Counteracting Warpage in Wooden Objects: Two New Approaches

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Abstract: Two treatment approaches offer the ability to reduce disfiguring cross-grain warpage in wood. Both approaches are designed to counteract warpage by minimizing the measurable difference in the widths (cross-grain dimension) of the concave and the convex surfaces of a warped panel. The approaches differ significantly, however, and each is employed only upon consideration of the specific circumstances of the warpage (the term "warpage" here will refer to the most common form of the defect found in historic artifacts –the troughlike cupping of a board or panel). One technique, *Induced Compression Set*, **shrinks a convex surface** to the narrower width of the opposing concave surface, using moisture and physical constraint. The other technique, *Glycol-Stabilized Expansion*, **swells a concave surface** to the wider dimension of the opposing convex surface, using moisture followed by a bulking agent–low molecular weight polyethylene glycol–to maintain the swollen state indefinitely.

Conservators today rarely attempt to remove warpage from wooden objects. Indeed, it is both prudent and ethical to tolerate most warpage as a natural feature of furniture and wooden objects. It is so common in certain types of artifacts, in fact, that its presence may contribute to the confirmation of age and authenticity. Under certain circumstances, however, warpage leads to extreme structural and surface problems, and treatment may be warranted as a means to reconstitute an object's physical integrity.

Over the years traditional restorers struggled to understand the causes of warpage and to develop methods to remedy the condition. Many of the old explanations (and some recent ones), though based upon good observation, often betray a misunderstanding of warpage processes. A better-than-average restoration manual first published in 1967, for instance, offered a curious hypothesis on the photosensitivity of wood: a table top "curls upward at the edges" because "wood tends to curl this way towards the light" (*Hayward 1967*). Other authors attributed warpage to the tendency for "growth rings to straighten out over time," or resigned themselves to the notion that the defect in old furniture is "the natural result of gradual drying of the wood; and the wider the boards used… the more pronounced the warp" (*Ormsbee 1949*).

Because of such imperfect understanding of the causes of warpage, traditional remedies were often either highly intrusive or of questionable effect. Many authors acknowledged the difficult, unpredictable nature of the treatments, then proceeded to describe techniques which, at best, produce merely temporary results, and at worst, have potentially disastrous consequences. Much of the literature (including conservation literature related to the treatment of warped panel paintings) recommends treatment approaches involving severe alterations to the offending panels. Saw-kerfing and panel-thinning may be effective means to flatten panels, but they are unacceptable remedies to conservators interested in preserving original structure and materials. Less drastic alternatives, such as applying veneer to the reverse side of a warped panel, screwing rigid battens on the back, or employing various cradle supports, are now dismissed by most conservators as intrusive, unpredictable and potentially damaging.

Old techniques which involve no auxiliary restraints are equally misguided and unreliable. Manuals commonly recommend an old approach: swelling the shrunken concave side of a board with water, then clamping it flat until thoroughly dry. One author claims success with thin boards using this method, but admits that "on 90 percent of the thicker types the warp returns once the wood starts to dry out." The solution? "...it is imperative to solidly fix the top back on the base before this happens." (*Salazar 1982*). Such a recommendation could be disastrous: in cases of extreme warpage, the likely outcome of such a practice is an unwelcome split in the treated board.

Beginning in the late 1940s, Richard Buck, a paintings conservator working at the Fogg Museum in Massachusetts, began incorporating the science of wood technology into his work with warped panel paintings. Buck developed a working understanding of the rheology of wood as a viscoelastic material capable of considerable flow and deformation. As a result of his research he began to question many of the then-standard treatments for panel paintings, believing them to promote dangerous stresses which could result in irreversible damage (*Buck 1975*).

The treatments that grew out of Buck's research remain problematic, particularly for a furniture conservator, because of his use of a variety of bulky backings to maintain the planarity of a panel painting after treatment. Nonetheless, conservators of wooden objects benefit from his theoretical knowledge, published experiments, and his recognition that the science of wood technology provides direction to the study and treatment of historic wooden artifacts.

Conditions Which Lead to Warpage

Developing an understanding of wood's elasticity, plasticity, its response to moisture, and the processes of wood warpage is essential to the development of effective treatments. While detailed information on wood distortion is found in the technical literature (*Hoadley 1984; Panshin and de Zeeuw 1980*), a brief discussion below will define some useful terms, will introduce the conditions which lead to cross-grain warpage, and will lay the groundwork for the subsequent proposals for its reduction. Throughout this article, the form of warpage under discussion is cupping–the trough-like cross-grain distortion of a board or panel caused by a discrepancy in the shrinkage of the opposing surfaces. Bowing, crooking, and twisting–longitudinal forms of warpage less common in historic artifacts–are not under consideration here.

Tangential versus radial shrinkage: Woodworkers have long understood the material's natural shrinkage differential: when dried from its green state, an average wood species experiences negligible shrinkage along its length, about 4% shrinkage perpendicular to its growth rings (radial direction), and twice that amount–approximately 8%–parallel to the growth rings (tangential direction). Since most boards are plainsawn–neither perfectly radial or tangential in orientation–they tend to dry with a natural warp, cupping toward the surface which shrinks the most: the side exhibiting the greatest tangential character, as illustrated in Figure 1.

