/– 7.4 N, respectively. They both compromise the joint, leading to failure at lower loads, which are less predictable.

Contaminants with Hairline Joints

The results for hairline joints were consistent with those for Resin W with fillers and the same contaminants. Brittle failure in the wood occurred at a peak load of 139.7 N +/– 5.5 N for samples with hide glue contaminant. It is reasonable to suggest that the aqueous Resin W hydrates the hide glue and therefore forms a strong bond when adhered to the porous wood. For Paraloid B-72 contaminant, mainly brittle failure occurs at the contaminant-wood interface, with some loss of wood at a peak load of 108.6 N +/– 11.9 N. For dammar and BEVA 371 contaminant, adhesive failure occurs with peak load values of 38.1 N +/– 11.7 N (brittle) and 28.4 N +/– 3.3 N (ductile).

Discussion and Conclusion

In assessing the data from the thermally aged samples, it should be taken into account that, with the exception of the Araldite 1253, thermal aging was carried out above the glass transition temperatures of the pure adhesives used (table 1). For many polymers the addition of filler raises the glass transition temperature (Chartoff 1981, 536–37). For standard-formulation polyvinyl acetate (PVA) wood adhesives, the addition of filler does not significantly change their glass transition temperature, but it does increase their stiffness and hardness (Qiao et al. 1999, 26). While thermal aging does not necessarily mimic the kinetics of molecular changes that occur in the natural aging of viscoelastic materials, the results show the same general trends as for the naturally aged samples. Thus, the results do provide a guide as to which materials are highly likely to change with age. However, the methodology for thermally aging viscoelastic materials needs to be investigated.

Figure 7 shows a comparison of the maximum stiffness and peak load for the natural and thermally aged samples. Also plotted is the stiffness of the wood (49.6 +/– 4.9 N/mm at 20 N) and the range and bulk wood failure load (av. = 129 N). If one assumes that the gap filler should have stiffness similar to that of the wood and a peak failure load just below that of the wood, then one can say that, for the type of gap-filler application described here, RWCoMi and EA1253 have the required stiffness but are too strong for the cases in which a panel might exhibit large deformations.

Cohesive or adhesive failure, after curing and before testing, occurred for the stable acrylic (Paraloid B-72), PVA, and ethylene vinyl acetate (EVA) adhesives investigated, and therefore these are not suitable alternatives to commercial wood glues, wood fillers, and epoxies. Jade 403N had inadequate stiffness to serve as a structural adhesive.

EA1253 produced a very good bond with the wood, resulting in brittle fracture in all cases, often initiating in the wood and running into the wood-adhesive interface. Contaminants dammar and BEVA 371 weakened the joint, while Paraloid B-72 and hide glue strengthened the joint.

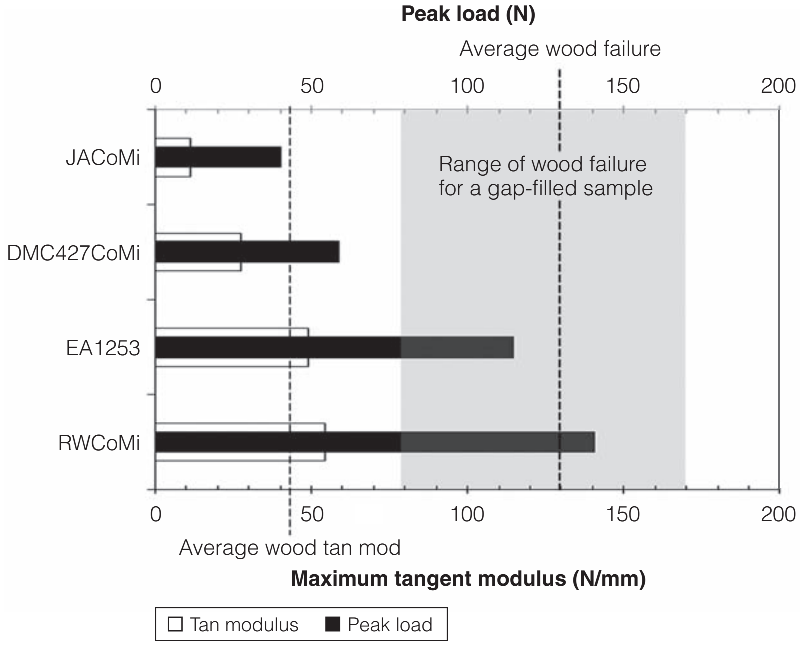


Figure 7
Comparison of the uncontaminated aged gap-filler samples at their measured maximum stiffness and peak load. Samples are coded, with first letters indicating the adhesives Jade 403N (JA), Mowilith DMC 427 (DMC 427), and Evo-Stik Resin W (RW). The added filler is identified as coconut shell flour and microballoons (CoMi). The range for the peak load (80–170 N) at which wood failure occurred in the gap-filled blocks is shown by the shaded area.

For RWCoMi, stiffness and peak load increase with natural and thermal aging. Aged RWCoMi behaves similarly to EA1253. Less damage to the wood occurs as the bond is not as good, and interfacial failure occurs preferentially. Hide glue and Paraloid B-72 contaminant samples failed in a cohesive ductile manner. Hide glue did not compromise the joint, while Paraloid B-72 gave a slight reduction in the strength of the joint. Dammar and BEVA 371 both compromised the joint, leading to less predictable failure at lower loads.

For DMC427CoMi, stiffness and peak load increase linearly with natural and thermal aging. The DMC427 copolymer formulation requires a separate study to determine its long-term stability and suitability for conservation. However, assuming from the results presented here that any changes occur relatively early, the nature of its failure mode (ductile and cohesive) means that it may still be suitable in some applications, when compared to other PVAs of the required stiffness that become brittle.

Brittle adhesive failure occurred for all samples with hairline joints. Where Resin W and/or hide glue were present as an adhesive or contaminant, the failure was at the wood interface, and the material often removed a small sliver of wood on failure. The results for hairline joints are consistent with those for Resin W with fillers and the same contaminants. Dammar and BEVA 371 compromise the joint.

Podany showed that Paraloid B-72 did not impair the tensile and shear strength of a structural joint when used as a reversible barrier layer between the substrate and a less reversible structural epoxy adhesive (Podany et al. 2001). These results have also been confirmed by Ellis (Ellis and Heginbotham 2004). Both findings are consistent with the data presented here for EA1252 and Paraloid B-72 when present as contaminants, where in these tests the acrylic resin strengthens the joint when it is subjected to bending. Their results, specifically aimed at the conservation of wooden objects, may imply that Paraloid B-72 could be applied as a reversible release layer for joining panel paintings, especially with EA1253. However, because in a hairline joint Paraloid B-72 led to an increase in strength and brittle fracture at the interface, further testing is required to establish safe parameters for its use. Preliminary tests have found that when microballoons are added to EA1253, the sample exhibits cohesive failure at a lower load.

Given the presently available options for adhesive-filler combinations, the modification of epoxies, the use of release layers, and the development of stable stiffer PVAs warrant further investigation. Measurement of fatigue lifetimes of the gap fillers in joints, under small cyclic changes in RH and temperature, is also essential for understanding their long-term performance.

Acknowledgments

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Note

1 The painting shown in figure 1 is constructed from two tangentially cut oak boards and is thought to have been thinned in the past, resulting in a current thickness of 2–4 mm (0.08–0.16). The panel has a history of splitting and repair of the splits. In 1988 it underwent treatment for splits, during which operation a cradle, buttons, and strips of canvas were removed from the reverse, and cracks were realigned and rejoined using Cascamite (urea formaldehyde) adhesive. It was then reframed with a foam block panel tray and returned to Trerice for display. The conservation treatment illustrated in figure 1, however, was necessitated after a subsequent heating failure at Trerice that resulted in a large change in RH, which caused new splits along the original central boards joint and other points of weakness.

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Further Studies on the Benefit of Adding Silica Gel to Microclimate Packages for Panel Paintings

Mervin Richard

Abstract

Panel paintings are frequently housed in microclimate packages when exhibited in less-than-ideal environments. At the "Museum Microclimate" conference in Copenhagen in November 2007, the author presented results of studies on the behavior of panel paintings in microclimate packages to which silica gel had been added (Richard 2007). These studies were undertaken to address a concern raised by some conservators and conservation scientists: since the adsorption properties of silica gel and the wooden support of the painting differ, might the disparity result in damage to the painting when a microclimate package is exposed to temperature variations? The author's research indicates that, while silica gel is unnecessary in well-designed and well-constructed packages, adding moderate quantities of properly conditioned silica gel is not only safe but potentially beneficial for packages with an air exchange rate that is higher than anticipated. Studies carried out since the Copenhagen conference lend further support to these findings.

Introduction

Extensive research and practical experience have demonstrated that microclimate packages are an effective way to exhibit panel paintings in less-than-ideal environments (Wadum 1998). In an environmental test chamber, panel paintings enclosed in microclimate packages were exposed to variations in temperature and relative humidity (RH). During these experiments, the dimensional activity of the paintings was measured with strain gages, and the environments inside the packages were monitored with electronic sensors. Additionally, microclimate packages sent to other museums were monitored for temperature and RH within and outside the packages.

Many terms have been adopted over the years for these kinds of enclosures—*clima-box, microclimate box, microclimate vitrine, microclimate frame*—but the one presently in currency at the National Gallery of Art, Washington DC, is *microclimate package*. Initial designs from the early 1980s, which enclosed both the painting and its frame, were large, heavy, and unattractive. In an effort to improve upon these designs, boxes were subsequently made of acrylic, glass, and/or metal to fit within the frame rabbet. While initial versions were less obtrusive, they were nonetheless heavy and often required enlarging the frame rabbet. Most microclimate packages today consist of a glazing material and lightweight barrier films.

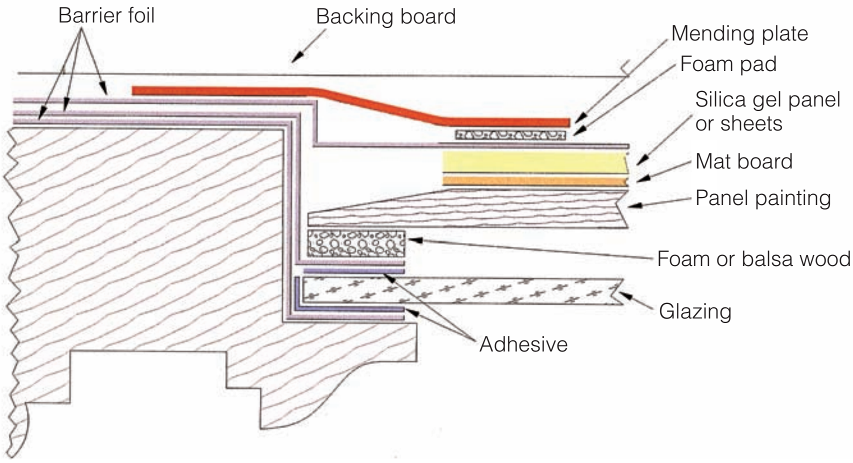


Figure 1
Design of microclimate packages often used at the National Gallery of Art, Washington DC.

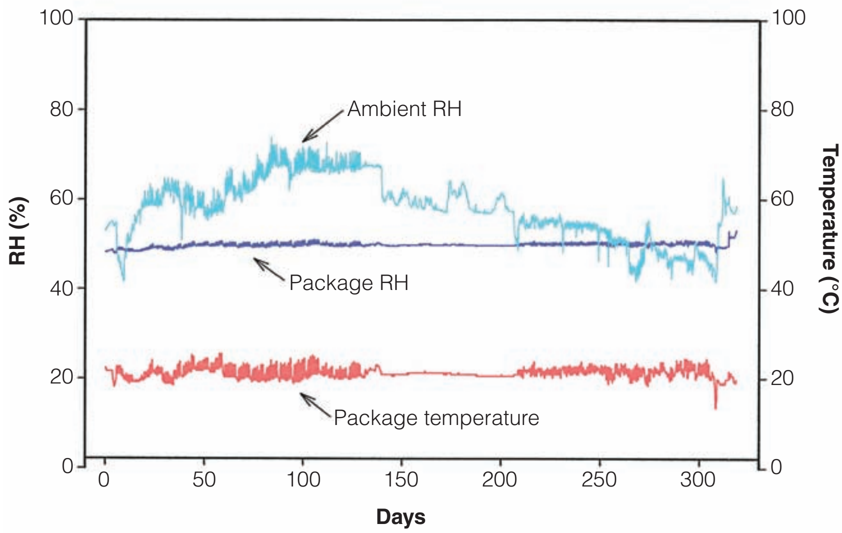
Figure 1 represents the basic design now favored at the National Gallery of Art. Two types of barrier films have proved successful: Marvelseal 360 and Mitsubishi PE/AL/PE/PET Sealing Foil. In most cases, a double layer of the laminate is used, with one layer adhered to the front and side of the glazing material and the other adhered to the inside surface. While various types of laminated glass and acrylic glazing materials have been employed, an antireflective, antistatic, clear-coated acrylic glazing is the preferred material today.

The choice of an appropriate adhesive is critical to making a well-sealed package. Over the past twenty-five years, many materials have been tested at the National Gallery of Art. Two hot melt adhesives manufactured by 3M—Scotch-Weld 3748 and 3797—have been especially effective. These materials were developed as high-performance, noncorrosive, hot melt adhesives for bonding plastics, including polyethylene and polypropylene, on electronic components. Recently 3M Scotch brand adhesive transfer tape (no. 908) has also proved effective. The acrylic adhesive has no carrier, is easily applied, and bonds well to glazing materials.

A variety of approaches have been used to contain silica gel within microclimate packages. Silica gel panels made with polystyrene egg-crate lighting diffusers and polyester mesh fabrics were the norm in early packages. The quantity of silica gel placed in these panels typically ranged from 50% to 100% of the weight of the panel. In an effort to lessen the weight, silica gel panels were later made of acid-free blotter paper and a paper honeycomb. The blotter was adhered to one side of the honeycomb with a polyvinyl acetate emulsion; silica gel was then added, and subsequently the panel was covered with a second layer of blotter paper. In recent years, one to two layers of the sheet-type Art Sorb have been used as a buffer. A piece of mat board or acid-free cardboard is often included to provide a margin of support to the rather flexible Art Sorb sheet. These materials do not have the high buffering capacity of the earlier silica gel panels, a factor that should be considered when preparing microclimate packages for venues with extreme RH conditions.

The leakage rates of several packages, all following the design in figure 1, have been evaluated with a carbon dioxide monitor (Calver et al. 2005). The observed air exchange rates for CO_2 varied from 0.1 to 0.3 air

Figure 2
Temperature and RH both inside and outside a microclimate package buffered with Art Sorb (panel painting by Lorenzo Lotto).



exchanges per day. This is quite good—indeed, significantly better than the air exchange rates of most museum display cases. Variations on this basic design—packages that travel without a frame, for example—have also tested successfully over the years. Package designs relying on gaskets, rather than on adhesives, to seal the metal foil laminate to the glazing material have proved less successful, exhibiting leakage rates in the range of 2 to 3 air exchanges per day.

Environmental Conditions in Microclimate Packages for Paintings on Loan

The National Gallery of Art has used hundreds of microclimate packages for paintings on loan to other institutions. In many instances, environmental conditions, both inside and outside the package, were monitored with dataloggers. The RH in all of the monitored packages remained extremely stable. Following are two examples that were chosen because they represent situations in which ambient conditions were unusually extreme. The results presented in figure 2 were recorded during the loan of a panel painting by Lorenzo Lotto to an exhibition with two venues.[1] The painting was enclosed in a microclimate package similar to the one seen in figure 1. Two layers of sheet-type Art Sorb were included to increase the buffering capacity of the package. While the temperature remained reasonably stable, the RH in the ambient environment varied from approximately 40% to 72%. The RH inside the microclimate package remained very stable for the entire period of the loan.

Environmental conditions outside and within a microclimate package for a canvas painting by Robert Henri are shown in figure 3.[2] While this paper focuses on panel paintings, the Henri loan serves as a good example of a package without silica gel exposed to a relatively extreme environment that varied from 15% to 55% RH. While the package design was similar to that for the Lorenzo Lotto (fig. 2), the RH within the package was less stable. It gradually dropped from approximately 52% to 44% during the period of the loan. The decline in RH resulted from the daily exchange of air with the surrounding environment. Unquestionably, silica gel would have improved the performance of this package.

