The structural conservation of canvas paintings: changes in attitude and practice since the early 1970s

Paul Ackroyd

Abstract

Most developments in the structural conservation of canvas paintings since the Greenwich Lining Conference in 1974 are discussed, but the review is not intended as a complete historical survey. Attention is focused on the impact of the principles of minimalism on conservation practice, and the results of research into the mechanical aspects of structural treatments are summarised, particularly regarding lining and moisture/flattening processes.

Introduction

Since the 1970s, changes in practice and attitude to the structural conservation of canvas paintings have been more dramatic than at any other time. This review takes a selective look at some of these changes in order to put into perspective the present attitudes towards the structural repair of paintings and highlight areas where future research might be helpful. It is not possible within the scope of the review to do justice to the amount of controversy that has surrounded this subject over the last forty years. Good accounts of lining developments and a review of the application of mechanical engineering to paintings as structures exist elsewhere [1, 2].

Lining adhesives

The Greenwich Lining Conference

The 1974 Greenwich Lining Conference provides a good starting point for discussion as it has often been regarded as a seminal moment, signalling a re-evaluation of structural treatments. The conference provided an opportunity to express serious doubts over lining that many practitioners had felt throughout the previous decade. The keynote address, given by Percival-Prescott, entitled 'The lining cycle' [3], proposed a reconsideration of the way in which paintings were treated and retreated by a cycle of lining, de-lining and relining – a spiralling process that has a cumulative effect on the painting's deterioration. The aim of the paper was a call for a reduction in the scale of lining activity and this has been influential, perhaps carrying more currency today than it did thirty years ago.

By contrast, the conference also presented new lining methods and materials alongside traditional practices, namely glue-paste and wax-resin lining, which had dominated debates on lining prior to the 1970s and were seriously questioned for the first time at the Greenwich meeting. It is useful to summarise some of the main concerns surrounding these methods because they had an impact on future developments.

Glue-paste and wax-resin

Glue-paste and wax-resin adhesives irreversibly impregnate paintings by varying degrees. Both perform several functions in one process and lack a degree of in-built control; stiff lining supports are attached while the effects of impregnation ensure good adhesion of the painting's components. Glue-paste methods also enable the flattening of serious surface deformations (e.g. tears or cupping), thereby improving the painting's visual appearance. This is achieved by the combined application of heat and moisture that have a plasticising effect on the paint and ground layers. Pressure, normally exerted by hand irons, flattens the distortions, while the restraining effect of a stiff, strongly adhered, support is thought to control their reappearance.

Glue-paste methods, however, may cause shrinkage in some original canvases with a subsequent loss of paint and ground. Though non-aqueous wax-resin processes avoid this risk, the possibilities of flattening surface distortions are limited.

Wax-resin impregnation is thought to reduce harmful stresses caused by the painting's hygroscopic response, which thereby preserves its condition. The introduction of additional hygroscopic material from a glue-paste lining, on the other hand, may increase the picture's susceptibility to atmospheric humidity.

Wax-resin impregnation treatments, however, have become particularly controversial; certain paintings containing absorbent components may become permanently darkened and the continual presence of a hydrophilic material can hamper future treatments.

Hand irons

The traditional use of hand irons in these methods exposed paintings to variable heating conditions and risked incurring damage to surface impasto. The introduction of the vacuum hot table from the mid 1950s, specifically designed for use with wax-resin adhesives, achieved more uniform conditions of heat and pressure and, during the 1960s, brought greater confidence in wax-resin lining, especially in the UK and North America. Hot table processes, however, expose paintings to longer periods of heating than in hand lining, and practitioners employed increasingly high table pressures which led to new kinds of textural change (weave interference, weave emphasis and imprinting, etc. [4, 5]). Confidence in wax-resin lining dissipated and the Greenwich Conference reflected a general disillusionment with the then current methods of lining.

It was against this background that new techniques were evolved from the late 1960s and perhaps the most important of these to be presented at Greenwich were heatseal lining with BEVA 371(Lascaux), formulated by Berger [6], and cold lining with Plextol B500 (Röhm & Haas), introduced by Mehra [7].