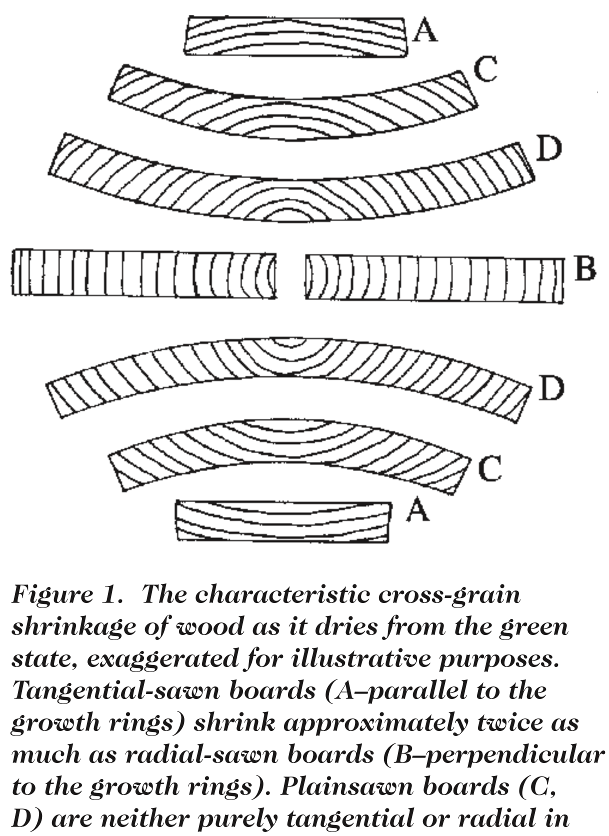

Figure 1. The characteristic cross-grain shrinkage of wood as it dries from the green state, exaggerated for illustrative purposes. Tangential-sawn boards (A–parallel to the growth rings) shrink approximately twice as much as radial-sawn boards (B–perpendicular to the growth rings). Plainsawn boards (C, D) are neither purely tangential or radial in character, so they shrink unevenly–cupping toward their tangential faces.

Woodworkers contend with this annoying natural characteristic by carefully drying (curing) green rough lumber, then planing the dried boards flat prior to their fabrication into finished products. Despite these efforts, historic wooden artifacts often still exhibit natural cupping. In worst cases, this may be caused by improper or insufficient initial curing; in mild cases, it is evidence of residual uneven shrinkage.

Compression set shrinkage: Less understood are the effects of compression set shrinkage, a process which commonly occurs after the fabrication of a wooden object and is responsible for a variety of structural problems, including loose joints, split carcase sides, and pronounced warpage. Compression set develops when wood is in some way restrained from its natural compulsion to swell in width (cross-grain dimension) in response to elevated relative humidity. Prevented from expanding naturally as they absorb moisture, wood's water-swollen cells are compressed. The cells remain permanently compressed when the relative humidity returns to its former level, and the wood shrinks to a dimension narrower than its original width.

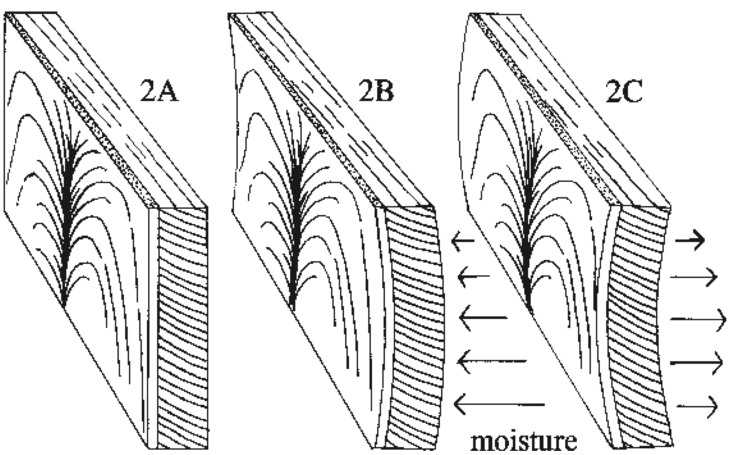

Figure 2. A veneered or painted panel undergoing compression set shrinkage. 2A: a newly-constructed flat panel, with a veneer or paint "moisture barrier" on the presentation surface; 2B: the absorption of moisture by the unfinished reverse surface, with swelling impeded by the stable presentation surface; 2C: as moisture evaporates, the compressed reverse surface shrinks to a smaller dimension, and a permanent warp appears.

Warpage resulting from compression set shrinkage is common in panels and boards where the presentation surface is relatively stable–shielded by an effective moisture barrier (paint, varnish) or held rigid by a physical addition (perpendicularly-laid veneer)–while the reverse, uncoated surface is open and responsive to relative humidity fluctuations. In such panels, the stable presentation surface acts as a restraint, causing the uncoated, moisture-responsive surface to undergo compression set shrinkage. This shrinkage affects the entire panel in the form of a pronounced warp, convex across the width of the presentation surface *(fig. 2)*.

Two Approaches to Counteract Warpage

From the discussions above, it is apparent that cross-grain warpage in wood, regardless of the conditions which led to it, is the gross visible manifestation of a barely perceptible surface-width imbalance: a warped panel is measurably narrower in width (the cross-grain dimension) on its concave face than on the opposing convex face. This simple premise is the basis for the following treatment approaches. In spite of significant differences in application, each approach attempts to remedy warpage, whether resulting from wood's natural shrinkage differential or from post-construction compression set shrinkage, in a similar manner–by minimizing the characteristic surface-width imbalance. Each approach addresses this imbalance through a single-sided treatment–there is little or no effect upon a presentation surface throughout the process, a factor of critical importance to conservators attempting to conserve painted or veneered surfaces.

The first method presented here, *Induced Compression Set*, actually replicates the conditions which cause wood to shrink, and it is designed to minimize the warpage of boards or panels in which the presentation surface is concave. The process employs moisture and, if necessary, physical constraint–not to swell and flatten the concave presentation surface, as in traditional misguided approaches to warpage reduction–but to induce compression set shrinkage in the convex reverse of the board, thereby narrowing its width to that of the presentation surface.