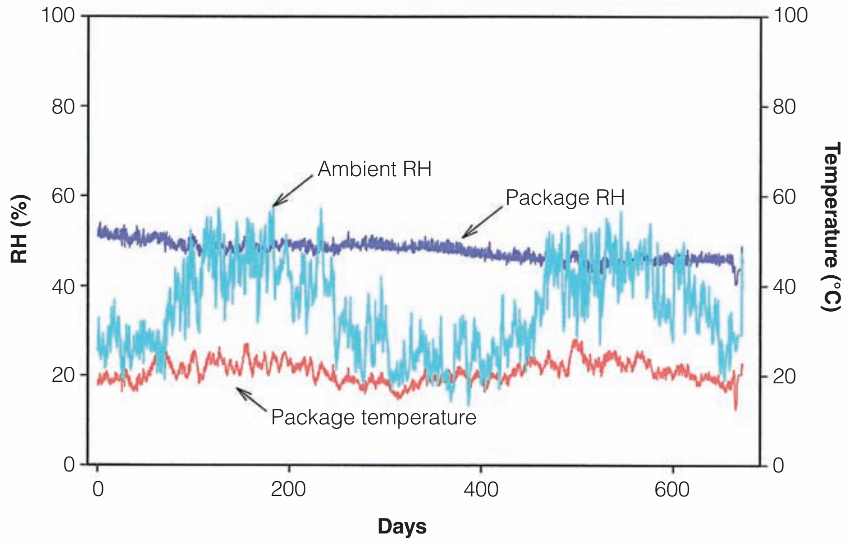


Figure 3
Temperature and RH both inside and outside a microclimate package without silica gel (canvas painting by Robert Henri).

Physical Properties of Materials in Microclimate Packages

The equilibrium moisture content (EMC) of all hygroscopic materials is affected by both temperature and RH. Wood has a higher moisture content in a cool, damp environment than it does in a hot, dry one. If the temperature remains constant while the RH increases, wood will adsorb water until a new equilibrium is reached. If the RH remains constant while the temperature increases, wood will desorb water until equilibrium is reestablished. Dimensional changes in the wood will accompany changes in moisture content.

The dimensional response of wood to variations in RH is far greater than that observed with temperature; thus, the effect of temperature on panel paintings is often ignored. However, temperature should always be taken into consideration when panel paintings are transported in cold environments. Wood is a relatively susceptible material to temperature variations. The linear coefficient of radial expansion of white oak, *Quercus alba,* is 32×10^{-6} per degree C. By comparison, the coefficient for copper is only 17×10^{-6} per degree C. It has been demonstrated that the dimensional response of panel paintings in microclimate packages, albeit small, results almost exclusively from temperature fluctuations (Richard 1991; 2007).

The physical properties of wood have been thoroughly studied. It is relatively easy to predict the moisture content and dimensional variations of wood surrounded by a large volume of air. Either a change in ambient RH at constant temperature or a change in temperature at constant RH will alter the moisture content of a panel painting. A panel painting exhibited in a room maintained at 25°C and 50% RH will have an EMC of approximately 9.1%. If the room temperature drops to 15°C without affecting the RH, the moisture content of the wood will gradually increase, to approximately 9.4%.

It is important to understand that the circumstances are different when a panel painting is placed in a microclimate package. Since there is a small volume of air surrounding the panel, there is a tiny quantity of water available for sorption. Consider a panel enclosed in a microclimate package when the temperature decreases from 25°C to 15°C. The cooling wood will adsorb water from the air until equilibrium is reestablished at a slightly lower RH. The final RH depends on the size of the panel, the species of wood, and the volume of the package, but in this example it is assumed to be 48.5%. Given the small volume of air in the package, only a tiny quantity of water must be adsorbed to lower the RH to 48.5%. The moisture content of the wood remains nearly the same. Modern packing techniques for paintings take advantage of this phenomenon by requiring paintings to be wrapped, usually in polyethylene sheeting, to create a moisture barrier.

The Debate Regarding the Use of Silica Gel

In 1966 Nathan Stolow published the results of his study of environments inside packing cases exposed to temperature variations during transit. He observed that for silica gel, unlike most hygroscopic materials, temperature has a negligible effect on EMC (Stolow 1966, 11). Stolow saw this as an advantage, because it meant that silica gel could be used to stabilize the RH in packing cases during transit. Others recognized, however, that if Stolow were correct, stabilizing the RH with silica gel would alter the quantity of water sorbed by hygroscopic materials under temperature variations (Hackney 1987; Toishi 1994). The theory was that dimensional responses accompanying excessive adsorption or desorption could damage works of art. Accordingly, word spread that silica gel should not be added to microclimate packages.

Research undertaken at the National Gallery of Art has shown that Stolow's observations on the EMC of silica gel as a function of temperature do not hold true for the silica gel products most often used by museums. The EMC of several types of silica gel, as well as other materials, has been studied with a water vapor sorption analyzer. Data extracted from Stolow's publication is plotted in figure 4, along with

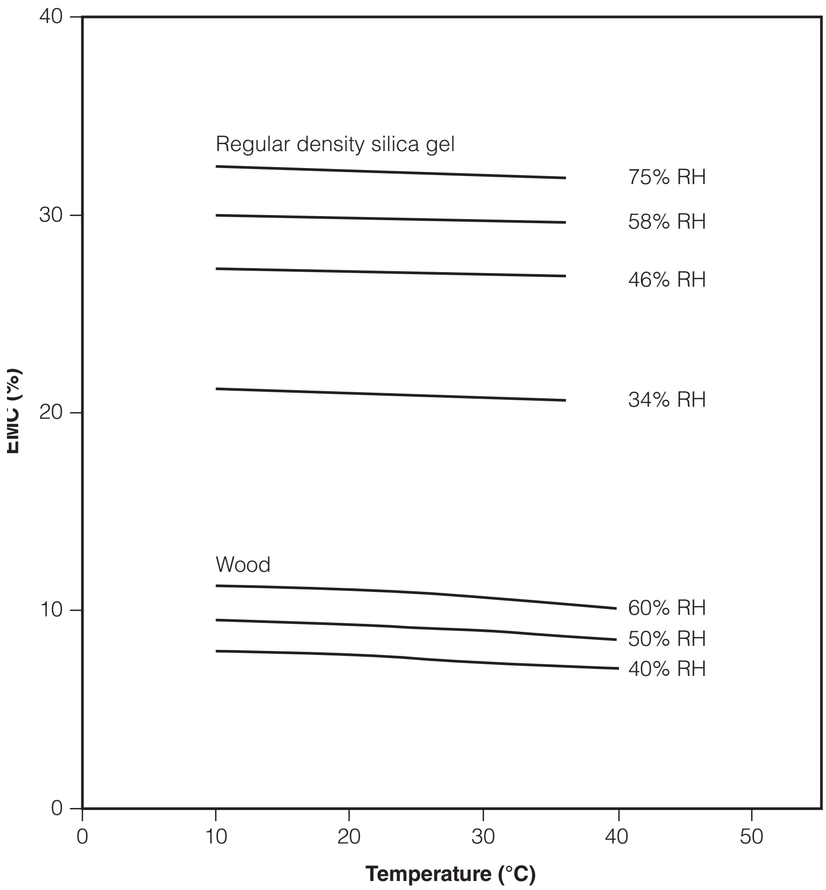


Figure 4
Relationship among temperature, RH, and equilibrium moisture content (EMC) of wood and regular density silica gel (Stolow 1966, 4).

Figure 5
Relationship among temperature, RH, and equilibrium moisture content (EMC) of wood and regular density silica gel.

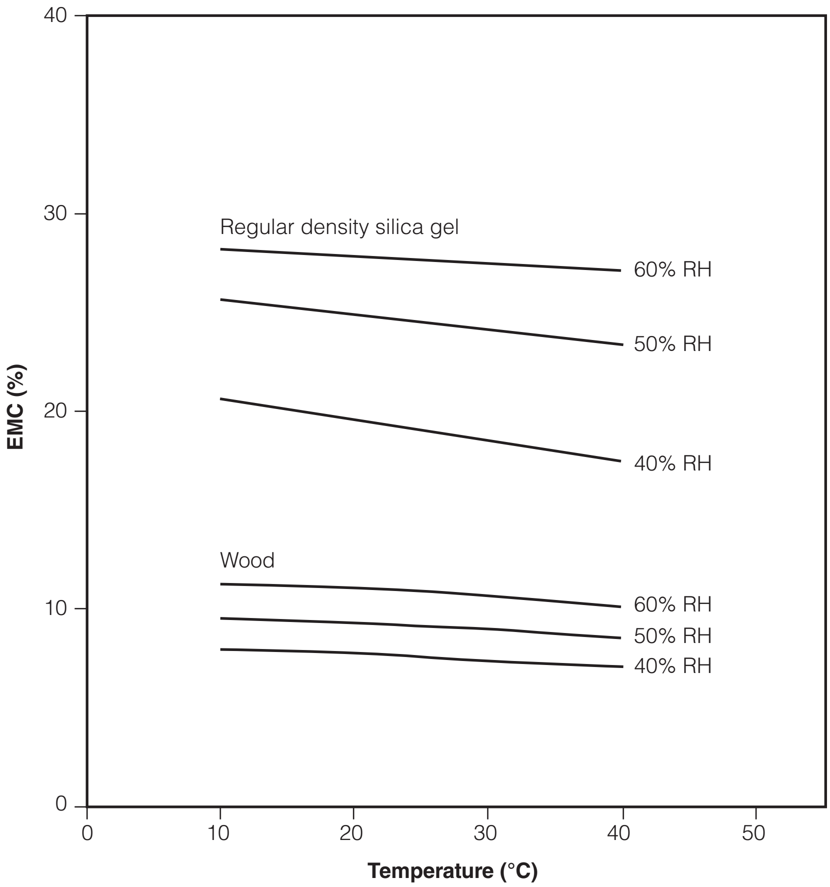
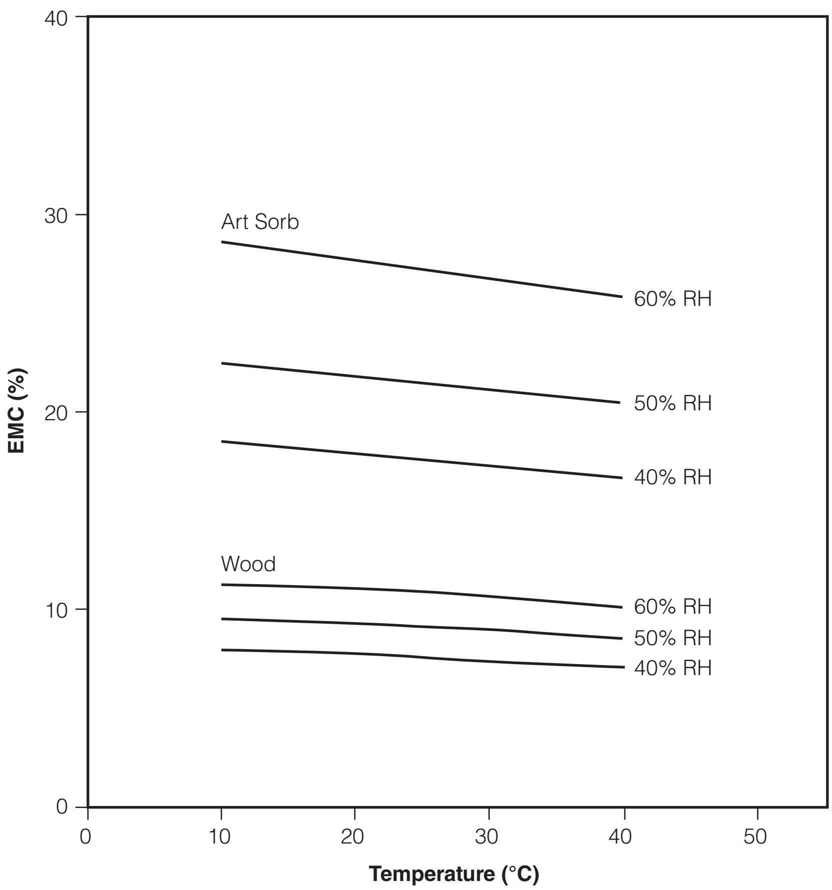


Figure 6
Relationship among temperature, RH, and equilibrium moisture content (EMC) of wood and Art Sorb.



sorption curves for wood at 15°C, 25°C, and 40°C (Stolow 1966, 4; Forest Products Laboratory 1999, 3–7). While Stolow's curves may accurately reflect the sorption behavior of the silica gel he evaluated, they differ from results obtained at the National Gallery of Art. The sorption properties of regular density silica gel and Art Sorb measured with the water vapor analyzer are found respectively in figures 5 and 6. These results demonstrate that the effect of temperature on silica gel is significant. In fact, the effect of temperature on silica gel is slightly greater than that on wood.

Conclusion

Microclimate packages are beneficial for panel paintings exhibited in less-than-ideal environments. Silica gel is not required for well-constructed microclimate packages that contain a relatively small volume of air and that are exhibited in moderate environments. But if a microclimate package has significant leakage, a moderate quantity of properly conditioned silica gel will improve its performance without adversely affecting the encased painting. The dimensional changes that occur result from the thermal responses of the wood, not from moisture content variations.

Notes

1 Lorenzo Lotto (Italian, ca. 1480–1556/57), *Saint Catherine*, 1522. Oil on panel, 57.2 × 50.2 cm (22.5 × 19.8 in.). National Gallery of Art, Washington DC, Samuel H. Kress Collection, 1939.1.117.

2 Robert Henri (American, 1865–1929), *Catharine*, 1913. Oil on canvas, 61 × 51 cm (24.0 × 20.1 in.). National Gallery of Art, Washington DC, Given in memory of Mr. and Mrs. William J. Johnson, 1948.7.1.

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Mitsubishi PE/AL/PE/PET Sealing Foil, Mitsubishi Polyester Film Inc., Polyester Film Division of Mitsubishi Plastics Inc., 2001 Hood Road, P.O. Box 1400, Greer, SC 29652, USA.

Q5000SA Water Vapor Sorption Analyzer, TA Instruments, Corporate Headquarters, 159 Lukens Drive, New Castle, DE 19720, USA.

Scotch ATG Adhesive Transfer Tape 908, 3M Corporate Headquarters, 3M Center, St. Paul, MN 55144, USA.

Scotch-Weld hot melt adhesives 3748 and 3797, 3M Corporate Headquarters, 3M Center, St. Paul, MN 55144, USA.

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Microclimate Vitrines for Panel Paintings: An Update

Laurent Sozzani

Abstract

Since the early 1990s, the practice of protecting panel paintings against short-term environmental changes by housing individual objects in microclimate vitrines has become a widely used procedure in museums around the world. This paper provides a brief update on the use of microclimate vitrines for framed paintings, following up on a previous work on the use of the picture frame as the primary vitrine housing. Construction techniques and materials for creating microclimate vitrines that use the picture frame are reviewed. Brief observations are also made on the use of buffering materials, on framing concerns, and on record keeping. New developments using the flexible laminate material Marvel Seal are introduced. Early examples of sealed packages from the National Gallery of Art in Washington DC are described, as is the construction of a sealed envelope microclimate vitrine system frequently used at the Metropolitan Museum of Art in New York. Outstanding questions concerning the conditions inside sealed microclimate vitrines—issues such as temperature difference within the closed system; occurrences of condensation, bloom, and mold; and the effect of off-gassing on a work of art—are considered, as pointers to further research on this form of environmental protection for panel paintings.

Introduction

Since the early 1990s, the Rijksmuseum in Amsterdam, as well as many other museums worldwide, has increased the use of microclimate vitrines to house paintings on wood panels and other sensitive works of art. Microclimate vitrines are used to protect paintings both during transit and while on temporary or permanent display. For paintings on wood panels, a closed sealed microclimate vitrine has been recognized as offering optimal protection from fluctuations in ambient relative humidity (RH) and temperature. The large number of loans of panel paintings made yearly by the Rijksmuseum led to the development and use of a microclimate vitrine that utilizes the painting's frame as the primary housing, a design that can be easily constructed in-house at minimal cost and with minimal effort (fig. 1). That design concept is one step in the ongoing development of methods for protecting panel paintings. This development continues in many institutions and has recently led to the use of the sealed envelope (fig. 2).

Figure 1
A microclimate vitrine that uses the painting's frame as the housing. Gabriel Metsu (Dutch, 1629–1667), *The Old Drinker,* ca. mid-17th century. Oil on panel, 22.0 × 19.5 cm (8.7 × 7.7 in.). Rijksmuseum, Amsterdam, SK-A-250. Photos: Laurent Sozzani.