New lining adhesives

The main concerns behind the development of new lining adhesives throughout the 1970s and 1980s were to improve the reversibility and stability of the materials employed and to reduce lining conditions, (e.g. heat, pressure, moisture), in order to minimise the risks of incurring physical damage to paintings.

BEVA 371

BEVA 371 (a complex synthetic resin and wax mixture) was formulated as a stable adhesive capable of providing strong, reliable bonds. It was initially intended to be applied to both the lining canvas and the back of the original, and though Berger [8] continues to employ impregnating treatments, he has adapted the method to produce non-impregnating nap-bonds where the adhesive is applied to the lining support only [9]. The combination of reliable adhesion and improved reversibility is the prime reason why BEVA 371 has become the most widely used adhesive for lining and strip lining [10].

The versatility of BEVA 371, in gel form and as a dried film, enables its use for a variety of tasks (strip lining, consolidation, facing, etc.), and a wide range of bond strengths are achievable [11-13]. Since higher temperatures and longer periods of heating are required with BEVA 371 than most other forms of lining, further adaptations to the lining technique have been made: operating temperatures and bond strength can be reduced in 'flock lining' [14] where the adhesive is sprayed onto the lining canvas, to produce a flock-like texture; 'drop lining' [15], where the picture is positioned onto the preheated adhesive and immediately cooled under pressure, also shortens the painting's exposure to heat.

Furthermore, Berger [8] has increased the rigidity of BEVA 371 linings to enable the transfer of tensile stress away from the painting to a stiffer support. This development is based on the theory that the greatest tensile load in a stretched painting is carried by the stiffest layers. Therefore, if the lining is equally as stiff as the painting it will bear approximately half the load, and might be expected to reduce the likelihood of mechanical damage, such as cracks in the image layers. Increased lining stiffness has been achieved by incorporating interleaf materials (e.g. Mylar/Melinex (ICI) and monofilament polyesters).

Despite a recent ageing study by Down *et al.* [16], which has shown that BEVA 371 is reasonably inert, both physically and chemically, there are reservations over its potential for producing overly strong bonds and its future removability [10, 17].

Acrylic adhesives

As first used, Plextol B500 (an aqueous acrylic dispersion) was applied wet, without heat, and required airflow tables to facilitate drying. The adhesive dries to form a moderately stiff film and uniform but relatively weak bonds that enable reversibility of the lining. During the 1960s and 1970s conservators had a cautious approach to water-based treatments and it is not surprising, therefore, that Plextol B500 has not found the wide acceptance given to BEVA 371. In order to avoid moisture-related damage, Mehra pre-impregnated paintings with an acrylic resin (Plexisol P550 in petroleum spirit) to provide a moisture barrier prior to lining [18]. Moisture was later eliminated from the process by a solvent-activation technique where the dried adhesive film was sprayed with solvent (e.g. methylbenzene or propan-2-ol) to give it sufficient tack to produce minimal bonds [19].

Mehra's approach to structural conservation has become enormously influential. He maintained that the preservation of the painting's appearance and the positive aspects of its age (e.g. cupped or raised cracks) were more important than the choice of lining materials. Mehra also placed greater emphasis on the success of what were considered pre-treatments to lining (e.g. flattening, tear repair, consolidation). These were performed as separate processes to lining, which was considered only as a last resort to stabilise the painting's condition. This graduated approach allowed greater control over the entire treatment and contrasted with the traditional view that lining was essential for underpinning the success achieved during pre-treatment.