The second method, *Glycol-Stabilized Expansion,* is recommended for panels and boards in which the presentation surface is convex. In this treatment, moisture swells the reverse concave surface of a warped panel to a dimension comparable to that of the convex face. Then low molecular-weight polyethylene glycol–a proven wood stabilizer–is introduced, and as the water evaporates, the glycol remains to maintain the wood's swollen state indefinitely.

The following paragraphs discuss the background and theory of each treatment, offer criteria for determining the viability of treatment and selecting the appropriate method, and present treatment case studies. Advantages and disadvantages of each method are discussed, and questions for further research are presented.

Induced Compression Set

Occasionally the presentation surface of a panel or board exhibits extreme concave warpage. In furniture, this condition occurs most frequently on the tops and leaves of tables, and the sides and tops of case pieces. Usually these surfaces are (or were originally) finished with either a clear coating or paint, while the unexposed convex surfaces are usually unfinished.

The conditions leading to such warpage vary. If the board or panel is plainsawn and the presentation surface has more tangential character than the reverse, a concave warp probably developed simply from the natural shrinkage differential of the wood. Compression set shrinkage also produced many such warps, however. Utilitarian table tops, for instance, often received regular scrubbing with soap and water. Wetting, if sufficient to penetrate the coating of such a piece, caused the swelling of its surface. The dry underside of the top, however, restrained the expansion of the swollen surface, causing the compression of the surface wood cells. As moisture evaporated, compression set shrinkage of the top surface produced a concave warp. If this process were repeated, warpage severe enough to pull the outer edges of a top away from its fasteners could occur.

If concave cupping of a presentation surface is extreme and the integrity of an object's structure is compromised, a treatment using controlled compression set shrinkage may be devised to reduce the warp–regardless of the initiating conditions. This process involves the treatment of the convex reverse or underside of a warped board, and may be carried out with little or no intrusion upon the coating or the wood of the presentation surface. Effective treatments of this type have been carried out by the author since the early 1980s, and a successful treatment developed and carried out by Wallace Gusler, based upon suggestions from the author, was presented at the Wooden Artifacts Group Session at the 1986 AIC Annual Meeting in Chicago. Only a single published reference to this type of treatment has been located, however (*Trinder 1992*).

The treatment utilizes moisture to induce compression set shrinkage in the convex surface of a warped board or panel. At its most basic, treatment simply consists of repeated cycles of wetting and drying the **convex** surface, with the dry concave surface serving as a compression-inducing restraint. As the convex surface undergoes compression and gradually shrinks, the warpage is reduced.

In most cases auxiliary physical constraints help to control the process as well as speed its progress. Constraints are employed in the following manner: With the convex surface of a warped board facing up, light pressure is applied from above to gently flatten it. In extreme cases, constraining battens are also held in place along either edge to limit cross-grain expansion. While constrained in this manner, the convex surface is wetted. As it is unable to expand, the wood cells are compressed. The surface is kept wet overnight, then permitted to air-dry thoroughly for a day or two while remaining constrained. Once the constraints are removed, the board or panel is observed for an additional two days. If warpage is not sufficiently reduced, the process can be repeated.

The details of treatment may vary depending upon the extent of warpage, the thickness of the board or panel, the fragility of the presentation surface and other concerns. If there are concerns about accidental moisture damage, a water-sensitive presentation surface can be thoroughly masked with a moisture-barrier (such as Mylar sheet sealed at the edges with hot-melt EVA adhesive) and the convex side gently swollen in a humidity chamber. Conversely, if there is little or no coating on the presentation surface and no risk of discoloration, gentle swelling to flatten a warp can be initiated on the concave side, and the subsequent compression of the convex side may even be accelerated using heat and steam (see Case Study 1). Extreme warpage should be gradually reduced using several repetitions of the process (see Case Study 2), while less-pronounced warps can often be removed in a single application.

Note: Because of the danger of over-treatment, it is imperative that treatments using compression set shrinkage are undertaken only as a last resort, and that treatments should incorporate the mildest techniques necessary to produce the desired results. A few of the steps listed in the case studies below can cause damage if used inappropriately: they should be deferred until deemed necessary. These include 1) swelling the concave show surface to produce initial flattening, 2) the use of heat and steam, and 3) the use of cross-grain constraints (light pressure from above may be sufficient).

The following case studies illustrate this approach and the manner in which details of treatment are dictated by the situation.

Case Study 1: Yellow Pine Shelf Induced Compression Set

An 11.5 mm thick yellow pine shelf from a mid-nineteenth-century Virginia pie safe exhibited extreme warpage, with a maximum deflection of 11 mm at one end (a deflection is measured simply by laying a straightedge across the entire width of the concave surface of a board, then using a smaller ruled straightedge perpendicular to the first in order to measure the deepest point of the warp). The shelf exhibited a classic natural warp: sawn from the outer portion of a log, the plainsawn board showed far more tangential character on its shrunken concave face than on the convex underside. The surface-width imbalance was noted by measuring across the end showing the greatest warp: convex side, 393.5 mm wide; concave side, 391 mm wide. Assuming the board's edges to be perpendicular to its faces, this demonstrates that an exaggerated warp results from a relatively minor difference in surface width–approximately 0.6% in this case.

Conditions influencing the treatment plan included: a 1 mm split running half the length of the shelf; nail holes (some bearing rusty nail heads); and two layers of paint: old, thin, possibly original pale gray paint on both sides and a later flaking coat of black on the convex side. Treatment was carried out as follows:

1. To improve moisture permeability, the black paint was removed from the convex surface using 3M Safest Stripper (the paint remover had little effect on the thin coat of pale gray paint, which was deemed a negligible moisture barrier). After cleaning, the board was allowed to dry for a day prior to treatment to eliminate any swelling of the wood by the water-based paint remover.