Figure 2
An independent sealed envelope microclimate vitrine. Frans Post (Dutch, 1612–1680), *Brazilian Landscape,* ca. mid-17th century. Oil on panel, 22.5 × 28.0 cm (8.9 × 11.0 in.). Rijksmuseum, Amsterdam, SK-A-2333. Photos: Laurent Sozzani.

Background

Researchers internationally have validated the viability of enclosing panel paintings into simple sealed microclimate vitrines. In Holland initial research into the behavior of microclimate vitrines was carried out by the working group Research Program Microclimates: Paintings on Panel and Canvas, results of which were presented at the International Institute for Conservation of Historic and Artistic Works (IIC) Congress held in Ottawa in 1994 (Wadum et al. 1994). The following year, at the 1995 Getty symposium "The Structural Conservation of Panel Paintings," Jørgen Wadum presented an overview of the research and development of closed vitrines and microclimate systems for protecting works of art, from the early use of simple glazing and backings to modern closed microclimate systems and systems using inert gases (Wadum 1998). The proceedings of the conference "Museum Microclimates," held in Copenhagen in 2007, provide a good source of many up-to-date references on the science of environmental systems for the care of works of art, including paintings (Padfield and Borchersen 2007). These publications are important reference texts for the background and research that have led to the current construction and use of individual microclimate vitrines for panel paintings.

The use of microclimate vitrines and the principles of their construction, often intuitive, have developed hand in hand with advances in conservation science. Designs now in use are continually reevaluated in relation to the growth of knowledge in the field. As conservation science develops, it helps to define, refine, and validate the creative applications of these general designs.

The Microclimate Vitrine

Microclimate housings for works of art have been developing since the beginnings of modern conservation in the mid-nineteenth century. An intact frame sealed in the late nineteenth century, housing a Turner painting at the Victoria and Albert Museum in London, is an early example that is often cited (Hackney 2007). Microclimate vitrines for individual paintings have a practical modern history from the 1980s, and they have come into widespread use since the early 1990s. In summarizing the designs of completely closed microclimate housings, Wadum described schematically four different microclimate housings for paintings. These designs proceeded in development from a simple sealed box encasing an unframed painting, to one that encased the painting with its frame, and on to a small independent sealed box holding the painting and set into the frame (Wadum 1998). In each of these designs, a buffering material (usually a form of silica gel) was also enclosed with the painting. Further development led to the fourth design, an independent sealed box to be framed, containing the painting without extra buffering material—the exclusion of the extra buffering material being the result of research showing that in a well-sealed vitrine with minimal air volume, the moisture equilibrium between the wood of the panel and the surrounding air is maintained with little moisture exchange as temperature varies (Kamba and Nishiura 1993; Wadum et al. 1994).

An important goal in the development of microclimate vitrines has been that the painting be framed with little or no change to its overall appearance, other than its being glazed. Considerable criticism was leveled at early closed systems because of the way the construction interfered with the aesthetic appearance of the framed painting, minimal visual reference to the vitrine being important not only to the single object but also to the continuity of an exhibition.

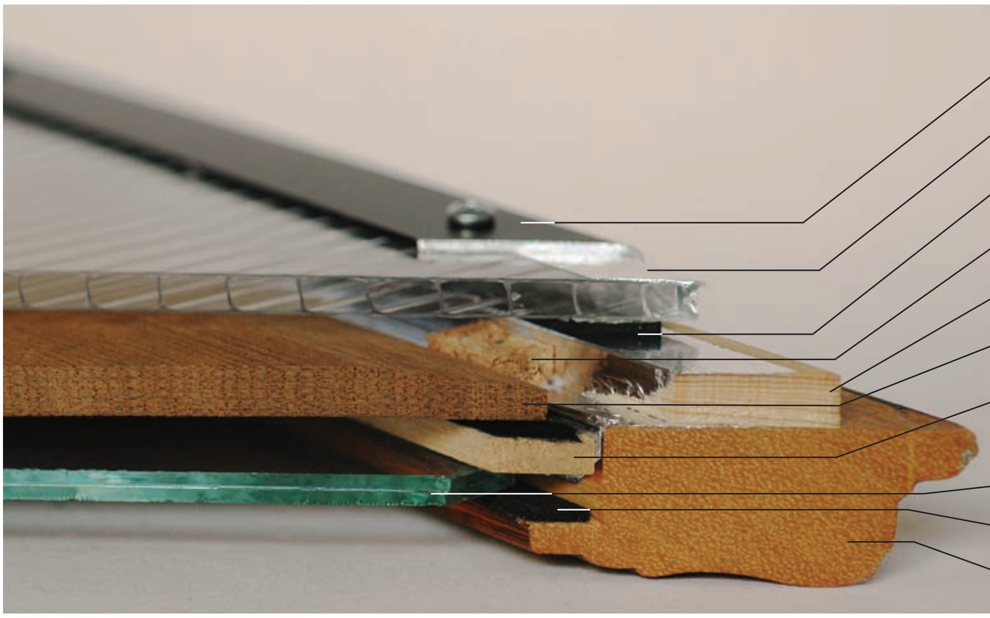
Some of the basic designs and practical applications of microclimate vitrines, as well as their advantages and disadvantages, are summarized in the following discussion.

The Picture Frame as the Primary Housing

In 1997 I described an economical design for making a microclimate vitrine using the picture frame as the primary housing (Sozzani 1997). In this design the picture frame becomes a microclimate vitrine by simply sealing it closed with glass and an impermeable backing board. There is no independent housing for the painting, only the sealed frame. However, if the interior of the frame is covered with an impermeable material, in essence an inert box is created. Variations of this simple design are now widely used in museums and private collections (fig. 3).

Specific Design Aspects: Changes, Advantages, and Disadvantages

When an institution is faced with having to construct many vitrines, as often occurs in museums with active loan programs, simplification of the vitrine design and standardization of materials are important. At the Rijksmuseum, as with other similar collections, standardization is important because of the large number of panel paintings that travel or, as is the case today in the Rijksmuseum, are on exhibit in small galleries with very large numbers of visitors. Even so, standardization is always only a starting point, as each painting and frame combination will pose its own requirements for configuring the various components of the vitrine.



The Back Plate

The first vitrines made in the Rijksmuseum that utilized the frame as the primary housing used stainless steel plates for closing the back. The edges of the metal plate were bent over to provide the rigidity needed for a good seal (Sozzani 1997). An alternative back plate material proposed at that time was polycarbonate twin-wall sheeting. However, by the time of publication, polycarbonate had already become the material of choice at the Rijksmuseum. Lightweight, semitransparent, and easy to cut, it became a viable substitute for the heavier and more costly metal plate. In order to seat the bent edges of the metal plate, a buildup on the back of the frame was always required. With the polycarbonate, a buildup is only necessary to accommodate the thickness of the painting.

When the polycarbonate is used, aluminum strips are attached along the back edges of the polycarbonate. The aluminum has one rounded-over edge, similar to the bent edges of the steel plate. The bent edge adds rigidity to the strip, and when it is screwed down over the polycarbonate, it ensures that the neoprene gasket, which is attached to the inside of the plate, is evenly compressed against the back of the frame, giving a good seal. The aluminum is either painted or anodized black, and as a rule of thumb, the screws holding the back plate are no farther than 10 cm (3.9 in.) apart. This design allows the back to be easily opened and reclosed whenever necessary.

Polycarbonate backing plates have also been used without the aluminum strips. To prevent possible leakage, some designs have used aluminum tape to bridge the polycarbonate and the back of the frame (Instituut Collectie Nederland 2004). Though initial adhesion is strong, the tape is vulnerable to losing adhesion or tearing.

On occasion, it can be necessary to open a vitrine during travel. A successful procedure of opening and resealing the vitrine depends on the understanding and capacity of the courier or technician present and on the availability of proper materials. A well-taped join, created with any of a variety of relatively impermeable tapes, should ensure a stable microclimate for at least the duration of the average loan exhibit.

Figure 3 (opposite page)
Cutaway view of the basic configuration and elements of a microclimate vitrine that uses the picture's frame as the primary housing. Photo: Laurent Sozzani.

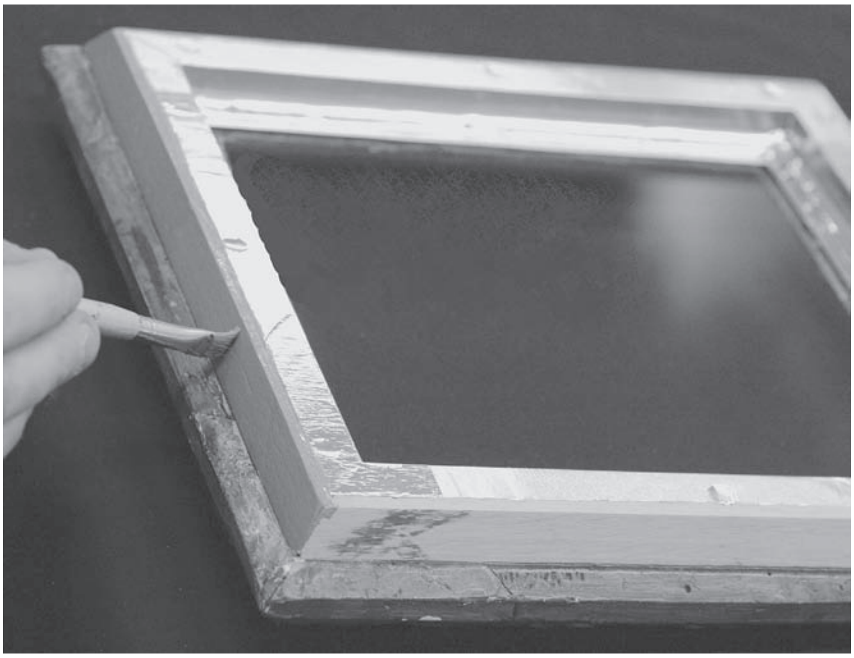


Figure 4
A buildup at the back of the frame in the process of being painted. Note the sloping angle of the outer edge of the wood addition, a feature of a traditional frame design. Photo: Laurent Sozzani.

Interior Taping

Aluminum tape is often used to completely cover all exposed interior wood surfaces of a frame. The tape closes small holes and cracks, creating a barrier to moisture exchange with or through the frame. Application of the tape can be tedious, and the tape can be difficult to remove. A thin low-tack tape placed directly on the wood below the aluminum tape can facilitate removal.

Appearance of the Back of the Frame

A minor but important point to consider when adding a buildup to the back of the frame is the appearance. Even though it will generally be out of sight, it is important to take into consideration how it will look if viewed from the side. If the buildup has any height, it is visually more pleasing to cut the addition at a slight angle and then to tone it dark or to paint it with a traditional frame color, such as deep ocher (fig. 4).

Extra Buffering Material: Silica Gel and Museum Board

In researching the use of silica gel, Mervin Richard has shown that there is little difference in dimensional changes of panels in well-sealed vitrines when silica gel is present and when it is not (Richard 2007). At the Rijksmuseum, as in many other institutions, silica gel is not used in sealed microclimate vitrines. This practice follows the notion that in a well-sealed vitrine, little moisture will be exchanged between the wood panel and the small volume of enclosed air when there are changes in temperature. Further, inclusion of silica gel may be undesirable if a microclimate vitrine remains at an elevated temperature, during which time the silica gel can become an unwanted sink, absorbing moisture being released from the panel. Conversely, a drop in temperature could trigger a release of moisture from the silica gel that could then condense on the inside of the glass or on the painting.

When a wood picture frame is used as the vitrine housing, it is assumed that the exposed wood interior reduces the burden of moisture

Figure 5
A simple framing attachment along the central axis, in the direction of the wood grain of the panel. Gerard van Honthorst (Dutch, 1590–1656), *Amelia van Solms,* ca. 1647. Oil on panel, 74.3 × 59.8 cm (29.3 × 23.5 in.). Rijksmuseum, Amsterdam, SK-A-573. Photos: Laurent Sozzani.

exchange between the panel and the air space within the vitrine. Covering the interior of the frame with aluminum tape eliminates this effect. Richard notes that, in order to replace this benefit, a thin sheet of museum board is placed behind the painting as a temperature-responsive buffer. Richard has also confirmed this to have a slight buffering action, slowing changes in RH.

Framing Basics

It is recognized that framing can directly affect the stability of a panel painting. Although framing attachments are meant to be protective, when there are too many holding the panel in place, the movement of the wood can be restricted, and cracking and paint loss may occur.

It is important that the painting be held securely without there being any restriction on potential dimensional changes, especially those perpendicular to the wood grain that might result from changes of internal moisture, even if in a closed system. Though more sophisticated framing methods can be necessary for especially sensitive, fragile panels, in general and in the simplest form, panel paintings at the Rijksmuseum are secured in their frames with either wood or metal blocks and cork or foam that are attached to the frame only (fig. 5). These blocks hold the panel solidly in position along only the central axis in the direction of the grain of the wood. This scheme allows free lateral expansion and contraction and does not restrict concave deformation at the back of the panel. A panel with severe or complex surface deformation may also require special adaptation of the frame rabbet to accommodate the curvature. A simple added precaution, used occasionally during transport of larger, flexible panels, is to place soft foam blocks between the frame and panel to dampen movement without restricting dimensional changes.

Developments Using Flexible Plastic Laminates for Vitrine Construction

An alternative to using a solid backing plate and directly lining the frame rabbet with aluminum tape is to substitute both with impermeable laminate sheeting. The National Gallery of Art in Washington DC has used flexible laminated moisture barrier films for microclimate packages since 1992 (Richard 2007).

On such film, Marvel Seal, is a versatile material used in commercial packaging. It is also used to seal art objects for transport and to make enclosures for anoxic treatment of works of art. It is a nylon-aluminum-polyethylene triple laminate that has the advantage of being very strong (from the nylon) and virtually 100% impermeable (from the aluminum). The polyethylene allows it to be heat-set to itself. Other similar impermeable plastic laminates, also used in packaging and in anoxic treatments, have the added advantage of being clear and can be used if visibility of the back of the object is desirable or necessary.

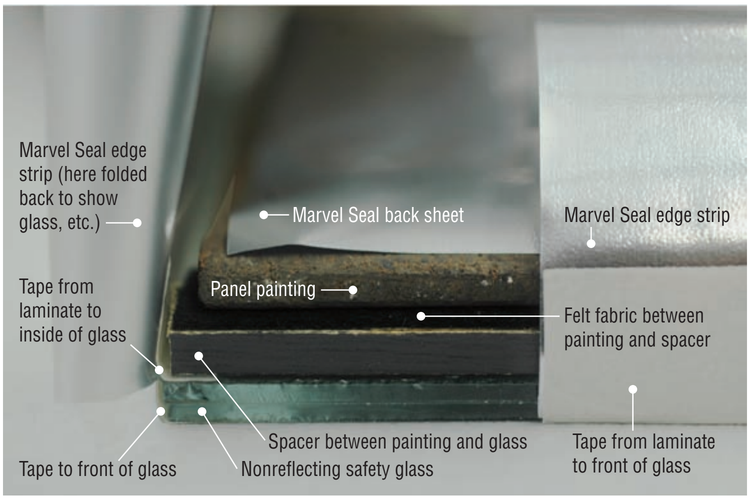
In one configuration used at the National Gallery, the Marvel Seal is sealed onto the glass and loosely lines the frame rabbet. The painting is secured in the frame, and a sheet of Marvel Seal is heat-sealed to the rabbet lining. This creates the closed microenvironment. A backing board attached to the frame protects the laminate sheeting. In another configuration, the Marvel Seal is attached to the glass, wrapped around the painting, and heat-set to transparent acrylic sheeting. Other institutions have used Marvel Seal to line the inside of wood backings, rendering the wood impermeable.

Sealed Envelope Microclimate System

The innovations that use laminated sheeting have led to the development of the "sealed envelope." Simply stated, the sealed envelope is an independent package of laminate attached to the glazing that contains the painting. This design can be routinely used and has the potential to reduce dramatically both the materials and the time necessary for enclosing a painting. Many designs rely in some way on the frame for construction. More recently, as with earlier criticism regarding aesthetic presentation, concern has arisen regarding the amount of alteration or intervention to the frame that is necessary when a frame is transformed into a microclimate vitrine. Keeping intervention to a minimum is of particular concern when an antique or original frame is being used. Newer design concepts have now minimized this problem.

The sealed envelope is closely related to an earlier concept, also an independent enclosure, which is generally known as the Wight box, named after its manufacturer George Wight (Bossard and Richard 1989; Bossard 1990). It, however, uses a rigid metal box as the housing. In contrast, the new sealed package is constructed by attaching only the flexible laminate to the glazing. The laminate wraps around the painting and is sealed, enclosing the painting. The painting is then framed. Many institutions have now adapted the method.