Later lining developments have built upon the minimal approach represented by Mehra. The introduction of low-heat activated acrylic lining by Ketnath [20] using Plextol D360 (an acrylic dispersion prepared as a dried, flexible film and normally heatsealed at temperatures below 50ºC); cold-lining with pressure-sensitive adhesives such as Fabrisil (a Teflon-impregnated glass fibre fabric coated with a cured silicone adhesive), advocated by Fieux [21] but no longer available; and further developments in solvent-activation lining and pressure-sensitive adhesives [22, 23] have all sought to minimise bond strength, improve reversibility, remove moisture and either reduce or eliminate heat from lining processes. Interestingly, some practitioners have adapted BEVA 371 linings with similar aims in mind: Hawker [11] and Katz [13] have examined low-heat and cold, solvent-activated BEVA 371 linings respectively, and Heiber [24] has recently proposed a low-heat, low-pressure, hand lining method using BEVA 371 film.

As with BEVA 371, the acrylic lining adhesives are versatile and can be used in aqueous, solvent-activation and low-heat methods, sometimes incorporating interleaf materials to improve lining stiffness. They are now the second most popular form of lining after BEVA 371 [10]. (The most commonly used acrylic lining adhesives are Plextols B500, D360, D498 and D541 (Röhm & Haas), occasionally employed in mixtures. Pre-thickened D360 and D498 are available as Lascaux 360 HV and 498 HV). Plextol D360 and Lascaux 360 HV have performed well in ageing studies [16,25], as has Plextol B500, though this has been found to yellow under light ageing conditions [26]. This may exclude its use as a consolidant but should not affect its performance as a lining adhesive.

Phenix and Hedley [27] expressed general concerns over the poor and uneven bond strengths achieved by some contact, pressure-sensitive and solvent-activated adhesives. Similarly, Duffy [28] has recorded low bond strengths for a number of solvent-activated acrylic linings, except in the case of Lascaux 360 HV which, in some cases, produced extremely strong bonds.

Lining equipment

Since the 1970s, the aims behind the introduction of new lining equipment were to reduce and improve control over temperature, pressure and moisture. Vacuum envelope systems, proposed by Hedley *et al.* [29], reduced the duration of heating and avoided surface texture change in the original. These are still employed, albeit to a lesser extent than the type of heated low-pressure tables first devised by Hacke [30], which have become even more popular than conventional vacuum hot tables and Mehra's cold-lining tables [10]. Increased interest in heated suction tables has been due to their improved control over pressure and moisture treatments, and their versatility; most forms of table-lining can be performed and, more recently, the function of this equipment has moved towards carrying out alternative treatments to lining.

Lining fabrics

An exploratory period with synthetic lining fabrics in the 1960s and 1970s has had a limited impact on modern practice and, overwhelmingly, traditional linen fabrics remain the preferred choice for lining and strip lining [10].

Hedley [31] has given a good appraisal of a number of lining fabrics, many of which have been discarded or are seldom used, either due to their poor mechanical performance or instability to light, humidity and pollutants (e.g. polypropylenes, polyamides, polyvinyl alcohols and glass fibre fabrics). Nowadays the most commonly employed synthetic fabrics are the polyesters [10]. Polyester sailcloth (Hayward & Co), a heat-treated, multifilament fabric, proposed by Hedley and Villers [31, 32], satisfies many criteria for lining supports; its high uniaxial tensile stiffness, good isotropic behaviour and surface texture, and resistance to degradation, stress relaxation and relative humidity (RH) are distinct advantages over linen and other multifilament polyesters. It is thought that the stiffness of sailcloth provides an effective support for paintings because it is able to carry a greater share of tensile load than more flexible supports and lowers the loads needed to re-stretch a lined painting. In traditional lining methods, increased rigidity is largely conferred by stiff, impregnating adhesives (e.g. glue-paste or wax-resin) that have a stiffening effect upon the lining and original canvases. However, with the rising popularity of non-impregnating, synthetic adhesives that are comparatively less stiff, greater onus has been placed on the supporting role of the lining fabric.

Although the tensile properties of most new linen canvases are less favourable than those of sailcloth, biaxial tests have shown that, under the low strains by which most paintings are stretched (2-3% maximum), the stiffness and isotropic response of sailcloth are only marginally better than those of linen [33]. The aesthetic qualities of linen, however, outweigh those of most synthetic materials, and go further towards maintaining the original characteristics of traditional painting materials.