2. On the convex side, the 1 mm split and nail holes were filled with soft wax (Styx Mounting Adhesive, Lea A-V Service, 1017 Shasta Drive, Madison, WI 53704) to prevent water from reaching the concave side during treatment.

3. Clamps and battens were readied for treatment. Three rigid cross-battens were cut slightly shorter than the width of the board. Because of the severity of warpage, treatment was designed to gradually reduce warpage in two or more steps. Each cross-batten was bandsawn lengthwise into two pieces with curves somewhat shallower than the warp (determined by laying the board concave face down, then placing each cross-batten lengthwise against its end, pressing the warp lightly downward with fingertips to reduce its deflection, then tracing the shallower curve to the side of the batten). Two additional straight cauls were cut to match the length of the warped board.

4. The shelf was laid, concave face down, above the three bottom sections of the cross-battens, which were placed on a rigid work surface with

their convex curves up. With the long cauls in position alongside the board's edges, three bar clamps were then placed across the assembly and lightly adjusted to hold the cauls against the board. *Note:* No force was used to tighten the bar clamps, as their purpose was solely to resist the impending expansion of the formerly convex surface, not to compress it in its relatively dry condition. *(fig. 3)*

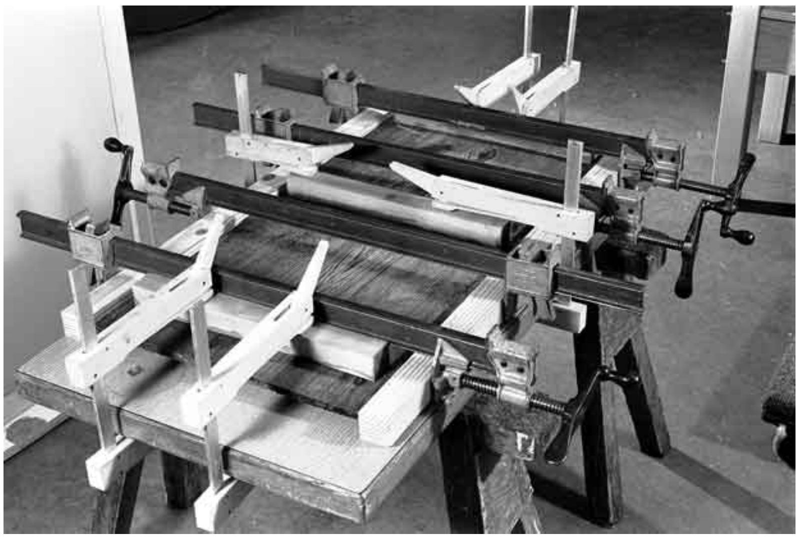

Figure 3. Inducing compression set shrinkage in the convex side of a warped yellow pine board (Case Study 1). With the water-saturated convex side facing up, cam clamps apply light downward pressure on the warp while optional bar clamps restrict cross-grain expansion.

5. The convex face was saturated with warm water. The three upper curved cross-battens were immediately positioned above their counterparts. Deep-throated wooden cam clamps were then applied with sufficient pressure to reduce the warp of the board to the shallower curve of the cross-battens *(fig. 3)*.

6. Wet cotton towels were laid on the surface not obscured by battens and the assembly was allowed to rest overnight. Towels were removed the following day, and the surface air-dried under constraint for two days. The clamps and cauls were then removed, and the deflection measured at 7.5 mm, a reduction of 4 mm.

7. Steps 3 through 5 were then repeated, this time with straight cross-battens in order to flatten the warped board completely. Two days after completion, however, the warp returned to a deflection of 6 mm. The process was repeated a third time, with the final, acceptable result a deflection of 3 mm. Widths of both faces of the board now both measured at 38.9 cm. The formerly convex side of the board measured 4.5 mm less than before treatment–good evidence of compression set shrinkage. However, the formerly concave face also measured less than before (1.5 mm). This may imply that the concave face also experienced compression shrinkage, but may also indicate pre- and post-treatment differences in relative humidity. Other changes after treatment included the widening of the split in the board on the formerly convex side from 1 to 1.5 mm, an undesirable by-product of the compression set shrinkage, and slight discoloration of the formerly convex surface where battens were placed.

Case Study 2: Top to Chest of Drawers– Induced Compression Set

The warped top to an early nineteenth-century American chest of drawers was treated in 1988. The 53.3 x 106.6 x 2.2 cm. top consists of two formerly edge-glued tulip poplar boards with outer edges banded in curly maple veneer. The presentation surface retains an old, possibly original red pigmented wash, while the underside of the top was never coated. Prior to treatment, shrinkage caused the glue joint between the two boards to fail, resulting in a gap and fracturing the edge veneer bridging it. In addition, the 31.7 cm. wide front board warped upward, showing a deflection as great as 4 mm.

In most cases a deflection of 4 mm is not extreme. Here, however, the front edge of the warped board remained securely fastened to the chest carcase, causing the rear edge to rock upward a full 8 mm out of plane with the matching edge of the rear board. This lack of planarity exacerbated the edge veneer problems, and the jagged fractures emphasized the misalignment of parts. Following are the steps taken to correct this problem.

1. The warped board was removed from the top, with care taken to avoid damage to the jagged fractures of the edge veneer.