One great advantage over built-in-the-frame housing is that only minimal or no extra intervention to the frame is necessary. It is not necessary to enlarge the frame rabbet, as was often the case with the rigid box. Sealing the interior of the frame is no longer necessary, and a buildup on the reverse is only needed in frames with the most shallow rabbet, or when there is a desire to add protection to the package rather than to create the microclimate enclosure.



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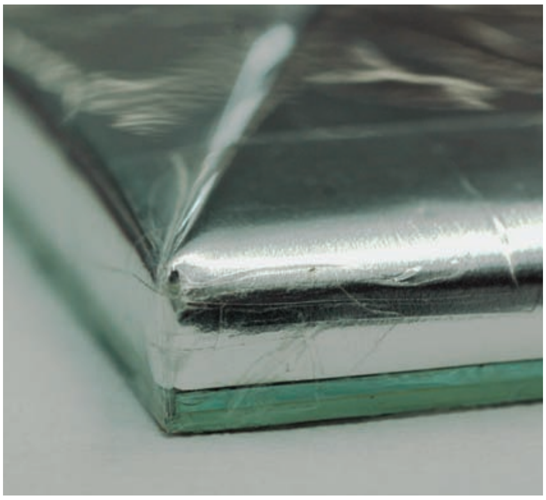


b

Figures 6a and 6b
A sealed envelope microclimate vitrine: Cutaway view of the basic configuration and elements (a); the same package after completion (b). Photos: Laurent Sozzani.

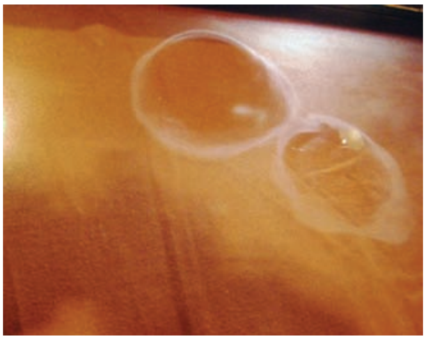
At the Metropolitan Museum of Art in New York, George Bisacca and Alan Miller have been refining the construction of the sealed envelope since early discussions with Richard (see poster by M. Alan Miller, "Marvel Seal Envelopes at the Metropolitan Museum of Art," in this volume). The basic materials for the sealed envelopes constructed at the Metropolitan Museum are glass, polyester tape, and Marvel Seal, plus spacers to separate the painting from the glass and any additional material necessary for centering the painting. In short, a tray is made by taping a strip of Marvel Seal around the edge of the glass. To reduce the possibility of leakage, tape is attached just over both the inside and the outside edges of the glass, sandwiching the Marvel Seal in between. The spacer and painting are set into the tray and covered with a back sheet of Marvel Seal. The strip is folded over and sealed closed with tape (figs. 6a and 6b).

If the sealed envelope is carefully made, there should be no leaks, and when the plastic laminate is pulled tightly against the panel during closing, the panel and spacer should stay in position. If the glass, spacer, and/or painting differ in size, additional shims may be required at the sides to center the picture. Securing these extra pieces, as well as the spacer, also prevents them from shifting out of place. If necessary with a fragile or uneven panel, adding a piece of museum board into the envelope behind the painting can provide a smooth, solid surface to aid in closing the package tightly. It may also be necessary to build up the inlay to conform to the configuration of a distorted panel. As with any general design, adaptations can always be expected.

A tight, solid, and secure construction is very important. Closing the package tightly around the contents reduces the air volume, thus maintaining the moisture equilibrium with the least amount of water migration. The package can be secured into the frame with normal hardware. If necessary, after framing, the addition of a normal backing board can protect the plastic laminate.

Record Keeping

An important document that can travel with a microclimate vitrine is a description of the construction along with a diagram and/or photo. Opening a microclimate vitrine during a loan is undesirable, but it has occasionally been necessary, usually to clean the glass or remove an unsightly piece of debris. Regardless of who has the responsibility for opening the



a

b

Figures 7a and 7b
Problems associated with excess moisture: Condensation on the inside of the glass of a vitrine, after the artwork had traveled to two loan venues (a); mold that developed in a vitrine that housed a painting on exhibit in an unclimatized castle in the Netherlands (b). Photos: Laurent Sozzani.

vitrine, a description explaining the construction is helpful: first, for evaluating whether the problem is worth the effort; and second, for conveying what opening and reclosing the vitrine will entail. Also important is a label on the back plate indicating that the painting is housed in a microclimate vitrine and should not be opened without permission of the owner.

Summary and Future Considerations

The use of microclimate vitrines is widely accepted as a safe and nonintrusive conservation practice. However, problems have occurred that raise questions regarding long-term use of closed systems, and questions remain to be addressed. Differences in the environment (temperature, RH, and/or composition of the air) in front of and behind the painting due to lack of circulation will occur. Can the differences be great enough to cause a problem? Can the addition of a buffering material, be it silica gel or simple cardboard, accentuate any difference?

Problems associated with excess moisture—such as condensation on the inside of the glass, development of mold, or bloom on the surface of the painting—have all been noted at the Rijksmuseum and by other users (figs. 7a and 7b). What conditions lead to these effects? It has been shown that elevated temperature will result in elevated RH in a closed system containing hygroscopic material. High RH followed by a drop in temperature can result in condensation accumulating on the inside of the glass, the cool surface of which would have an affinity for attracting moisture. What can or should be done to avoid these problems?

Cleaning the interior and contents of the vitrine before assembly can reduce the possibility of mold development. Avoiding elevated temperatures can also be a general precaution; however, closed vitrines are often used because the picture is being displayed in a room where temperature fluctuations are outside the acceptable range. What are the limits of acceptable fluctuations for panels in sealed microclimate vitrines?

Another issue is that of off-gassing of materials enclosed in the vitrine. Can off-gassing of the adhesives, the gasket materials, any paint or other materials used, or compounds from the painting itself cause a problem or aggravate an inherent problem in the artwork? As off-gassing occurs, will an equilibrium be reached that slows or stops the off-gassing? Or is there a need for the addition of a pollutant-absorbing material in the vitrine? Is it necessary to “air out” a closed system? Can being in a sealed vitrine ever be more dangerous for the object than being in the open air?

These questions, and others that will inevitably arise, will eventually be answered by the research that continues in the area of closed systems for the conservation of our patrimony. However, for the present, a well-constructed, well-sealed vitrine with minimal internal air volume can be considered the best protection for a panel painting when it is in transit, or when it is kept in a less than stable environment.

Acknowledgments

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Materials and Suppliers

Luxar glass, www.luxar.ch/en/luxar/index.html. Search site for local distributors.

Barrier films: **Marvel Seal 360** (aluminized polyethylene and nylon film) and **FR1275B** (aluminized polypropylene film), available through many conservation suppliers. Both films resist the transmission of water vapor and other atmospheric gases.

Schott Mirogard Protect Glass, www.schott.com. Search site for local distributors.

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Allowable Microclimatic Variations for Painted Wood: Direct Tracing of Damage Development

Roman Kozłowski, Łukasz Bratasz, Łukasz Lasyk, and Michał Łukomski

Abstract

Specimens simulating historic panel paintings were subjected to cycles of mechanical stretching and compression to imitate dimensional changes induced by repetitive fluctuations of relative humidity (RH) in the microenvironment of painted wood. Up to 36,000 cycles, equivalent to 100 years of diurnal fluctuations, were performed in order to estimate the cumulative damage of strain cycles. Development of cracks in the decorative layer was monitored using a laser speckle decorrelation technique that enabled physical fracturing to be monitored at the microlevel before damage was discernible from the macroscopic perspective. Plots of cumulative crack length versus number of cycles causing that fracture were obtained. Strain of 0.15% was found to be tolerated by the specimens even for the maximum number of cycles, whereas strain of 0.25% produced initial cracking after 5000 cycles only. Therefore, strain of approximately 0.2%, close to the yield point of gesso, was confirmed as a critical level that the polychrome wood could endure without damage. Local variations in strain reflecting the anisotropic elongation of the wood substrate need to be determined to assess the magnitude of RH variations necessary to cause the critical strain. The slow response of panel paintings to rapid variations in RH and their usual deformation, which reduces the effective movement experienced by the decorative layer, as well as stress relaxation of gesso during long-term variations, all have a bearing on the susceptibility of painted wood panels to cracking due to cyclic environmental changes.

Introduction

Uncontrolled variations of ambient temperature and relative humidity (RH) are the principal hazard to the preservation of panel paintings, which are frequently exposed to real-world, dynamically changing environments. Materials that constitute panel paintings, such as hide glues, gesso, paints, and varnishes, respond to these variations by gaining moisture when humidity is high and losing moisture when the surrounding air is dry. The materials respond dimensionally to the sorption and desorption of moisture; they shrink as they lose moisture and swell when they gain moisture. A notable effect is that panel materials each respond differently to the loss and gain of moisture, which induces high stress in the different layers of painting, leading to damage if the strength of a given material is exceeded.

Substantial investigations have been undertaken to quantify mechanical properties and swelling response of materials that constitute painted wooden objects (Mecklenburg, Tumosa, and Erhardt 1998;

Richard, Mecklenburg, and Tumosa 1998). The yield points (that is, the strain levels at which materials begin to deform permanently) have been determined as 0.4% for woods, paints, and glues, and 0.25% for a brittle gesso found in historic panel paintings. Much higher strains—0.9% or greater—were found necessary to cause failure. Swelling responses of the panel materials were measured for a full range of RH and expressed as rates of dimensional response—that is, variations in strain per unit change in RH. While these rates are low, in the range of 40–60% RH, the wood and glue show dramatic increases outside the range when compared to far less responsive gesso and paint. The mismatch in the response of gesso and wood, especially in the most responsive tangential direction of the wood, has been identified as the worst-case condition: upon desiccation, the shrinkage of wood overrides that of the gesso, which undergoes compression, whereas upon wood swelling, the gesso layer experiences tension. If the uncontrolled changes in the dimensional change go beyond a critical level, the gesso can crack or delaminate. We have assumed that the strains induced by the mismatch in the dimensional response should not exceed a yield point for gesso, either in tension or compression. Therefore, allowable changes in RH were calculated as those inducing in the gesso layer a strain level of 0.25%. As the rates of dimensional changes depend strongly on RH, the allowable RH variations were presented as functions of starting RH levels; for example, the allowable increase of RH is 12% for a painting on a substrate of cottonwood (*Populus* spp.), equilibrated at 50% RH before tensile yielding in gesso occurs, while the allowable decrease in RH is 17% before the compression yielding.

The approach just described, however, raises further questions. Is the yield criterion (0.25%) really a critical strain above which damage in gesso occurs? As stressed in the literature (Mecklenburg, Tumosa, and Erhardt 1998), the criterion is conservative, and it would be interesting to explore to what extent it actually applies. Furthermore, the critical strains—both yield points and strains at failure—are measured in mechanical testing programs by loading the specimens and recording the stress-strain relationships. They represent, therefore, strains for deformation or failure in a single loading cycle only, whereas smaller repeated strains resulting from many cycles of humidity fluctuations may lead to fatigue fracture as a consequence of the cumulative strain effects. The necessity of a correction of critical strains due to fatigue from multiple fluctuations has already been stressed (Michalski 1991; 2009), but there has been little research in this area. Yet the continuous accumulation of slight changes, rather than infrequent serious damaging events, accounts for much of the deterioration of painted wood observed in museums and historic interiors.

The aim of the present paper has been to establish experimentally the *S-N* relationships for specimens imitating historic panel paintings, where *S* is strain leading to fracture of gesso, and *N* is the number of cycles that caused that fracture. Cycles of strain were produced by mechanical stretching and compression of the specimens, which simulated dimensional changes induced by repetitive fluctuations of RH. Fracturing of the gesso layer was directly and accurately monitored with a laser speckle decorrelation technique, which is capable of monitoring physical damage at the microlevel before it is discernible visually.

Materials and Methods

Preparation of Specimens

Lime wood (*Tilia* spp.) was selected as the wood substrate, as this wood species was widely used in central Europe in the past to produce wooden sculptures or supports for panel paintings, for reasons of availability and ease of processing. The specimens were cut from the outer part of the trunk and air-seasoned for three years under shelter. Their dimensions were 15 cm (5.9 in.) parallel to the grain and 7.5 cm (3.0 in.) transverse to the grain. The thickness of the specimens was 1 cm (0.4 in.).

The wood substrates were sized with the rabbit-skin glue prior to being coated with gesso. The gesso was composed of rabbit-skin glue and ground chalk; the ratio of the inert solid to glue, expressed as the pigment-volume concentration (PVC), was 92%. The PVC value was practically selected by a participating restorer as being that which has been commonly used in the restoration of panel paintings. Six coatings of gesso were applied, and the thickness of the dried gesso layer was approximately 1 mm (0.04 in.).

Strain Cycling

The dimensional changes were mechanically simulated using the Universal Testing Machine from Hegewald and Peschke. The specimens were securely clamped in the machine, as shown in figure 1, and subjected to stretching and compressing at selected amplitudes. The frequency of the strain cycles was approximately 0.3 Hz, and the specimens

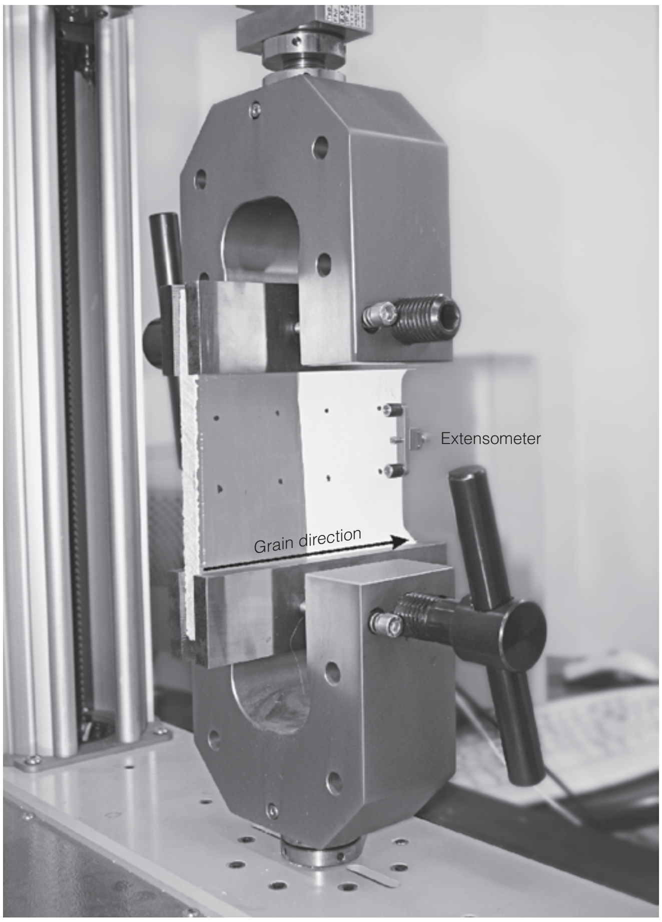

Figure 1
A specimen imitating a historic panel painting subjected to cycles of stretching and compressing in a machine for mechanical testing. The specimen accommodates two testing fields: plain gesso and gesso covered with stiff and brittle alkyd paint. Photo: Roman Kozłowski.

were subjected to 36,000 cycles (unless the specimen had been damaged before), approximately equivalent to one hundred years of diurnal climatic fluctuations producing the same dimensional response. A MINI MFA2 extensometer from FM Mess- & Feinwerktechnik GmbH was used to monitor the strain of the specimens continuously; in this way an accurate measurement was obtained of the strain undergone by the area being monitored for damage development. The experiments were conducted under a constant RH of 50%, maintained in the laboratory by humidifying/dehumidifying equipment controlled by a humidistat. The specimens were taken out after a predetermined number of strain cycles, and the fracture development in the gesso was monitored by the speckle decorrelation technique.