Attempts at producing linen-look polyesters are promising but they have not gained widespread acceptance, (e.g. Lascaux P110, and an experimental polyester sailcloth produced by Hayward & Co). Fine, monofilament polyesters have been used occasionally for lining, but have been employed mostly as interlining and strip lining materials since the late 1980s. These are thought to combine high tensile and low flexural stiffness, but their mechanical behaviour and suitability as lining fabrics have not been properly investigated.

De-lining

The removal of old lining adhesives often involves crude and laborious mechanical processes that can further weaken the original and, as Percival-Prescott noted [3], may restrict the options for re-treatment and relining. A recent survey [10] has shown that the reversibility of linings remains an important issue but few improvements have been made to de-lining methods.

Glue-paste and wax-resin

Makes [34] proposed using enzymes to facilitate the removal of degraded glue-paste adhesives. These are not widely employed due to difficulties in controlling the specific conditions needed for effective enzymatic action, and in preventing the enzyme from attacking original proteinaceous materials (e.g. glue size layers). Furthermore, the enzymes are carried in aqueous suspensions and methods for inhibiting the action of water on the original are problematic.

A pilot study [35] using Femtosecond lasers to remove old lining glues, or to denature them and increase their friability, has encountered similar problems in differentiating between organic layers in the lining adhesive and those in the original. The technique's ability to distinguish between the layers may be improved by research into the preliminary mapping of the surface topography, or the use of a technique known as fluorescence lifetime, which has been shown to give unique signatures for canvas and glue.

Complete extraction of impregnating adhesives (e.g. wax-resin, glue-paste, BEVA 371) from the original is practically impossible to achieve, and any consequent colour change in the original cannot be fully recovered [36]. An improved method to remove wax-resin adhesives, however, has been demonstrated using a cold suction table and a non-polar, organic solvent gel [37].

Synthetic adhesives

Concerns have been raised over the reversibility of synthetic lining adhesives, particularly BEVA 371 and Plextol D360 [10, 17]. The adhesive properties of both materials are sensitive to their conditions of use; variations in lining temperature, duration of heating, pressure, thickness of the adhesive coats and the sizing of lining fabrics provide a wide range of bond strengths.

An empirically judged scale of peel strength was proposed by Phenix and Hedley [27] as an approximate guide to a lining's bond performance: average peel strengths of around 300g/2.5cm (2mm/min peel rate) were thought to provide minimum working bonds, strengths of 800-1,000g/2.5cm suggested reliable adhesion, while those in excess of 1,500g/2.5cm could present difficulties with future reversibility [38]. Though these parameters are useful, Daly Hartin *et al.* [12] have emphasised that they are not an absolute means of assessment because what might be considered too strong is dependent on the relative strengths of the lining fabric and painting.

Hawker [11] and Daly Hartin *et al.* [12] found that some heatseal nap-bond BEVA 371 linings give exceedingly strong bonds, in some cases more than doubling the upper parameter of 1,500g/2.5cm, and therefore, may be difficult to remove.

Generally, bond strengths of Plextol D360 heatseal linings were found to be lower than those achieved with BEVA 371, though Hawker [11] demonstrated that the former can produce moderately high peel strengths (1,850g/2.5cm) when additional adhesive coats or temperatures above 50ºC were employed. More significantly, some Plextol D360 and Lascaux 360 HV solvent-activated linings provided exceptionally high peel strengths. Hawker [12], Katz [13] and Duffy [28], each employing different lining materials and conditions, demonstrated that such linings can exceed the upper parameter by approximately 50% (Hawker), 70% (Katz) or 300% (Duffy).

Although many linings tested in the above studies were acceptable, the ease with which some BEVA 371 and Plextol D360 linings could be removed was a point of concern. This issue has not been fully investigated in paintings conservation.