2. The concave presentation surface was tested to determine if the red wash was water-sensitive. No blanching or dissolution was noted, and the warp was initially flattened by laying the board concave side (show surface) down on a bed of damp cotton towels for approximately two hours. *Note:* This step hastens the effectiveness of treatment, but is rarely possible because of the limited permeability of most coatings, the potential for blanching and discoloration of the presentation surface, and the concern that the warp will actually worsen if treatment is interrupted at this point (we want to induce compression set shrinkage in the convex side, not this one).

3. During the initial swelling process, clamps and cauls were readied for the treatment as in Step 3 of Case Study 1. In this case, however, the warp was not extreme, so straight cross-battens were used from the outset.

4. Once flat from absorption of moisture into the concave surface, the board was constrained as in Step 4 of Case Study 1.

5. See Step 5 of Case Study 1.

6. Wet cotton towels were laid on the surface not obscured by battens, and the surface was steamed with a flat iron for several minutes. *Note:* Steam is optional and should not be used on highly-sensitive objects. It should be considered only if milder treatments are ineffective. Steaming hastens moisture absorption and increases the depth of penetration, and was used here because of the significant thickness of the warped board (7/8" or 22 mm).

7. Following steaming, additional water was brushed onto the towels and the assembly rested overnight. Towels were removed the following day.

8. The surface was air-dried for two days under constraint, then the clamps and cauls were removed. After several days of observation with no return of warpage, the treatment was deemed successful.

The treated board received no additional conservation at this time (coatings, veneer repairs, regluing, etc.), and the chest was placed in storage with the treated board resting in its original location without fasteners. In spite of moderate humidity fluctuations in the storage space, the board remains completely flat eight years after treatment.

Conclusions: Induced Compression Set

The success of the case studies indicate that disfiguring warpage can be reduced by inducing compression set shrinkage in the convex underside or reverse of a warped board or panel. Advantages include the relative simplicity of treatment as well as the benefit of carrying out treatment upon the backside of a board, with no visible effect upon the paint, varnish, or wood color of the presentation surface. Treatments can also be custom-designed to suit the circumstances, with very mild techniques recommended for delicate objects.

Treatment, it should be noted, has little effect on the dimensional stability of a board or panel: treated wood will continue to shrink and swell in response to humidity fluctuations. This is of little consequence to unrestrained members (table leaves, floating panels, desk lids). However, if treated wood is returned to a restraining structure (e.g., a chest or table top is securely fastened on all edges to a rigid frame), warpage may return or splitting may occur. Rigid structures, therefore, should be reassembled with alternative "floating" fasteners designed to permit the natural movement of wood.

Disadvantages of treatment include a degree of unpredictability, the potential for some discoloration of the formerly convex side, and an acknowledgement that treatment is an irreversible process. Dimensional change resulting from treatment is also a concern: the convex face is not returning to its original dimension, but becomes slightly narrower to match the already-shrunken concave face. The reassembly of treated boards or panels must take into account these new dimensions. Finally, any extant splits in the formerly convex surface may be slightly widened by treatment.

Further research is necessary to quantify the least intrusive methods for obtaining successful reduction of warpage. Studies should also be carried out to examine the potential for stress, strain and moisture damage to the untreated presentation surface, both during and after treatment, before treatment can be recommended for objects with delicate, friable coatings.

Glycol-Stabilized Expansion

Painted or veneered wood panels sometimes exhibit pronounced convex warpage, often severe enough to fracture associated restraining members or supporting frames. Such extreme warpage is almost invariably caused by an imbalance of the opposing surfaces. The painted or veneered surface acts as a moisture inhibitor, restricting the transpiration of moisture vapor to and from the face of the panel. Paint materials or veneer (particularly veneer with grain perpendicular to its support) may also act as nearly rigid restraints, preventing the movement of the adjacent wood substrate even if moisture penetrates its surface. Consequently, the presentation surface of a painted or veneered panel may be nearly dimensionally stable–unaffected by relative humidity fluctuations.

On the other hand, the opposite surface, whether the reverse of a panel painting or the underside of a veneered table top, is often completely unfinished. On such surfaces moisture transpiration is entirely unimpeded. Movement of the wood in response to this transpiration, however, is hindered by the relatively rigid painted or veneered face. Natural expansion of the unfinished surface during periods of high humidity is restrained, causing the swollen wood cells to compress. When the relative humidity drops and moisture leaves the wood, the surface experiences compression set shrinkage and becomes narrower than the painted or veneered face. As a result of this surface-width imbalance, the panel warps, with the narrower unfinished surface becoming concave.

In 1987, the author began experimenting with a method to reduce extreme convex warpage in painted or veneered panels by swelling and stabilizing their unfinished concave surfaces with glycol/water solutions. Polyethylene glycol has a history of use since the 1950s as a wood stabilizer. Conservators of marine archaeological materials commonly use it to maintain the structural integrity of deteriorated waterlogged wood (*Florian 1977; Grattan 1981; Hoffman 1986*), and craftsmen working with green wood use it to avoid disfiguring shrinkage and splitting (*Stamm 1959; Spielman 1985*). Polyethylene glycol differs from other common wood consolidants and stabilizers in its strong chemical affinity for cellulose. PEG is soluble in water, and when introduced to waterlogged or green wood in an aqueous solution it gradually supplants water within the swollen cell walls of the wood (most other consolidants and stabilizers simply fill cell voids, acting merely as "internal coatings"–see *Rowell 1984*). As the water evaporates, PEG remains within the cell walls, maintaining the wood at or near its formerly water-swollen dimensions and minimizing shrinkage.