Speckle Decorrelation

A thorough description of the application of speckle methods for the analysis of panel paintings was published in a review paper by Ambrosini and Paoletti (Ambrosini and Paoletti 2004). In simple terms, a speckle pattern—a granular pattern of light and dark—is produced whenever a rough surface is illuminated by a laser source as a result of interference between the source and the reflected light. When a deformation of the same order of magnitude as the wavelength of the laser is induced on the surface, a change in the speckle pattern occurs. In this study, a digital image correlation system for the analysis of speckle decorrelation was developed using a continuous-work diode-pumped Nd:Yag laser (100 mW) from Power Technology, and a BCi4-6600 CCD camera from C-cam Technologies (6.6 MPixel; 2208 × 3000 pixels). The specimens were heated with a halogen lamp (the increase of the surface temperature was approximately 2–3°C), then the cooling process was registered. Immediately after the lamp was switched off, the speckle pattern on the gesso surface was recorded as a reference image, and then the consecutive images recorded at time intervals below one minute were subtracted from the reference one and displayed on the computer monitor. If the images were perfectly correlated, they would cancel completely when subtracted. If there were some difference—in the present case, a different deformation of fractured area on cooling—the defects were visible as bright areas. By way of example, figure 2 shows the development of fractures in the gesso layer traced by speckle decorrelation in the course of mechanical cycling of a specimen at a strain of 0.25%. The experiment shows that the speckle decorrelation technique can provide quantitative information about the number of cracks in the surface layer and their length. Consequently, an assessment of the cumulative damage as a function of the number of cycles was possible.

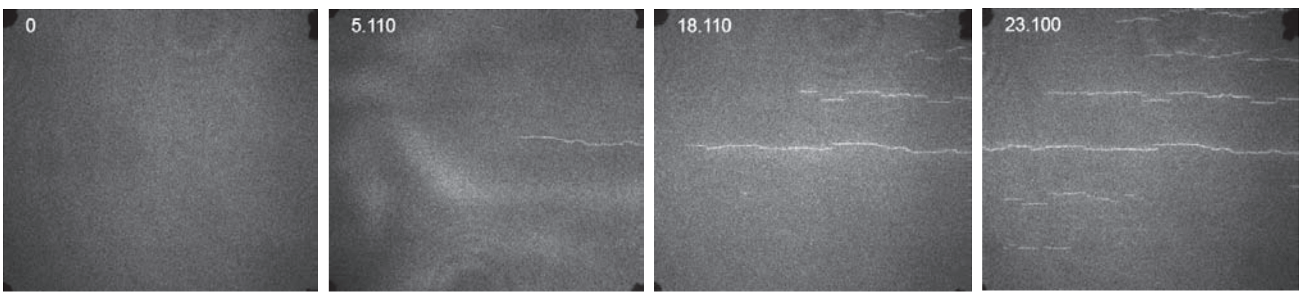

Figure 2
Development of gesso fracturing at four intervals in the course of mechanical cycling of a specimen at a strain of 0.25%, as visualized by speckle decorrelation; the number of cycles is given on each image. The dimensions of the areas covered by the images are 35 × 35 mm (1.4 × 1.4 in.). The progressive development of crack networks generally perpendicular to the direction of the applied strain is clearly evident. (Note that images obtained by laser speckle decorrelation are, by nature, intrinsically grainy.)

Results and Discussion

Figure 3 shows plots of the cumulative crack length versus the number of cycles for a range of strains between 0.15 and 0.5%. Three specimens were tested at each strain level. Good repeatability was observed in the number of strain cycles necessary to cause the first fracture on the virgin gesso, as illustrated by coincidence of the three sets of results for strain of 0.35% that are plotted in figure 3. The small number of specimens tested at each strain level does not allow for experimental uncertainty analysis. However, the difference in the number of cycles leading to the first fracture at strain levels of 0.4% (3 cycles) and 0.5% (10 cycles), respectively, provides some estimation of the uncertainty of the measurements. The results indicate that the critical strain for gesso is approximately 0.2%: no fracture after 36,000 cycles (approximately equivalent to one hundred years of diurnal variations) was observed for strain of 0.15%, whereas strain of 0.25% produced first cracking after 5000 cycles only. Strains of 0.4–0.5% caused fracturing in just a few cycles.

Figure 4 shows an *S-N* curve for the specimens investigated, where *S* is the strain leading to fracture and *N* is the number of cycles to cause the first incidence of fracture at that strain. The general curve shape is sigmoid, starting from the stress for fracture in a single cycle or a few cycles, and dropping to a plateau where cyclic stress can be tolerated indefinitely; the strain of 0.15% was assumed to be close to that value for any practical assessment of the risk of damage. So the strain tolerable indefinitely is approximately one-third of the single-cycle fracture strain.

The results have confirmed the assumption of earlier research that the yield point for gesso corresponds approximately to the critical strain above which damage appears. It should be recalled at this point that the yield point corresponds to the amount of strain at which the material, in this case gesso, goes beyond the elastic (fully reversible) region to the plastic (irreversible) region. Therefore, the yield point can be considered as a minimum strain at which any risk of nonrecoverable change in gesso appears. The results presented have confirmed that using the yield point of gesso to determine the allowable RH fluctuations is a fairly conservative approach, as several thousands of stretching cycles at the strain corresponding to the yield point were necessary to observe

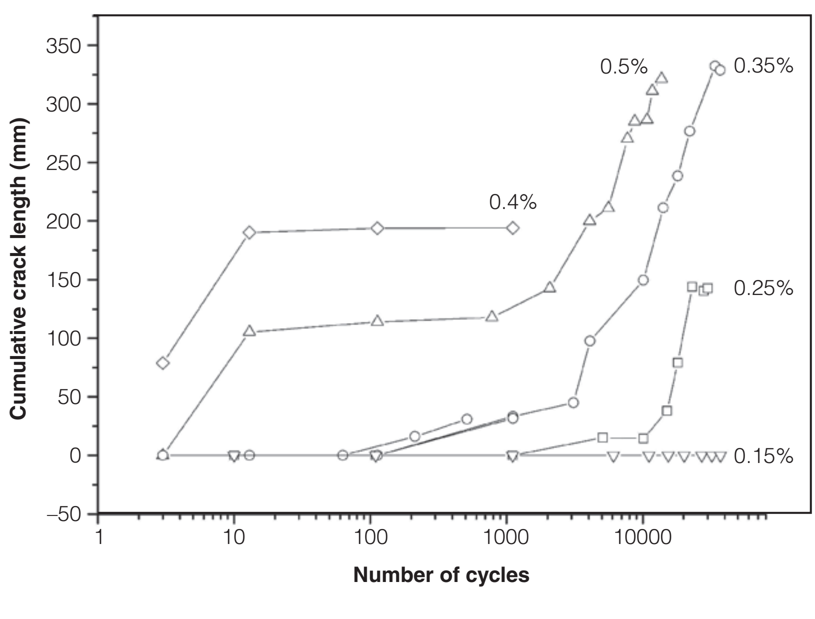

Figure 3
Cumulative crack length versus number of cycles for a range of strains between 0.15% and 0.5%. Three sets of results for strain of 0.35% are plotted; they illustrate that a consistent value for the number of cycles leading to the first fracture on the virgin gesso is obtained in the experiments.

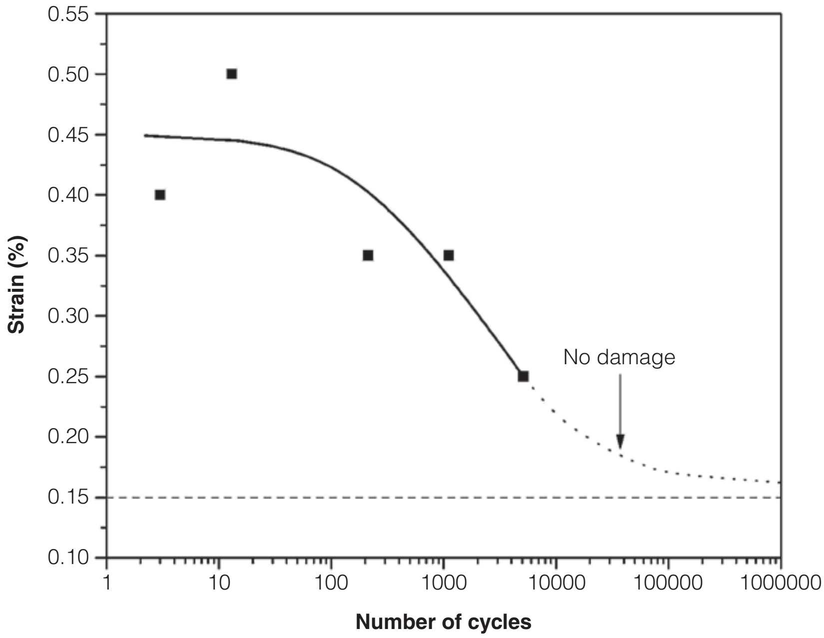

Figure 4
Strain leading to fracture versus number of cycles to cause fracture at that strain.

the first incidence of cracking. In the tests of Vici, Mazzanti, and Uzielli (Vici, Mazzanti, and Uzielli 2006), the time required for a 4 cm (1.6 in.) thick poplar board to reach equilibrium to new humidity conditions was three months. Only four RH cycles per year, therefore, are able to subject the gesso to full strains corresponding to new equilibrium in the wood support for such a category of objects. Five thousand strain cycles needed for the first incidence of cracking to appear would correspond to a very long time of exposure of more than one thousand years.

Conclusion

The experimental approach involving mechanical stretching and compression of specimens imitating historic panel paintings and monitoring the development of cracks in the gesso layer with the use of laser speckle decorrelation has allowed for better insight into the allowable levels of climate-induce strains in the environment of panel paintings. A strain of 0.25%, corresponding to the yield point for gesso, was confirmed as the critical strain at which damage appears. The investigations have also confirmed that the assessment is very conservative, as fracture at that strain has appeared only after several thousands of cycles.

Assessing the magnitude of RH variations necessary to cause the critical strain on swelling or shrinkage requires further experimental research and numerical simulations. Local variations in strain in the gesso reflecting the anisotropic elongation of the wood substrate will be determined. Slow response of panels to short-term variations and their usual deformation, which reduces the effective movement undergone by the decorative layer, as well as relaxation of the gesso during the long-term variations, will all have a bearing on the susceptibility of painted wood panels to cracking due to cyclic environmental changes and must be taken into account. The ultimate aim of the project is to establish realistic RH ranges that are safe for panel painting preservation. This, in turn, should allow for less restrictive environmental control, thereby enabling the use of less and simpler climate-control equipment and lowering maintenance and energy costs.

Acknowledgments

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Gaseous Pollutants inside Microclimate Frames: Results from the PROPAINT Project

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Abstract

PROPAINT is a European research project in which the protection of paintings kept in microclimate (mc) frames is studied. Major air pollutants in museum environments are ozone, nitrogen dioxide, and organic acids. Volatile organic compounds (VOCs) are often observed in high concentrations inside mc-frames; however, their effects on artists' materials are largely unknown. The level of external pollutants inside mc-frames will be low compared to the level in the ambient rooms because of large inner frame surface areas and a low air exchange rate. However, internally generated pollutants may occur at extremely high concentrations if a source is present inside the frame. Pollution measurements conducted in thirteen mc-frames are reported in this paper. Inside the frames ozone was observed in the range of 0.5–6.0 $\mu g\ m^{-3}$, and nitrogen dioxide was seen in the range of 0–4 $\mu g\ m^{-3}$. Organic acids (the sum of acetic and formic acid) ranged between 100 and 2100 $\mu g\ m^{-3}$, and other VOCs ranged from 100 to 4500 $\mu g\ m^{-3}$. A special "worst-case" mc-frame containing an emissive mock-up painting had extremely high concentrations: 2800 $\mu g\ m^{-3}$ organic acids, and for other VOCs, 28,000 $\mu g\ m^{-3}$. Organic acids were always observed in higher concentrations (10 times or more) inside the mc-frames than in the rooms. It is concluded that a low air exchange of mc-frames effectively protects against the ingress of external pollutants. However, care should be taken to avoid high emission of organic compounds from frame construction materials—for example, by using inert materials for inner frame structures or by lining emissive surfaces with impermeable barrier films.

Introduction

As part of the ongoing European research project PROPAINT ("Improved Protection of Paintings during Exhibition, Storage, and Transit," February 2007–January 2010), a detailed study is being carried out on the protection for paintings achieved by microclimate frames (mc-frames) and varnishes (Grøntoft et al. 2008).

PROPAINT comprises seven partners, three subcontractors, and eight end-user art museums. The partners are research institutes and universities in the fields of air research, chemistry, and conservation; a conservation institute; conservation departments within museums with much activity in the field of exhibitions; and one international art transport and frame design company, SIT Transportes Internacionales, Madrid. The art museums connected to the project as so-called end users primarily offer one or more field test sites—e.g., an mc-frame in exhibition or in storage (fig. 1). Partners and end users are located throughout Europe, with the exception of one end-user museum located in Mexico.[1]

Figure 1
A PROPAINT test site at the National Museum in Kraków, Poland: A large display-case-style mc-frame with panel painting (*Lady with Ermine* by Leonardo da Vinci). The inset photo shows how pollution samplers were placed inside the frame. Photos: PROPAINT.

Microclimate frames are used in museums for the protection of paintings on exhibition, in storage, and in transit. Microclimate frames protect the paintings physically and against externally generated pollutants and provide climate buffering (Wadum 1998 and references therein). The positive effects are assumed to outweigh the negatives of added weight, difficulty of access, cost, and the risk of creating a less beneficial micro-environment. Concern has been raised over the risk of trapping internally generated pollutants in very airtight mc-frames and the possible negative effect of these compounds on the enclosed works of art, a problem similar to that presented by display cases (Camuffo, Sturaro, and Valentino 2000).

This paper will discuss the issue of air pollutants and mc-frames, from the perspective of the ingress of external pollutants and of the generation of compounds inside the frames. Results are reported from the PROPAINT field measurement campaign.

Air Pollution: Sources and Effects

A number of compounds are recognized as pollutants from their ability to cause deterioration of materials when present in the air and under certain conditions. Key pollutants include ozone and nitrogen dioxide, both originating almost entirely from outdoor sources, and organic acids, which are mainly generated indoors (Brimblecombe 1990; Hatchfield 2002; Tétreault 2003). The sources of outdoor pollutants are atmospheric reactions and/or the combustion of fossil fuels, and these substances may act as oxidizing agents or cause acid hydrolysis. Ozone, for example, is a powerful oxidant. It is well known that ozone will oxidize traditional artists' colorants. It attacks the double bonds in the chromophore groups of pigment and dye molecules, causing the color to fade (Shaver, Cass, and Druzik 1983; Whitmore, Cass, and Druzik 1987; Whitmore and Cass 1988; Cass et al. 1989). Likewise, nitrogen dioxide causes fading effects of a range of pigments, dyes, and iron-based inks (Whitmore and Cass 1989).

Of the several hundreds of compounds generated in indoor environments, the most corrosive group of compounds is the organic acids. Acetic acid is released by decomposition of wood, and formic acid is also emitted from wood and oil paints or is the product of the oxidation in air of formaldehyde (released from glue, paint, etc.). The sources are solely indoors. As they are emitted by furniture and construction materials, the organic acids are especially problematic in spaces where the surface-to-volume ratio of the emissive materials is high and where the air exchange rate is limited. Examples of damage caused by organic acids are corrosion of certain metals (Tennent, Tate, and Cannon 1993; Tennent and Baird 1992) or degradation of cellulose fibers. It has been reported from laboratory tests that paper loses fiber strength after exposure to acetic acid at high concentrations (3–200 mg/m^3) in air (Dupont and Tétreault 2000).

Volatile organic compounds (VOCs) make up a large group of organic compounds, which readily exist in the vapor phase because of their high volatility. As for the organic acids, their sources are mainly the emission from construction materials, such as, for example, the emissions from lacquers or paints, adhesive, or glue inside a frame. However, the importance of damage to materials caused by this group of compounds is still uncertain. No direct link between the presence of VOCs and material deterioration has been established. The knowledge about possible negative effects of VOCs on artists' materials and the related establishment of threshold levels for specific compounds are questions that warrant further investigation because of the importance for protection of works of art. The phenomenon of blurry deposits on the inside of frame glass has, however, been attributed to the evaporation of organic compounds (fatty acids) inside picture frames. The rate and direction of the recondensation of the compounds elsewhere inside the frame may be controlled by temperature gradients, for example, between the glass and the painting's surface, causing the so-called "ghost images" (Williams 1989; Koller and Burmester 1990; Michalski 1990; Schilling, Carson, and Khanjian 1999). As the interest in VOCs has increased, research has been performed to determine their indoor sources in museum environments (Schieweck et al. 2005; Schieweck, Markewitz, and Salthammer 2007). Previously, VOCs have been identified in showcases (Blades 1999) and plastic storage containers (Larkin, Blades, and Makridou 2000).

It should be noted that for all the species of pollutants, thresholds, or acceptably low levels, still need to be defined. It is generally acknowledged that external oxidizing pollutants can be accepted only in very low levels (a few μg m^{-3}). The effect of VOCs, including organic acids, on artists' materials is, however, still largely unknown.