Changes in attitude to lining

After a period of rapid growth in lining technology in the 1970s and 1980s, a relatively static position has now been reached with regard to lining; synthetic lining adhesives (BEVA 371 and acrylic dispersions) are the most popular choice and co-exist alongside a declining use of natural lining adhesives (glue-paste and wax-resin). Prior to the mid 1970s, most conservators tended to rely on one form of lining to deal with the majority of paintings, but nowadays there is a greater diversity in the selection of methods and materials and many practitioners employ two or more different types of lining [10]. This has led to a greater awareness of the technical advantages and disadvantages of most methods, and has allowed conservators to tailor treatments to meet the specific needs of individual paintings.

Comparatively few improvements have been made in lining technology over the last fifteen years but the major change has been a continuing shift in attitude towards minimal intervention, which has gained considerable momentum. In the 1970s and early 1980s changes in practice were caused by concerns over reversibility, exemplified by a preference for non-impregnating adhesives, and aesthetic concerns for eliminating textural change in the image by reductions in lining temperatures and pressures. Though these remain prime concerns, the recent trend towards minimalism has been driven by a greater consideration for the meaning and function of art objects in a historical context, brought about by an increased mobility between art historians and conservators. The increased frequency with which more recent paintings are treated and the move towards preventive conservation, with its emphasis on improved environmental control and collections management, have also made an impact on modern conservation practice. Consequently, there is a desire to preserve the authenticity of paintings as objects. Considerable importance is now attached to structural treatments which aim to conserve the naturally occurring evidence of age, not just in the physical signs of deterioration in the image, such as cracks, but in the entire object. Whereas, since the mid-nineteenth century, the historical aspects of conservation treatments focused on the presentation of the visual image, old stretchers, tacks and tacking margins are no longer considered ephemeral.

Changes in the criteria for lining

In the current minimalist climate, lining is no longer considered as an inevitable occurrence and is a less favoured option, with radical changes having been made to the past criteria used to justify the treatment. These criteria are summarised and discussed below in the light of recent research into the long-term effects of lining on paintings.

To retard physical deterioration caused by environmental conditions

It has been a long-held view that lining acts as a preventive or precautionary measure against deterioration caused by environmental change. Restoration manuals from the nineteenth and mid-twentieth centuries testify to the importance given to this aim which led to an indiscriminate use of the treatment, often carried out before damage had occurred in the painting.

Research has shown that unlined canvas paintings respond rapidly to small temperature and humidity changes [39, 40] but, thus far, biaxial mechanical tests on the ability of lining to prevent or retard the painting's response have drawn different conclusions. According to Berger and Russell [39] an impregnating BEVA 371 interleaf-lining (polyester canvas and a Mylar interleaf) delays and reduces the painting's response to humidity and small temperature variations. In the same publication, the authors maintain that glue-paste and wax-resin linings perform the same function, although glue-paste was found to be less effective. By contrast, Young and Ackroyd [40] found that simple nap-bond BEVA 371/linen and glue-paste/linen linings are unlikely to protect adequately a moisture-sensitive painting from RH change. A nap-bond BEVA 371/sailcloth lining was less sensitive to humidity than an equivalent lining with linen. A wax-resin/linen lining was the only one tested that effectively retarded the painting's response to humidity, so long as the original and lining canvases were fully impregnated with adhesive. Though further research is necessary to establish firm conclusions, both studies suggest that complete impregnation and protection at the reverse of the picture are necessary effectively to reduce its sensitivity to humidity. Impregnation treatments, however, inevitably compromise minimalist objectives for improved reversibility.

To reduce mechanical damage in paintings by allowing the lining to carry a greater share of load

As mentioned earlier, mechanical damage in paintings may be reduced if tensile loads are transferred from the original to a rigid lining support. Young *et al.* [41], using Electron Speckle Pattern Interferometry and uniaxial tensile tests, confirmed that loads are shared proportionately according to the relative stiffnesses of the painting and lining, so long as there is negligible shear strain within the adhesive bond. In uniaxial tests on a nineteenth-century primed canvas without tacking margins, lined with BEVA 371/polyester sailcloth, loads were shared according to the relative stiffnesses of the 'painting' and lining except for a transition region a short distance in from the edges. In this transition region the strains in the lining were greater than those in the 'painting'. In the same study, uniaxial tests demonstrated that both the lined and unlined 'paintings' cracked at approximately identical strains, but the loads at which cracking occurred increased in the lined samples. This confirmed earlier work by Michalski and Daly Hartin [42] and indicated that lining might offer some degree of physical protection to paintings. However, under the low strains normally experienced by paintings, the stiffnesses of most naturally aged primed canvases used in this study and in related work [43] were not significantly increased by lining. It is debatable, therefore, whether simple nap-bond linings would adequately protect stiff and brittle paintings from mechanical damage.