Results from initial experiments with single-sided applications of glycol-water solutions on samples of mahogany, tulip poplar, pine and walnut were presented in 1988 (*Howlett 1988*). A range of glycols were included in the study, and those lowest in molecular weight were most successful at inducing warpage in flat samples and at reducing warpage when applied to the concave surfaces of warped samples. Differences in the swelling of radial and tangential surfaces were noted, as well as differences in the responses of wood species: softwoods generally responded better than hardwoods, unstable woods always responded better than stable ones. The tendency for treated surfaces to darken was also noted.

Additional experiments and continued examination and analysis of the initial samples, along with two experimental treatments, were presented two years later (*Howlett 1990*). Significant findings at this time included evidence that treated surfaces, though hygroscopic, were dimensionally stable. In addition, measurements indicated that glycol continues to slightly swell a treated surface for a few months after treatment, possibly because of the slow permeation of wood cell walls by free glycol in the cell voids. Evidence also suggests the volatility of very low molecular weight glycols over time: treatments using glycol below 300 M.W. were losing effectiveness (see also *Hoffman 1988*).

Since 1990 the experimental treatments have been monitored and two additional treatments carried out. The following case studies outline one of the initial experimental treatments, a mahogany-veneered white pine desk lid (Case Study 3), as well as a treatment performed in 1995 upon two yellow pine painted panels (Case Study 4). Though both treatments were successful, the latter reflects a refinement in treatment techniques as well as a greater knowledge of the efficacy of the various molecular weights of polyethylene glycol. As such, the latter treatment required approximately one third the labor for successful completion.

Case Study 3: Mahogany-Veneered White Pine Fallboard: Glycol-Stabilized Expansion

An early 19th century writing table and bookcase made in Richmond, Virginia entered the collection at Colonial Williamsburg in extremely deteriorated condition, with its worst problem a severely warped and split fallboard *(Fig. 4)*. Because of severe structural failure associated with the warpage, the fallboard was an ideal candidate for an experimental warpage reduction treatment using glycol.

The fallboard, constructed of a single 64.8cm wide white pine board bound at both ends by pine battens, is veneered with highly-figured mahogany in imitation of a pair of panelled doors. The reverse of the lid is edge-banded with mahogany veneer framing a black-painted writing surface originally covered with textile. Shrinkage of the wide white pine board, hindered by the mahogany face veneer as well as the perpendicular end battens, resulted in a number of severe problems.

A large split (as much as 3 mm across) ran the length of the board at its mid-section, completely

Figure 4. Early nineteenth-century Virginia writing table and bookcase before treatment; fallboard dimensions: 64.8 cm. W X 48.6 cm. H X 2 cm. thick.

dividing it into two independent members and disrupting the face veneer. Several smaller splits ran from either end but stopped short of the center. On either side of the large split, the veneered face developed pronounced convex warps, and the shorter splits partitioned each half into smaller, less-pronounced convex divisions. A straight-edge placed across the entire width of the fallboard showed deflections as great as 6 mm.

The severe warpage of the wide pine board overcame the restraint of the battens, splitting both of them. The lower end of one batten projected 6 mm from the surface of the fallboard *(see Fig. 5)*. The other batten incurred a ten inch split near its midpoint which projected 4 mm above the adjoining surface. Because of these and other structural problems, veneer was fractured, detached, and

Figure 5. Close-up of a projecting batten and associated veneer damage on the warped fallboard in figure 4, before treatment.

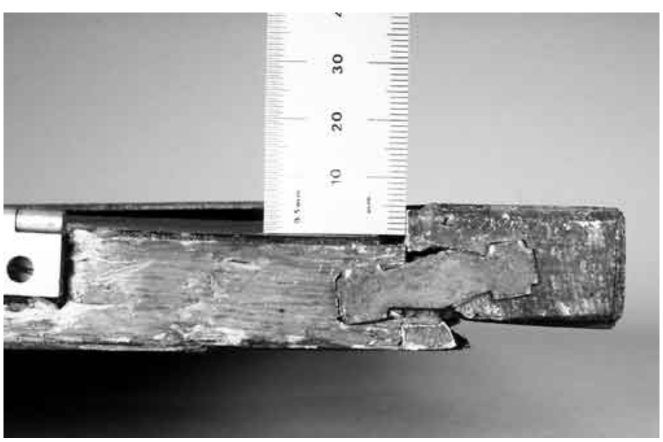

Figure 6. Edge view of the projecting batten in figure 5, significantly out of plane with the warped pine fallboard before treatment. A handyman made a vain attempt to realign the parts with a strap-nail.

missing in many areas. In addition, the deformation broke the hinges (old replacements) out of their mortises, rendering the fallboard entirely non-functional. Realignment of the structural members, repair of the veneer, and reattachment of the fallboard to the desk were impossible using standard techniques *(fig. 6).*

A successful treatment had to accomplish a number of goals. Reduction of the warpage was necessary in order to engage the hinges and bring the battens into plane for regluing, thus reestablishing the object's structural integrity, improving its appearance and making veneer repairs possible. All this had to be accomplished without jeopardizing the fragile early coating on the face of the fallboard. The treatment could not impede the appearance or the function of the writing table and bookcase, i.e., no bulky supports or moisture barriers could be incorporated (as in Buck's panel painting treatments). Ideally, treatment would result in a writing surface as dimensionally stable as the veneered face of the fallboard. Treatment also had to be durable, yet the object re-treatable should initial treatment fail.

Treatment of the writing surface with a chemical stabilizer was viewed as the treatment most likely to satisfy all of the above requirements. Based upon the author's earliest experimentation, dipropylene glycol (Aldrich Chemical Co., Inc., Milwaukee, WI 53233) was selected as a good choice for a trial treatment. Of all the glycols tested, it produced the most effective initial reduction in warpage under mild treatment conditions. Also, unlike the others, dipropylene glycol (DPG) did not appreciably increase its effectiveness over several months: the risk of inadvertent over-treatment would be minimal. In addition, DPG produced the least "oily" surface upon initial drying, probably because of its more immediate penetration into the cell walls of the treated samples. As for the suspected volatility of DPG, this possibility was viewed as a positive factor: if over-treatment occurred, slow evaporation of the glycol would be the safest means to prepare the fallboard for re-treatment.