Pollution Pathways

Air pollutants move around with the free airflow and will infiltrate a building from the outside through open doors and windows, ventilation ducts, and other routes of air exchange. As they are transported from one room to another or into a display case or picture frame, the pollutants will constantly decrease in concentration as they deposit to most surfaces met on the route. For internally generated compounds, the concentration in air may be high near the source of emission. As the pollutants move away from the source or from confined spaces into more and more open areas, they will at the same time become diluted, and the concentration will decrease.

On deposition on an object's surface, a pollutant molecule may react by oxidation or by acid hydrolysis, depending on the pollutant compound and on the surface properties, including moisture conditions. The concentration and flux of air pollutants to surfaces are therefore mainly controlled by two factors: the air exchange rate and the rate of surface reaction.

For external pollutants, a simple mass balance model describes the decay in concentration as the pollutant moves from the ambient into an enclosed space (Weschler, Shields, and Naik 1989):

$$C_i = \frac{C_o \times n}{n + S} \tag{1}$$

where C_i is the indoor concentration of pollutant (g m^{-3}), C_o is the outdoor concentration of pollutant (g m^{-3}), n is the air exchange rate (s^{-1}), and S is the surface removal rate (s^{-1}).

The typical air exchange rate for a normal room is of the order of 0.5 to 2 room volumes per hour. However, higher ventilation rates are possible when mechanical ventilation is used. For low-activity spaces such as storage rooms, much lower air exchange rates have been observed in situations where no mechanical ventilation is used.

The surface removal rate S in equation 1 is important. It describes the rate at which air pollutants move from the air to deposit on surfaces. Most of a highly reactive pollutant, such as ozone, is removed indoors through this route. The surface removal rate is directly comparable to the air exchange rate; if, for example, a room has a surface removal rate of 1 room volume per hour, then pollutants will deposit on the indoor surfaces at a rate equal to the removal rate of the pollutants by ventilation at 1 air change per hour. For normal museum rooms (galleries, large storage rooms), the surface removal rate for ozone will usually be of the same order of magnitude as that of the air exchange. For a general discussion of pollution mass balances, see Ryhl-Svendsen 2006.

For indoor-generated compounds, a mass balance similar to equation 1 describes the concentration, which will occur at steady state, in the enclosed space of the emission source:

$$C_i = \frac{\left(\frac{G}{V}\right)}{n + S} \tag{2}$$

Where G is the generation rate of pollutant (g s^{-1}), and V is the volume of the room (m^3).

The mechanisms that determine the level of air pollution in a large gallery or inside a picture frame are the same in principle. However, the conditions in the two types of situations are very different.

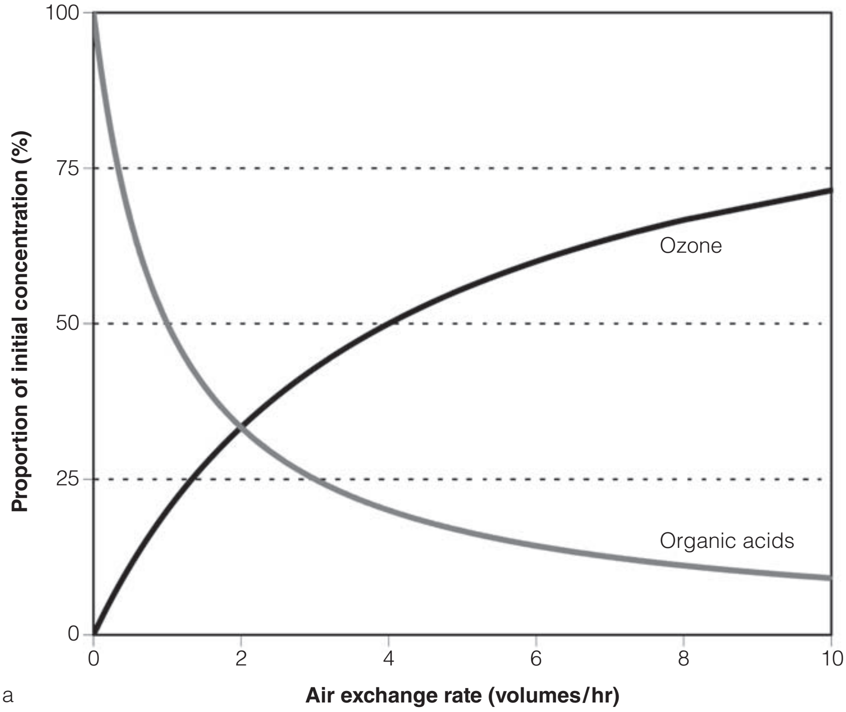
On a room scale, the surface area-to-volume ratio is typically low: on the order of 0.5–2 m^2/m^3, which allows ventilation (air exchange) to be the main factor controlling the pollution level. However, in rooms with large additional surface areas and/or with large amounts of reactive surface materials (carpets, curtains, etc.), the surface reactions can become the most important factor in determining the mass balance.

In figure 2a, the dependency between air exchange rate and the pollution concentration inside a typical room is shown. Illustrated by one external (ozone) and one internal (acetic acid) compound, the steady state concentration in air is modeled for changing ventilation. The change in concentration is shown as percentage of the highest achievable concentration at any ventilation rate, which for ozone is the outdoor level ("infinite ventilation") and for acetic acid is the buildup in concentration inside an enclosure when moving toward zero ventilation ("airtight").

In a small and confined space, such as inside a picture frame or a display case, the surface area-to-volume ratio is much higher than for a room or a building; typically it is in the order of 50–200 m^2/m^3, so the microenvironment will be completely dominated by surface reactions unless the space is intentionally ventilated at a very high rate. External compounds readily deposit on surfaces inside the frame as they enter. The high total deposition rate of ozone will constantly keep the concentration inside the frame at less than about 25% of the ambient level (fig. 2b). Internally generated compounds will, in contrast, remain in high concentrations despite the increasing ventilation rate, if a strong emission source is present. With strong emission sources of organic acids present inside a picture frame—such as wood, fresh lacquer, or adhesives—the internal concentration can therefore reach a level several orders of magnitude higher than that of the surrounding room environment. For acetic and formic acid, this can be several hundreds or thousands of $\mu g\ m^{-3}$.

Figures 2a and 2b

The steady state concentration of ozone and acetic acid for a standard room of 200 m³, at increasing air exchange rates (a), and the steady state concentration of ozone and acetic acid for a picture frame of 0.05 m³ at increasing air exchange rates (b); the frame contains a strong acetic acid source (e.g., wood boards). The models are based on equations 1 and 2 and take into account pollution infiltration, dilution, emission, and deposition rates. Initial concentration is, for ozone, the ambient room level, while for acetic acid, it is the highest achievable concentration at zero ventilation (airtight frame).



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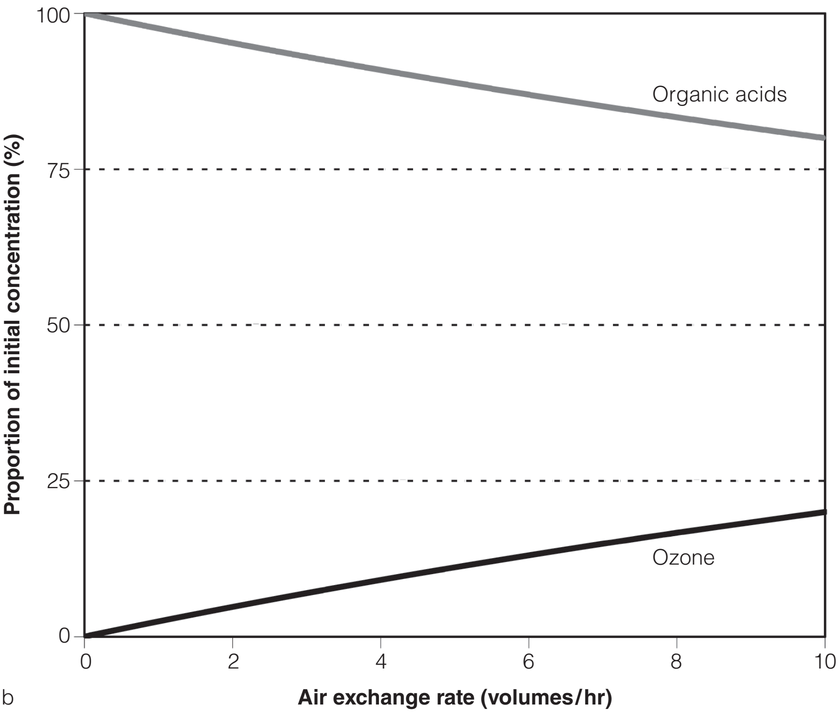


b

PROPAINT Field Tests

As part of the PROPAINT project, the air pollution levels were measured inside and outside different state-of-the-art mc-frames located in museums across Europe, in Mexico, and at one international art transport and mc-frame producing company located in Spain. The results from the investigation of thirteen of these mc-frames are reported; their properties are given in table 1. Both new and older mc-frames were investigated, some with panels and some with canvas paintings. Four frames were tested empty, and one frame (the SIT mock-up) was a special “worst-case”

Table 1 Properties of the selected mc-frames in the PROPAINT field test.

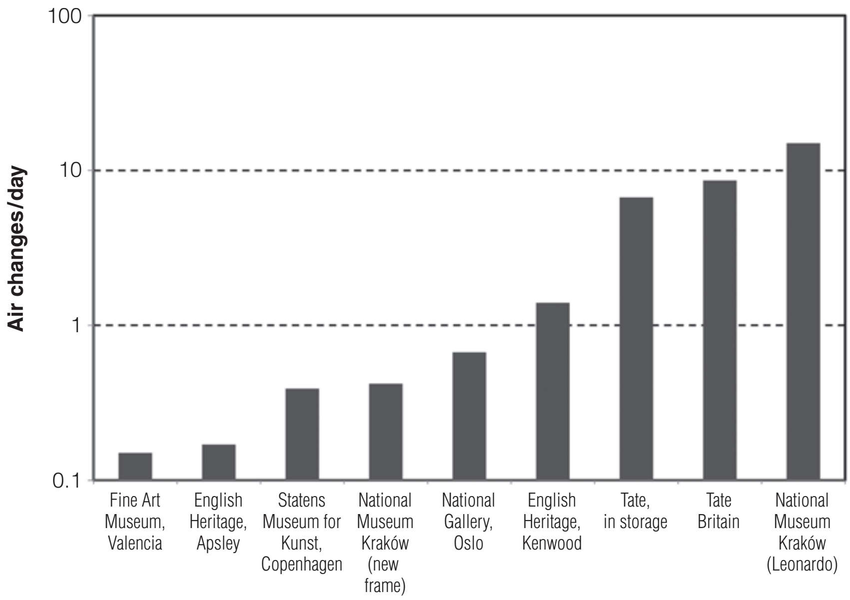
Site	Panel (P) or canvas (C) painting in frame	Modified original frame (M) or purpose-built mc-frame (P)	Age of mc-frame or mc-modification at time of investigation (years, approx.)	Volume of frame (m^3)
National Gallery, Oslo, Norway	C	M	40	0.0185
English Heritage, Kenwood House	P	M	20	0.0454
English Heritage, Apsley House	P	P	1	0.0111
Tate Britain, London	Empty	M	100	0.0102
Tate, London (frame in storage)	Empty	M	15	0.0275
Statens Museum for Kunst, Copenhagen	Empty	M	1	0.0244
National Museum, Kraków, Poland (new frame)	P	P	1	0.0758
National Museum, Kraków, Poland (Leonardo frame)	P	M*	5	0.3150
Fine Art Museum, Valencia, Spain	P	P	3	0.0563
Germanisches Nationalmuseum, Nuremberg, Germany	C	P	6	0.0604
Museo Nacional de Arte, Mexico City	P	P	New	N/A
SIT Madrid (mock-up painting)	P	P	New	0.0840
SIT Madrid (empty frame)	Empty	P	New	0.0840

* Large enclosure, almost display-case properties.

demonstration mc-frame prepared with a mock-up painting. This consisted of a fresh oak wood board, with fresh paint, varnish, and glue put inside the frame. This frame was prepared with the intention of creating a highly emissive interior microclimate.

The air exchange rate was determined for nine of the test frames by the use of carbon dioxide as a tracer gas. By injecting a high dose of the gas into a frame and then monitoring the concentration decay over time as the tracer gas was diluted when room air entered the frame, the rate of air exchange was calculated. It was found that the frames varied largely in air tightness: from very airtight frames (by deliberate design) with exchange rates of much less than 1 frame volume per day, up to the most leaky frame, with 10 or more air exchanges per day (fig. 3). For comparison, it can be noted that a normal exhibition gallery

Figure 3
Air exchange rates of nine mc-frames from the PROPAINT field test (note log scale of y-axis).



will have an air exchange in the order of 1 or 2 room volumes per hour in natural conditions—or even higher if mechanical ventilation is in use.

Measurements of air pollution concentrations inside and outside the mc-frames were carried out by the use of "passive gas samplers" (Grøntoft et al. 2008), in which the pollutants diffuse from the air into a sorbent media placed inside a sampling tube (fig. 4). After one month of sampling, the tubes were removed from the site and analyzed in a laboratory, where the collected pollutants were identified and quantified (for a general description on passive sampling techniques, see Grzywacz 2006).

During the PROPAINT measurements, the ambient pollution levels varied considerably among the sites because of local conditions. The room levels of the external pollutants ozone and nitrogen dioxide were measured to be in the range of 1–20 μg m^{-3} and 1–50 μg m^{-3}, respectively. Inside the mc-frames, however, these compounds were detected in much lower concentrations—often near the detection limit of the sampling methods. Ozone was observed in the range 0.5–6 μg m^{-3}, and nitrogen dioxide was in the range of 0–4 μg m^{-3}.

In contrast to these findings, the compounds that were generated by material emission inside the mc-frames were observed at much higher (and sometimes extremely high) concentrations in comparison to concentrations in the ambient rooms. Organic acids (the sum of acetic and formic acid) concentrations ranging from 100 to 2100 μg m^{-3} and VOC (excluding organic acids) concentrations ranging from 100 to 4500 μg m^{-3} were measured (fig. 5). For the special worst-case mc-frame containing a freshly made mock-up painting, even higher concentrations were observed: 2800 μg m^{-3} of organic acids and, for other VOCs, a total concentration of 28,000 μg m^{-3}. Among the VOCs, toluene, α-pinene, *p*- and *m*-xylenes, limonene, and 3-carene were observed in most or many frames. Chloroform and methylmethacrylate were found only in new frames. However, there is as yet no evidence for the damage impact of VOCs, except organic acids, on materials.

Figure 6 shows the distribution of the externally and internally generated pollutant levels inside the mc-frames (the extremes of the worst-case frame excluded), given as their ratio compared to the

Figure 4
Installation of passive samplers inside (left) and outside (right) mc-frame in Fine Art Museum, Valencia, Spain, performed by Guillermo Andrade of SIT Transportes Internacionales, Madrid. Photos: PROPAINT.