Research by Michalski and Daly Hartin [42] demonstrated that the long-term mechanical properties of BEVA 371/multifilament polyester, BEVA 371/sailcoth and wax-resin/linen linings may alter over time, and their ability to sustain load dissipates due to the effects of creep or stress relaxation. This means that in order to protect paintings from mechanical damage, or to restrain the reappearance of distortions (e.g. tears or cupping), the lining materials must stress-relax at a slower rate than those in the painting. Lining with BEVA 371/sailcloth produced the best results and, interestingly, locking the weave structure of linen by impregnation with wax-resin was found to be an important factor in improving fabric stiffness, though this had only a short-term effect.

It could be argued that full impregnation with BEVA 371, together with a build-up of lining and interleaf layers, may minimise stress relaxation in the support, and thereby preserve the painting's physical condition. But such linings contradict minimalist criteria because they incur a significant loss in the original tactile qualities and are irreversible.

Much attention has been focused on the reasons for employing rigid lining supports but the theoretical arguments for flexible linings have not received equal consideration. In treating a moisture-sensitive painting, for example, the dimensional movements of a flexible support in response to environmental change may be more compatible with those in the painting. A stiff, non-hygroscopic lining, by contrast, may restrain climatically induced movements in the original, resulting in a build-up of stress within the laminate.

To improve the legibility of the image by reducing surface distortions

In the past, importance has been given to the removal of distortions in the picture surface so as to re-establish a coherent reading of the image. Indeed, an attraction of glue-paste lining has been its ability to flatten surface distortions. However, so long as the edges of the painting/lining remain attached to the stretcher edges, the ability of most linings to restrain the reappearance of serious deformations may be short-lived, due to the effects of stress relaxation in the lining materials, as noted above. Additionally, the current preference for retaining some evidence of raised craquelure as a testament to the painting's age, and the practical considerations of flattening treatments, (e.g. a high risk of incurring damage during glue-paste lining and the failure of other methods to flatten cupping), have led to a reduced concern for this criterion.

To support an original canvas weakened by embrittlement or tears

According to a recent survey [10], the support of torn or embrittled original canvases is now, overwhelmingly, the prime reason for lining. The intention is to compensate for such weaknesses by providing a minimal amount of additional support, sufficient to stabilise the painting's condition. The recent interest in acrylic linings, which entail a greater dependence on pre-treatments, minimal bonds and flexible supports, reflects the importance given to this aim. Though some would argue that this lining type, without extra interleaf layers, may not adequately prevent the reappearance of surface deformations, it goes further towards satisfying minimalist criteria for a reduction in lining conditions, preservation of the original tactile qualities and reversibility.

There is scope for deferring the need to line by deacidifying original canvases in order to preserve their strength. Hackney and Hedley [44] have shown that degradation rates in old and new canvases can be retarded by deacidifying with an alkaline reserve or buffer. There are concerns, however, that the continual presence of alkaline reagents may discolour the canvas as well as other painting materials [45-47], and a better understanding of the long-term effects of these treatments is required. (Relatively safe and beneficial deacidification treatments have been recommended [45], e.g. for wooden stretchers, new linen lining or loose lining canvases and original tacking margins).

Many questions concerning the effects of lining on paintings remain unanswered but some limitations of the treatment are now better understood. Lining may offer some protection against physical damage, at least to paintings without brittle paint and ground layers. It has been shown that the painting's tension response alters dramatically during processes involving heat or moisture [40]. Non-impregnating linings, without interleaves, are unlikely to ensure the permanent removal of severe distortions in the picture plane, and it is debatable whether they adequately protect paintings from mechanical damage caused by environmental change.