The experimental treatment proceeded as follows:

1. The thin black non-original paint on the writing surface was removed with methanol. After the surface was thoroughly dry it was lightly abraded with very fine finishing paper (600 grit) to remove any remaining paint residue and aid subsequent surface wetting. All dimensions, crack widths and deflections were recorded.

2. Paraffin dams were applied around the perimeter of the pine writing surface and around each crack to contain the glycol/water solution.

3. With its concave writing surface facing up, water-saturated towels were placed on the fallboard surface to begin the swelling process. A thin sheet of plywood was placed an inch above the surface to slow evaporation. After several hours, the warpage of the fallboard had reversed slightly.

4. The towels were removed and a 25% solution of DPG in water was applied in a thin layer over the entire writing surface. The surface was again covered with plywood and polyethylene sheeting, and the treatment checked twice a day for the following month. Small amounts of solution were added as necessary, and water alone was added on several occasions to prevent the return of the warp (*fig. 7*).

Figure 7. Treating the writing surface of the fallboard with a glycol/water solution (Case Study 3). Paraffin dams prevent the solution from wetting the veneer edgebanding or entering the splits.

5. After a month of treatment (using approximately 75ml of DPG) the writing surface was dried in the lab environment (50% R.H. and 22 degrees C) for two weeks, and remaining glycol residue removed with a damp rag. After an additional week of drying measurements were taken. Though original warpage was reduced by 25%, the improvement was insufficient to permit regluing of the split battens.

6. The fallboard rested unrestrained with no measurable change in deflection for a period of eight months. The treated writing surface remained darker and slightly damp to the touch, although additional cleaning could have eliminated the dampness.

7. Following the eight month hiatus, additional treatment was begun on the fallboard, this time incorporating heat to enhance the treatment. The writing surface was again swollen with water, a 25% DPG solution reintroduced, and a tacking iron at a temperature of 70-75 degrees C used to speed penetration. Both the DPG solution and pure distilled water were on hand to replenish evaporated water (the glycol's boiling point of 222 degrees C precluded its evaporation). The small size of the tacking iron allowed very localized treatment, permitting concentration on areas either resistant to impregnation or exhibiting the greatest warpage. The tacking iron was used for thirty minutes twice a day over a three day period. While resting, the surface was covered as in the previous treatment.

8. After two weeks of uncovered drying all deflections were significantly reduced, contributing to a considerable improvement in appearance. However, the split battens still projected more than allowable for regluing, so the three-day heated DPG treatment was repeated. More effort was concentrated upon the areas of greatest need, and the combined heat treatments incorporated approximately 50ml additional dipropylene glycol into the surface.

9. Measurements were once again taken after drying, and further improvements in deflections were noted. The split battens, though still projecting nearly 2 mm out of plane, could now easily be pressed into proper position for routine regluing.

10. Paraffin dams were removed and veneer repairs undertaken using standard procedures. The old coating, which had fared well throughout treatment, was cleaned and resaturated with padded-on shellac. Hinge repairs were completed and the fallboard reinstalled on the bookcase. No top coating was applied to the treated surface.

Figure 8. The writing table and bookcase (Case Study 3) on exhibit following treatment. The object is exhibited closed at all times: the treated writing surface on the interior remains bare to permit monitoring.

Since 1990, the writing table and bookcase has been on exhibit in the Dewitt Wallace Decorative Arts Gallery at Colonial Williamsburg (see Fig. 8). Its condition appears stable more than five years after treatment, though slight increases in warpage are apparent in some areas, and the widths of splits on the writing surface (which had narrowed significantly after treatment) have widened slightly. These changes are probably an indication of the evaporation of dipropylene glycol, and the fallboard will eventually be retreated with less volatile polyethylene glycol.

Case Study 4: Architectural Painted Panels: Glycol-Stabilized Expansion

When Colonial Williamsburg's Brush-Everard House was closed for renovation of its mechanical systems in early 1995, a section of warped and damaged yellow pine raised panelling from the house's parlor was removed for repair. The floor-to-ceiling painted panelling, covering a side of the chimney breast projecting into the room, exhibited severe warpage on two of the boards comprising a large panel above the wainscot. The warpage, convex on the painted face of the boards, apparently resulted from compression set shrinkage of the reverse (*fig. 9*), probably brought about by periodic dampness associated with the chimney.

The force of the panel's warpage broke through the backside of the supporting frame, where a stile and a rail were already weakened by original adze-chopped clearance for the brick chimney (*fig. 10*). Previous attempts to repair or disguise this damage included an 8 mm putty fill in the resulting gap on the front face of the woodwork (*fig. 11*). Because of the frame damage and the unsightly fill, the following treatment was carried out to reduce the warpage of the painted panels. This treatment utilized polyethylene glycols 300 and 600 (Sigma Chemical Co., P.O. Box 14508, St. Louis, MO 63178) to ensure long term effectiveness.

Figure 9. The reverse side of the warped architectural woodwork removed from Colonial Williamsburg's Brush-Everard House (Case Study 4). Raking light reveals significant warpage to boards in upper panel.

Figure 10. A close-up of damage on the reverse caused by the force of the warping panel (Case Study 4). The stile and rail were initially weakened by early adze cuts which provided chimney clearance for the panelling.