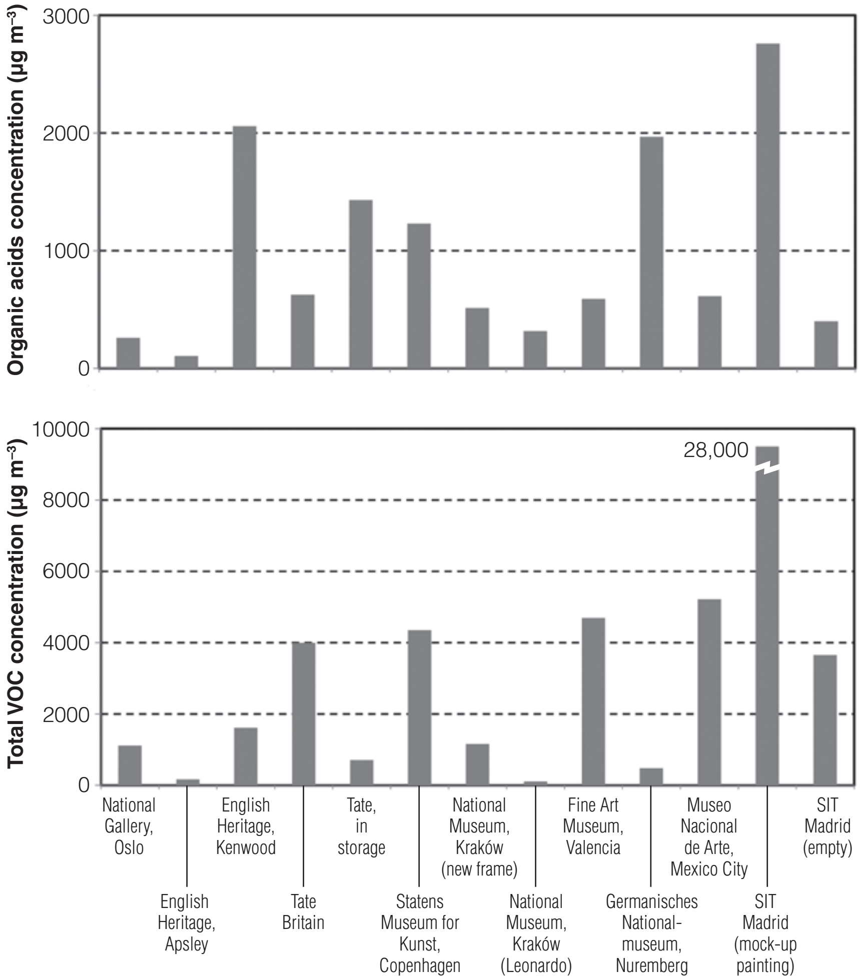


Figure 5
Concentration of organic acids (acetic plus formic) in thirteen mc-frames from the PROPAINT field test (top), and concentration of the sum of volatile organic compounds (except organic acids) in thirteen mc-frames from the PROPAINT field test (bottom). Note that the concentration for the SIT Madrid mock-up painting is off scale (28,000 µg m^{-3}).

room concentration. Following from figure 2b, it is to be expected that ozone levels inside mc-frames will be less than about 25% of room conditions at any realistic air exchange rate, and this is in accordance with the PROPAINT mc-frames observations. One observation of a significantly higher ozone ratio (0.43) is for the most leaky and rather large mc-enclosure (National Museum Kraków, Leonardo frame), which has almost display-case properties rather than those of a picture frame. In contrast to ozone, higher concentrations of the organic acids were always measured inside the mc-frames than in the room—for most of the frames, with a ratio of 10 times or more.

The frames have different properties and were located in different indoor environments, which makes a direct comparison difficult. However, a reverse relationship between the ozone infiltration and the buildup of organic acids inside the mc-frames is hinted by figure 6.

This illustrates how the mc-frame acts as a barrier for the pollutants. Because of a low air exchange rate, some mc-frames have high levels of internally generated compounds but, at the same time, low levels of the externally generated pollutant ozone. When the ozone ingress is high, because of a leaky frame, the concentration of organic acids is likely to be lower. Concentrations of organic acids are high near the sources, or where the air exchange is low. Therefore, room environments usually have low concentrations of the organic acids, which are exclusively products of material emissions.

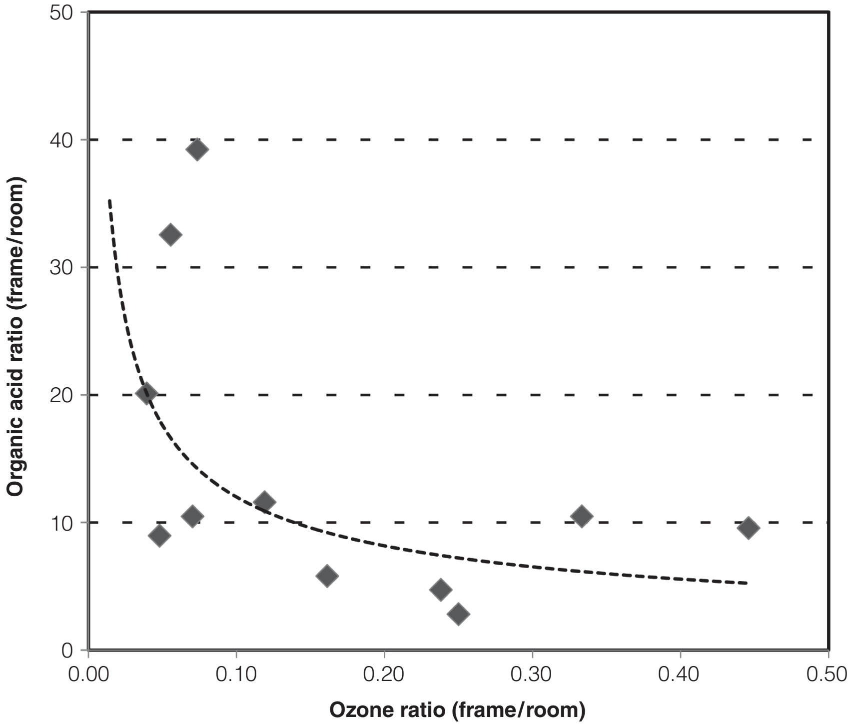


Figure 6
The relationship between the ozone ratio and the organic acid ratio (ratio between frame and room concentration) for the PROPAINT mc-frames. The relationship is suggested by a trend line. (Note that the number of observations is low and made under varied conditions, so the statistical significance is low.)

Recommendations and Conclusion

It must be noted that because of the small number of tested frames, it was not possible to arrive at conclusions about significant differences in, for example, the concentration of organic acids in the group of new purpose-made and the older retrofitted mc-frames. However, for VOCs there seemed to be some evidence for higher concentrations in the newest frames (fig. 5), due to increased concentration of some particular VOCs. In general it can be concluded that a low air exchange of mc-frames effectively protects against the ingress of externally generated pollutants, such as ozone and nitrogen dioxide. However, with a low air exchange and an emission source present inside the frame, concentrations of internally generated compounds, such as organic acids, will become high regardless of the type of mc-frame.

Considering only impacts of air pollutants, the current recommendation must still be to make mc-frames as airtight as possible—as long as there is little or no evidence for damage impacts from the organic acids and other VOCs—as airtight frames protect against strong external oxidants such as ozone. However, care should be taken to avoid high emission of organic compounds from frame construction materials. Inert materials (aluminum, acrylic, polycarbonate, etc.) should be used for inner frame structures, and emissive surfaces should be blocked by barrier foil lining. In this way the risk from internally generated pollutants will be minimized (figs. 7 and 8).

The appropriate balance between acceptable levels of external oxidizing agents and internally generated organic compounds may constitute a framework for the future design of mc-frames. However, threshold levels for volatile organic compounds—even organic acids—and their effect on paintings still need to be defined.

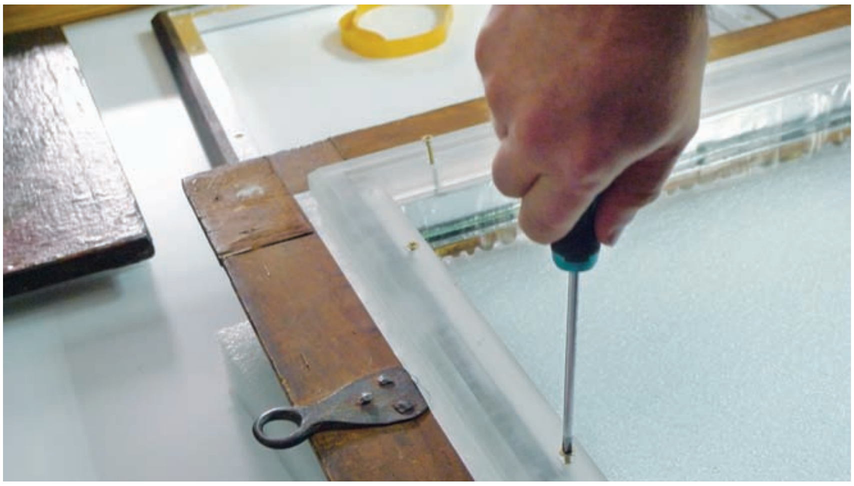


Figure 7
An mc-frame being built from acrylic profiles at SIT Madrid. The wood of the original frame is lined on the inside by an aluminum foil. The use of inert materials inside mc-frames lowers the risk of emission of compounds such as organic acids and VOCs. Photo: PROPAINT.

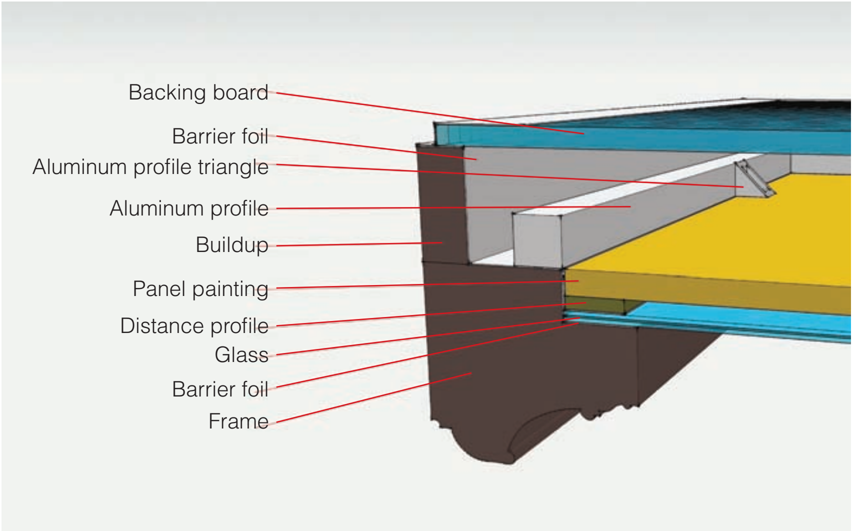


Figure 8
An mc-frame from the National Museum in Kraków, built with a wooden frame lined on the inside by barrier foils. The inner frame volume is equipped with inert profiles in aluminum. Drawing: Dennis Larsen/PROPAINT.

Acknowledgments

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Note

1 For further information on PROPAINT, see http://propaint.nilu.no/.

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Special Exhibitions and Panel Paintings: A Curatorial Perspective

Maryan W. Ainsworth

Abstract

On May 28, 1483, Hugo van der Goes's enormous triptych known as the Portinari Altarpiece, measuring 253 × 304 cm (99.6 × 119.7 in.) when closed, arrived at its destination, the Hospital of Santa Maria Nuova in Florence. The detailed account of its journey from Bruges to Florence would terrify any curator or conservator. Such a journey for a masterpiece of this importance would be unthinkable today; yet if it were deemed absolutely necessary, possible conservation intervention, safe packing, and transport could now be ensured in a way that never could have been imagined in the late fifteenth century.

The issue of the care and transport of panel paintings for special exhibitions has reached a somewhat confusing juncture—where everything is possible and nothing is possible. This paper explores the state of the question from the curator's point of view, in order to consider concerns of risk balanced against guaranteed benefits of sending panel paintings to special exhibitions. Museums have never been better informed about how to treat panels, pack them, and transport them for safe arrival at their destinations, yet attitudes and perceptions about lending panel paintings to exhibitions lag behind these new developments. Case studies are used to evaluate past and present decisions regarding panel paintings and loan shows.

On May 28, 1483, Hugo van der Goes's enormous triptych known as the Portinari Altarpiece, measuring 253 × 304 cm (99.6 × 119.7 in.) when closed, arrived at its destination, the Hospital of Santa Maria Nuova in Florence. The well-known, detailed account of its journey from Bruges to Florence would terrify any curator or conservator (Hatfield Strens 1968). This gigantic altarpiece, painted on commission for Tommaso Portinari, the representative of the Medici Bank in Bruges, was transported by ship from Bruges to a port in Sicily. Then it was transferred to a smaller vessel that sailed on the Arno from Pisa to Florence, where it was unloaded near the Porta San Friano (today called Porta San Frediano). From there, it was brought by cart with wooden wheels over rough, unpaved streets to the hospital of Santa Maria Nuova and installed on the main altar of the church of Sant'Egidio. No fewer than sixteen *portatori* participated in the transport. Needless to say, there was no climate-controlled crate and no air-ride truck.

Such a journey for a masterpiece of this importance—indeed the only securely documented work of Hugo van der Goes—would be unthinkable today. Yet if it were deemed absolutely necessary, possible conservation treatments, safe packing, and carefully considered transport could now be provided in a way unimaginable in the late fifteenth century.

The issue of the care and transport of panel paintings for special exhibitions has reached a somewhat confusing juncture—where everything is possible and nothing is possible. It is always easier to say no. Museum staff have never been better informed about how to treat panels, pack them, and transport them for safe arrival to their destinations, yet attitudes and perceptions about lending panel paintings to exhibitions lag behind these new developments. What of course needs to be considered—on a case-by-case basis—is the question of risk balanced against the guaranteed benefits of sending panel paintings from their home institutions to other locations nationally and internationally.

Years ago, in 1979, when John Brealey first came to the Metropolitan Museum as the new chairman of the Paintings Conservation Department, one of his first directives was to put a halt to lending paintings on panel. It was an absolute embargo, and his reason for doing so was to counter the indiscriminate lending of too many panels to too many exhibitions without proper consideration of issues of climate control or safe packing and transport. As one might well imagine, this stricture had a significant impact on relationships with other museums at the time.

It was only four years later, in 1983, that an important exhibition, *Raphael and America,* staged by David Alan Brown at the National Gallery of Art in Washington DC, combined with the strong will of Sir John Pope-Hennessey of the Met's European Paintings Department broke the ban in order to lend the Met's *Agony in the Garden* by Raphael (fig. 1) to complete the predella of the *Madonna of the Nuns of Sant'Antonio* that was to be installed in the show. This change in policy ushered in a new era, in which each request was judged on its own merits.

Figure 1
Raphael (Raffaello Sanzio or Santi) (Italian, Marchigian, 1483–1520), *The Agony in the Garden*, ca. 1504. Oil on wood, 24.1 × 28.9 cm (9.5 × 11.4 in.). The Metropolitan Museum of Art, New York, Funds from various donors, 1932, 32.130.1. Image: © The Metropolitan Museum of Art.

However, it was a decade after Brealey's embargo, in 1989, that the Met took the next step with its groundbreaking show *Painting in Renaissance Siena, 1420–1500.* The Museum's director at the time, Philippe de Montebello, had initially rejected the idea, assuming that the loans could never be assembled for a representative show. However, curator Keith Christiansen prevailed, and the exhibition actually took place, albeit with hardly any panel larger than a size that permitted its being hand carried in a protective Halliburton case. The Louvre did not participate because of its absolute refusal to lend panel paintings at that time, and the curator Dominique Thiébaut has always regretted that decision because of the new insights made possible by the assembled panels. Through this show, Met staff members demonstrated to lenders their expertise in the special care devoted to panel painting issues, mainly through the efforts of conservator George Bisacca, and by 1994 the situation had begun to change.

In preparation for the exhibition *Petrus Christus: Renaissance Master of Bruges* (1994), my colleagues and I actually had a wager going on how many panels could be assembled for the exhibition. Out of the small oeuvre of twenty-nine surviving works, nineteen panels and a handful of drawings came to New York, allowing for a reevaluation of this important fifteenth-century Netherlandish master in the first monographic show devoted to him (Ainsworth and Martens 1994). Even those panels that could not be lent were studied along with the others from the technical point of view. Thus, for the first time, a more or less complete picture of the working methods of the artist was offered. I have always believed that our thorough efforts regarding technical examination of all of the panels helped our cause with regard to institutional willingness to lend to the exhibition.

I am not so naive as to pretend there are not quid pro quo issues and political strong-arming that occur in the decision making of museums about which panel paintings may be allowed to travel to which exhibitions. One hears that there are even questions of special fees involved . . . Why else would the *Last Judgment* triptych, Hans Memling's monumental early work commissioned in 1467 by Angelo Tani, probably for the church of the Badia Fiesolana in Florence, and measuring 242 × 180.8 cm (95.3 × 71.2 in.) including the frame when closed, have been lent in 1993 to the Cologne exhibition on Stefan Lochner? This is an altarpiece that was one of two aboard a galley ship seized just beyond the Zwin River near Bruges on April 27, 1473, by the privateer Paul Benecke, working on behalf of the Hanseatic League (Białostocki 1966). The theft was reported to Tommaso Portinari on July 12 of that year. Despite the intervention of the pope and of duke Charles the Bold, the altarpiece, which was taken to Danzig (present-day Gdańsk) and installed on the altar of the Guild of Saint George in the Church of Our Lady, was never returned to its rightful owner. So it was from Gdańsk that the huge altarpiece was transported in 1993–94 to not just one but two exhibitions by truck over bumpy roads. It was shown first in the Stefan Lochner exhibition, where there was no apparent reason for its inclusion (Zehnder 1993). Memling's great altarpiece was influenced significantly by Rogier van der Weyden's Beaune *Last Judgment,* not by Stefan Lochner's work of the same theme. Subsequently it traveled to the 1994 monographic show on Hans Memling (De Vos, Marechal, and Le Loup 1994). For this, ironically, the mammoth altarpiece returned to Bruges, where, in the waterways just beyond the town walls, it had been stolen some 520 years earlier.