Alternative treatments to lining

As the scale of lining activity has declined dramatically, the use of alternative treatments (e.g. flattening, consolidation, tear repair, strip lining, loose lining etc.) has increased. With the exception of moisture/flattening treatments, there is a distinct lack of published technical research in these areas and it is impossible to give detailed discussions of these treatments, especially given the word restriction of this paper. It is worth highlighting some areas where future research might be beneficial, however.

The number of recent publications on tear repair demonstrates a considerable interest in the subject [48-51]. Rather than investigating the physical effects of repairs on paintings, these publications have concentrated on the refinement of manual skills and on methods that do not entail the painting's removal from its stretcher. There is considerable diversity in the choice of tear repair materials, which range from very stiff to very flexible materials, and a number of questions need to be answered before assessing which materials are the most suitable. What effects do repairs have on the overall strain distribution within paintings? How do the physical properties of mends alter and interact with paintings in response to environment change? What are the mechanical requirements of repair materials for aged and modern paintings? Since tears in paintings remain a prime reason for lining, published research in this area may lead to further reductions in lining.

An exploratory period with synthetic consolidants in the 1970s and 1980s and subsequent ageing studies on these adhesives [25, 26] has had a limited impact. Significant numbers of practitioners now favour natural animal or fish glues. These have advantages (e.g. good adhesion, good properties of flow and a long history of use), but concerns have been expressed over their introduction into the structure of paintings, and these have not been dealt with. A pilot study of animal and fish glues [52] indicated that isinglas is particularly responsive to humidity change and its physical stability may only be assured within a narrow RH range; at ambient temperatures isinglas films were brittle at 50%RH and plastic at 68%. Moreover, Mecklenburg [53] has concluded that glue size layers are the main cause of cracking in paintings and, if this is assumed to be correct, it might be argued that the introduction of more hygroscopic material into the original could exacerbate the likelihood of mechanical damage.

In strip lining, stress concentrations may develop at the edges of the strips positioned behind the image, and there is concern that these may damage the original. At present it is unknown whether stresses at these points, or those arising at corner joins in strip linings, are significant enough to cause concern.

The good state of preservation of some originally loose-lined, nineteenth-century, British paintings provides empirical evidence of the benefits of loose-linings for unlined pictures. The long-term effectiveness of loose-lining, however, is relatively under-researched and useful comparisons could be made with other methods that do not require the painting's removal from its stretcher, (e.g. encasing pictures in frames with sealed glazing and backboards [54, 55]; backboards adapted with foam or padded inserts to fill the voids between the stretcher bars [56]; stretcher bar-linings positioned behind the stretcher cross-members [57]).

Traditional wooden stretchers have been described as 'the most unrefined element of structural stabilisation' [1 p.31]. Despite their shortcomings many conservators replace old stretchers with wooden constructions, when the need occurs [10]. They have a number of faults: they create uneven strain distributions in paintings and variations in microclimate at the reverse, they are unable to maintain constant tension and are hygroscopic. Turnbull [58] has found that wooden stretchers take long periods to reach equilibrium in fluctuating environmental conditions and are unlikely to have a significant influence on paintings with short-term environmental changes, but may have an effect over long-term seasonal changes. Constant-tension stretchers are promising alternatives to conventional auxiliary supports. Several designs exist, some of which have been environmentally tested [59-61]. The picture is attached, usually to a metal stretcher, by moveable springs that maintain an even tension in the painting as it responds to its environment. In practice, however, as with traditional stretchers, the initial tensioning is often arbitrary, and more work is required to ensure that the function of the spring constants remains unaltered over time. Additionally, some practitioners have expressed a need for improving their aesthetic appearance [10].

Moisture/flattening treatments

A renewed interest in water-based treatments was initiated by a period of experimental research in the 1980s and a desire to avoid lining by improving existing flattening processes.