1. Upon removal from the house, the woodwork was first treated with a disodium octaborate biocide (Boracare; PRG, Inc., PO Box 1768, Rockville, MD 20849) because of evidence of powder post beetle infestation. The frame was then disassembled, the panel boards removed and measurements taken. Deflections of the 1.8M long X 29.5 cm. wide X 1.7 cm. thick warped boards ranged from 4 to 6 mm.

2. Prior to treatment, the painted surfaces of the boards were faced with a moisture barrier of Mylar (polyester sheet) sealed at the edges with hot-melt EVA adhesive. An iron cut nail projecting through one of the boards was cleaned and coated with Acryloid B48N (Conservation Materials, P.O. Box 2884, Sparks, NEV 89432) to prevent corrosion by the polyethylene glycol. Minor splits and checks in the rear, unfinished faces of the boards were filled with soft wax (Styx mounting adhesive).

3. In order to swell the concave rear surfaces of the boards, a humidifying table was constructed of plywood and polyethylene sheet (*Fig. 12*). The boards were placed concave side down above slightly undersized cut-outs in the plywood top, and steam was injected into the tented table. After approximately two hours, the boards exhibited very slight reverse warpage.

4. The boards were immediately laid on a flat work table, their formerly-concave sides up. Treatment commenced by brushing on 120ml of a 25% solution of PEG 300 in distilled water. This was rapidly absorbed, so an additional 120ml

Figure 11. The face of the painted panel opposite the damage illustrated in Figure 10. A large, tapered putty fill bridges the gap between the warped panel and the rail.

Figure 12. Beginning treatment: swelling the concave sides of the warped boards from the panel with steam using a humidity table (Case Study 4).

was brushed on four hours later. Between applications, the boards were loosely covered with polyethylene sheet to minimize evaporation (supports kept the sheeting a few inches above the treated surface). On each of the next five days, 100ml of a 25% solution of PEG 600 was brushed on. After the last application the polyethylene sheet was removed.

5. By the next evening, slight warpage had reappeared at the end of the board with the greatest initial deflection. An additional 30ml of the PEG 600 solution was applied to this area, using heat from a flat iron to aid penetration.

6. After drying for an additional four days, the boards appeared stabilized with warpage reduced to 2-3 mm: an improvement insufficient to reinstall the boards in their supporting frame. Treatment was resumed to achieve a greater reduction.

7. Peg 600 solutions were brushed on for three more days, again covering the boards with polyethylene sheet between applications. 120ml of 25% PEG 600 in water was added the first day, while each of the following days the boards received 100ml of 50% PEG 600. Heat from a flat iron again aided penetration in areas of greatest warpage. Following the third treatment, the polyethylene was removed and the boards dried.

8. While the warped boards were undergoing treatment, repairs were made to the damaged stile and rail. The uneven areas of greatest weakness on the reverse of each were reinforced with a carefully fitted 5 mm pine backing.

9. After three days of stability–with warpage no greater than 1.5 mm–the panelling was reassembled. No top coating was applied to the treated surface. However, prior to reinstallation at the Brush-Everard House, the entire assembly was backed with Tyvek sheet (available at building supply stores), which serves as a dust barrier and slows moisture transpiration.

Nearly a year after reinstallation, the panelling appears stable. The process required only 315 ml of polyethylene glycol to successfully treat a 1.1 sq. meter surface area (approx 12 sq. ft.), and though carried out over a three week period, required approximately 35 hours of labor.

Conclusions: Glycol-Stabilized Expansion

Research and the above experimental treatments indicate that low molecular weight polyethylene glycol is effective in the long term reduction and stabilization of warpage in instances where the presentation surface of an object, whether painted or veneered, exhibits convex cupping. Such a treatment offers the possibility of treating severely compromised, otherwise untreatable objects. It is a cost-effective process in terms of time and materials. Polyethylene glycol creates a stable panel–the treated surface, much like the opposing veneered or coated show surface, will experience little expansion or contraction in response to relative humidity fluctuations. Treatment will be durable, as the PEG appears to resist diffusion into or evaporation from the surface after treatment. Finally, the surface is retreatable if warpage should return over time.

Disadvantages include significant darkening as well as a damp, somewhat oily feel to a treated surface (low molecular weight PEG is a hygroscopic material and is liquid at room temperature). This aesthetic drawback precludes the use of Glycol-Stabilized Expansion on any visible surfaces, including such things as the interior surfaces of cupboard doors. Stable woods such as mahogany resist treatment, and treatment remains somewhat unpredictable because of the number of factors influencing the outcome (over-treatment is a concern). Though theoretically reversible, since PEG remains soluble in water, in practice the treatment is irreversible because of wood's response to moisture: removal of the PEG would probably cause worse warpage than before.

A great deal of research is needed in order to refine a warpage treatment using polyethylene glycol from a trial and error process into a predictable and reliable procedure. Many variables affect the outcome of a treatment: species, density, and thickness of the wood; glycol molecular weight; temperature and concentration of the treatment solution; duration of treatment; the magnitude and causes of warpage; the effect of pre-swelling, etc. Experiments should be conducted to determine the influence of each of these factors upon treatment. Other areas for research include studies in the efficiency of treatment (*Howlett 1990,* 89-93), the dimensional stability of treated objects, and the long term effectiveness of treatments. Of particular importance are studies which examine the volatility of glycol (*Howlett 1990, 21, 51*) and questions of its continued diffusion within the wood after treatment *(Howlett, 1990, 64-65)*. Finally, a search for other suitable stabilizing compounds should be undertaken.

Figure 13. A view of the treated panelling, reinstalled on the left face of the parlor chimney breast at the Brush-Everard House (Case Study 4).

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