Such loans, in my view, fall into the category of unreasonable risk, and if I were the responsible curator, I would not have put Memling's huge altarpiece in such jeopardy. Nor do I think that I would have allowed Hans Holbein the Younger's enormous masterpiece known as the Darmstadt Madonna (146.5 × 102 cm, or 57.7 × 40.2 in., Schlossmuseum, Darmstadt), to travel to Portland, Oregon, for *Hesse: a Princely German Collection,* a show on the treasures of the Hesse Dynasty (Hunter-Stiebel 2005). More appropriate for such an exceptional loan was its presence at the landmark show of Hans Holbein the Younger in Basel in 2005, where it could be seen in the context of the other works of the artist from the Basel years (Müller et al. 2006). Ultimately, the Darmstadt Madonna landed in long-term loan to the Frankfurt Städel Museum, where it can be enjoyed by the public.

This issue brings me to the question of what is reasonable risk for sending panel paintings near and far for special exhibitions. When do the benefits outweigh the dangers? The Metropolitan Museum owns some large works that are regularly requested for loan but may never travel anywhere because of the fragile state of the wood supports. Two examples are Bruegel's *Harvesters* (fig. 2) and the Dinteville Allegory (*Moses and Aaron before Pharaoh: An Allegory of the Dinteville Family,* 1537) by the Master of the Dinteville Allegory (fig. 3); both paintings are roughly comparable in height and width (116.5 × 159.5 cm, or 45.9 ×

Figure 2
Pieter Bruegel the Elder (Netherlandish, active by 1551, d. 1569), *The Harvesters*, 1565. Oil on wood, 118.1 × 160.7 cm (46.5 × 63.27 in.). The Metropolitan Museum of Art, New York, Rogers Fund, 1919, 19.164. Image: © The Metropolitan Museum of Art.

Figure 3
Master of the Dinteville Allegory (Netherlandish or French, active mid-16th century), *Moses and Aaron before Pharaoh: An Allegory of the Dinteville Family*, 1537. Oil on wood, 176.5 × 192.7 cm (69.5 × 75.9 in.). The Metropolitan Museum of Art, New York, Wentworth Fund, 1950, 50.70. Image: © The Metropolitan Museum of Art.

62.8 in.; and 176.5 × 192.7 cm, or 69.5 × 75.9 in., respectively) and are also similar in their extremely thin panels. How wonderful it would be to see *The Harvesters* reunited with the other four remaining months in Bruegel's series of six, made for Nicolas Jonghelinck in 1565 for his villa outside Antwerp at ter Beken! Or how interesting it would be to study firsthand the connections between the Met's Dinteville Allegory and Holbein's *Ambassadors* in the National Gallery, London! Both were commissioned by Jean de Dinteville and his brothers, and they once hung in close proximity in the Dinteville chateau at Polisy. *The Ambassadors* has its own checkered history of condition problems. When the remarkable exhibition *Holbein in England* was staged at the Tate Gallery in 2006 (Foister and Batchelor 2006), there was considerable public outrage over the fact that the painting could not be moved even a short distance across town, from the National Gallery to the Tate, in order to represent the peak of Holbein's production in his London years. Made of ten vertical planks planed to around 5 mm (0.2 in.) thick, the panel has a history of splitting and flaking paint, and it was just too risky to move it anywhere (Foister, Roy, and Wyld 1998, 88–97).

The same exhibition, *Holbein in England,* also presented a bit of a quandary for us at the Met. In 2003 the Mauritshuis in The Hague staged the exhibition *Hans Holbein: Portraitist of the Renaissance* and requested one of the most important paintings in our northern Renaissance collection, Holbein's portrait of Hermann von Wedigh (fig. 4). New technical research had been done on the fine collection of Holbein portraits at the Mauritshuis, and this exhibition promised to be revelatory about the artist's technique and handling. We deliberated long and hard about our portrait. Our concern was not over questionable state and condition; on the contrary, it was that we considered the Wedigh portrait to be in such remarkably fine condition that we felt reluctant to send it. Convinced

Figure 4
Hans Holbein the Younger (German, 1497/98–1543), *Portrait of a Member of the Wedigh Family, Probably Hermann Wedigh*, 1532. Oil on wood, 42.2 × 32.4 cm (16.6 × 12.8 in.). The Metropolitan Museum of Art, New York, Bequest of Edward S. Harkness, 1940, 50.135.4. Image: © The Metropolitan Museum of Art.

that the benefits of viewing the Wedigh portrait alongside others of the same period would outweigh the risks, we decided to lend it to The Hague. Imagine our quandary, then, when within the year we were approached again for the same portrait for a larger and even more important exhibition two years later, the *Holbein in England* show at the Tate, curated by my London colleague and the expert on Holbein's English years, Susan Foister.

The subtleties of execution and handling to be experienced and enjoyed in a portrait of such extraordinary fine condition as the Wedigh portrait are transforming. And it is especially through the opportunity to compare these qualities of Holbein's portraits that we come to understand what it was exactly that made him the most important portraitist of his day—the so-called Apelles of his time. How could any viewer understand this unless such comparisons could be made? So once again we agreed, exceptionally, to lend the Wedigh portrait to the very important Tate exhibition, where it was installed directly in the line of sight as the visitor turned to enter the room of Holbein's portraits of the Hanseatic League in London. There it provided the epitome of the artist's technical achievements in a painting of nearly pristine

Figure 5
Gerard David (Netherlandish, active by 1484, d. 1523), *The Annunciation: The Archangel Gabriel* and *The Virgin,* 1506. Oil on wood, angel, 79.1 × 63.5 cm (31.1 × 25.0 in.), Virgin, 77.5 × 61.9 cm (30.5 × 24.4 in.). The Metropolitan Museum of Art, New York, Bequest of Mary Stillman Harkness, 1950, 50.145.9ab. Images: © The Metropolitan Museum of Art.

state, against which all other portraits in the room and in the exhibition could be measured. We were very glad to have had the opportunity to see the Met portrait in comparison with the others of this date in London, such as the Berlin Gemäldegalerie portrait of Hermann Hillebrandt von Wedigh. The Met's Wedigh portrait is now home to stay for a good long time.

Of a rather different nature were our deliberations over whether or not to send our *Annunciation* panels (fig. 5) by Gerard David to Genoa, to the Palazzo Bianco, to be reunited with other panels from the same altarpiece. The Metropolitan Museum owns the largest collection of paintings by Gerard David in the world—although the collection does not include his large altarpieces, for which one needs to travel to Bruges. Out of character for early Netherlandish painting, the Met *Annunciation* is divided into two panels, with a perspective system indicated by the tipped-up floor tiles. The pair is meant to be viewed from below and at a considerable distance. Already in 1951, Castelnovi had proposed that three paintings in the Palazzo Bianco and one in the Louvre belonged with the Met panels in a configuration more typical of north Italian polyptychs (Castelnovi 1952). But it was not until my further research for a book on Gerard David in 1998 (Ainsworth 1998) that I became convinced that the Palazzo Bianco *Crucifixion* by David was also a component of this ensemble. From documentary evidence, we know that the altarpiece was commissioned in 1506 by Vincenzo Sauli for the high altar of San Gerolamo della Cervara, the Benedictine Abbey in Liguria on the coast of Italy. You can imagine my excitement when Clario di Fabio, then director of the Palazzo Bianco, approached us about reuniting all of the panels of this important altarpiece for an anniversary celebration of that Genoa museum. Such an opportunity would once and for all allow examination of my proposed reconstruction (fig. 6), as well as permit resolution of questions concerning the details of the commission for the in situ placement of this Italian-style altarpiece—or help determine whether David ever went to Italy for his most important foreign commission. The Met's Gabriel and Virgin Mary had never traveled to an exhibition since they came to the Met in 1940. The panels are not small—each measures around 79 × 64 cm (31.1 × 25.2 in.)—and they are uncommonly thick for Baltic oak planks—about 3 cm (1.2 in.). In discussions with George

Figure 6
Reconstruction of the Cervara Altarpiece for the Abbey of San Girolamo della Cervara. Reconstruction: M. Ainsworth and C. La Fontaine.

Bisacca, we carefully evaluated the questions of packing and transportation, and the Met's paintings were made ready for safe travel to Genoa.

We learned a great deal from a thorough technical examination that was undertaken on this altarpiece in a collaboration of the New York and Genoese colleagues, and subsequently we published this new information in a booklet at the time of the exhibition in Genoa (Di Fabio et al. 2005). Nothing in this publication, however, can compare with the experience of viewing all seven panels together in an arrangement very close indeed to Gerard David's most carefully planned and executed polyptych in Italian style for its 1506 installation on the high altar of San Gerolamo della Cervara. Like pieces of a puzzle, each panel locked into its proper place, instantly providing the hoped-for justification for the perspective system so carefully planned in the tile design of the first and second tiers of paintings, for the diminution of the scale of the figures in the first and second levels, and for the placement of the large-scale figure of the omnipotent, blessing God the Father in the lunette, with its looming presence. A small but highly focused exhibition such as this, which yields such stunning results, is powerful visual and scholarly justification for lending such panel paintings abroad.

A third reason for taking the risk of lending panel paintings to exhibitions is to help solve questions of attribution and dating. The Met's *Adoration of the Magi* was long considered a late pastiche of elements appropriated from paintings by Hieronymus Bosch. When dendrochronology of another version of the same composition in Rotterdam revealed a date of around 1540, the Met painting was placed in the same category of "late copy." However, the opportunity to compare the Met painting directly with the Rotterdam version in the monographic exhibition in Rotterdam in 2001 (Koldeweij, Vandenbroeck, and Vermet 2001) made it abundantly clear that they differed substantially in technique, handling, and execution. The Met painting fits in well with Bosch's works of around 1475–80, and the Rotterdam painting shows a later, less complicated layering structure indicative of developments of around 1540, which had been confirmed by the dendrochronological dating. Furthermore, the chance to compare the Met painting with the *Ecce Homo* from Frankfurt and other early Bosch paintings allowed *The Adoration of the Magi* to take its rightful place among the earliest of Bosch's paintings. Further technical examination of the Met's *Adoration* through dendrochronology, infrared reflectography, and microscopic examination of the paint layers supported this conclusion.

Certain exhibitions can only be planned for one venue. The Prado in Madrid was the only logical place for a once-in-a-lifetime exhibition on Joachim Patinir to be even contemplated. The Prado happens to own the majority of Patinir's large works and owns the most important ones by the artist. Therefore, when word reached us in 2005 that the Prado was contemplating a monographic show, the Met had to take it seriously (Vergara 2007). However, the request was for the Museum's *Saint Jerome Triptych* (fig. 7), a large work that had never traveled anywhere outside the museum since its acquisition in 1936. Careful study of the condition of the paintings with Hubert von Sonnenburg (then chairman of the Paintings Conservation Department) and George Bisacca led to the conclusion that the panels were actually quite secure and that therefore we could perhaps consider sending these paintings to Madrid. George recommended some work on the central panel that would additionally ensure a condition safe for travel. He soon set to work, carrying out this treatment on several small splits on the central panel so that the triptych afterward could be observed in our museum climate for a period of time, in order to evaluate any further developing issues before plans for travel were finalized.

Safe packing and transport were equally important and troublesome issues to consider. By the time of the exhibition, cargo planes no longer flew between New York and Madrid. Therefore, the triptych would have to go to an airport in France and then be sent by truck the rest of the way to Madrid. I wasn't comfortable with this scenario. Then George came up with a viable alternative. The wings of the triptych could easily be detached from the central panel. The wings could be packed together in one crate, while the central panel could be packed in another crate. The two crates would travel separately in two different planes with two different couriers, fitting, as they would now, into the cargo hold of a regular commercial airline. Therefore,

Figure 7
Joachim Patinir (Netherlandish, active by 1515, d. 1524), *The Saint Jerome Triptych,* ca. 1518. Oil on wood, central panel, overall with engaged frame, 117.5 × 81.3 cm (46.26 × 32.0 in.), each wing, overall with engaged frame, 120.7 × 35.6 cm (47.5 × 14.0 in.). The Metropolitan Museum of Art, New York, Fletcher Fund, 1936, 36.14a–c. Image: © The Metropolitan Museum of Art.

there could be direct nonstop transportation from New York to Madrid. George would be available on the other end in Madrid to reconnect the wings to the central panel and supervise the installation of the triptych along with me.

The Met's triptych was installed near the *Baptism of Christ* from the Kunsthistorisches Museum in Vienna, to which it has always been compared because of the similar figures in each scene of the baptism. Although both derive from the same motif in Gerard David's Baptism triptych, this factor has confused rather than clarified their relationship—even leading some to consider the Met's triptych as a late pastiche after works by Patinir. The chance to see the New York and the Vienna pictures side by side further clarified that the Vienna picture is indeed later and more sophisticated in composition, technique, and execution than the Met picture. In addition, comparisons with other paintings in the Madrid show, made possible by the loan of the Met triptych, allowed for the reconsideration of its date: we now believe that the traditional date of around 1518 is too late and think that it may well predate even 1515, when Patinir's name first appears in the records of Antwerp's painters' guild. We now consider our triptych to be Patinir's earliest surviving large-scale triptych, dating to around 1510–12.

In this curator's experience, there have definitely been risks worth taking in sending panel paintings to exhibitions where there are guaranteed rewards. Such rewards include a better understanding of the artist's technique and execution in extraordinarily well preserved pictures, the chance to see a certain painting reunited with others that are part of the same original ensemble, and clarification of attribution and dating issues. I realize, of course, that I have presented points here that are all key connoisseurship questions. That is not to say that I only favor sending panel paintings to exhibitions that primarily deal with connoisseurship problems. Certainly the case may be made stronger for such presentations. However, there are equally valid reasons for sending panels to other types of shows, but here the example requested might find ready substitutes in other more easily available works.

The preparations for the 2010 exhibition *Man, Myth, and Sensual Pleasures: Jan Gossart's Renaissance* at the Metropolitan Museum and the National Gallery in London provided new challenges in terms of the transport of panel paintings for special exhibitions. Gossart is credited with bringing Italian Renaissance art, especially large-scale nudes and mythological subjects, to northern Europe, in particular to the Burgundian Netherlands, for the first time. The only previous monographic show on the artist was in 1965 in Bruges and Rotterdam. In preparation for this show, I have endeavored (with excellent cooperation from conservators and conservation scientists at many museums) to make a technical study of as many of the paintings as possible. This effort has yielded extremely rich results that will contribute to a significant reappraisal of Gossart's oeuvre. The reasons for lending panels to this show in New York, which has a smaller second venue in London, are therefore even more fully argued than usual. It has been an enormous advantage in so many of these negotiations to have the expertise of George Bisacca in carefully evaluating the pros and cons of individual loans and in discussing these issues with the curators and conservators of potential lending institutions. It is most interesting, therefore, to see which panel paintings were easily lent to the 1965 Bruges and Rotterdam shows (such as the monumental Prague *Saint Luke Drawing the Virgin*) and which of these may still be lent now. We shall see in October of 2010 how fully represented Gossart will be, and I am very hopeful. But it has become quite clear to me that those institutions where the easy answer is "no" are not represented at this conference. They appear not to be involved in the current research and discussions on panel painting problems and solutions.

If I were to sum up my thoughts about special exhibitions and lending panel paintings, I would say the following:

- Although many museums now evaluate requests on a case-by-case basis, not all museums do this. My hope would be that the Getty Panel Paintings Initiative would become much more widely known, and this conference is a marvelous first step toward that goal. New initiatives need to be made with institutions, conservators, and curators in Germany, Belgium, and France who are not well represented here.
- The latest studies and information about the impact of various types of packing and transport conditions, and the effects of environmental differences from the home institution to that of the exhibition, need to be more widely disseminated.
- These recent advances in our knowledge need to be communicated not only to conservators but also to curators, who need to learn how to understand the data for evaluating a given loan request. We must find ways to enhance good communication between curators and conservators on these and other matters.

- Above all, let us keep in mind how best we can represent the achievements of old master panel painters in carefully thought-out exhibitions. Given developments in conservation treatments and in special care and handling in packing and transport over the last decade, the possible risks of lending panel paintings are now often smaller than the benefits of marvelous new insights into the works and artists of long ago. Let us collectively find ways to achieve advances in our knowledge and appreciation of the mastery of these painters.

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