In the 1960s and 1970s, practitioners adopted a tentative approach towards moisture treatments, and their effects were not fully understood, especially regarding the flattening of severe paint film deformations (e.g. cupping). Consequently, there was a reliance on heat, often applied during lining, and the use of combinations of water and organic solvents to increase the potential for plasticising the image layers [62]. Solvent/moisture treatments continue to be employed but have received little critical attention aimed at reducing the inherent risks involved.

Research

Mecklenburg

Several aspects of Mecklenburg's pioneering work [53] into the mechanical deterioration of canvas pictures in the early 1980s prompted a renewed interest in moisture treatments.

Using uniaxial measurements on restrained and unrestrained samples, Mecklenburg demonstrated the opposing mechanical behaviour of the individual layers in paintings as a function of humidity.

At humidities below 80-85%RH, linen canvas, when restrained in the warp direction, was low in stiffness, but above 80%RH the fabric contracted in the warp, becoming increasingly stiff. Mecklenburg concluded that canvases are only able to support paintings at high humidities.

Glue size films exhibited extreme mechanical behaviour. At humidities below 30%RH the restrained glue film was exceedingly stiff but reverted to a gel at humidities above 80%RH, and was unable to bear tensile stress. Mecklenburg concluded that the glue layer is the stiffest component in most conditions experienced by paintings and is the most important factor contributing to cracking.

Naturally aged oil paint films (36 months old) responded slowly to moisture sorption. After reaching equilibrium at above 90%RH, unrestrained paint films changed dimensionally, becoming flexible and exhibiting a plastic response. The degree of dimensional change and plasticity varied according to the type of paint. A restrained vermilion sample (42 months old) exhibited increased stress from 75% to 5%RH, but above 75%RH the film lost all ability to maintain tensile stress due to creep. Such findings were important in demonstrating the possibilities of using moisture to soften paint layer distortions. Previous industrial research and more recent work, have indicated that oil paint films become increasingly polar and hydrophilic on ageing [63, 64]. Macbeth [65] also demonstrated that nineteenth-century oil-based primings became pliable after three hours' exposure to 100%RH at ambient temperatures. She examined the moisture absorption rates of Mecklenburg's paint samples (by then 10 years old). Their moisture contents rose sharply around 94%RH at ambient temperatures and sorption rates varied considerably, showing a strong correlation with medium content. Paints with a high medium content (e.g. burnt umber) absorbed more moisture than low medium films (e.g. lead white). Most paints took approximately one week to achieve equilibrium conditions at high RH. By contrast, the response times of linen canvas and glue to moisture sorption are fast [66, 67]. In terms of moisture treatments, therefore, the various components of the painting exhibit different magnitudes and rates of response.

Having shown the differing mechanical behaviour of the individual layers Mecklenburg examined the general response of a painting, dated 1912. At low RH, large increases in stress developed in the painting due to contraction of the glue size; stress in the picture reduced between 50-80%RH and was followed by shrinkage and stiffening of the canvas above 80%RH.

Mecklenburg's work highlighted a dilemma in treating paintings with moisture: the high humidities needed to achieve sufficient plasticity in paint films could cause canvas contraction.

He explained the occurrence of cupping in paintings in terms of stress realignment. Since it is thought that the greatest tensile stress in paintings is carried by the layers with the highest stiffness, Mecklenburg concluded that in ambient conditions and below, the majority of stress tends to be situated in the middle of the glue size (Figure 1a). However, as the painting cracks the geometric centre of force is disrupted (Figure 1b). There is a natural tendency for the misaligned stresses below the cracks to realign, and in order to do this they are displaced upwards towards the picture plane. At the points of cracking, this has the effect of pulling the canvas upwards, lifting the paint and ground layers into a cupped configuration (Figure 1c). Subsequently, as the painted layers undergo compression at low humidities, the edges of the cracks become raised (Figure 1d). This model partly describes the generation of cupping; other factors are likely to have a contributory effect, such as differential shrinkage in the cracked paint film, which occurs as the exposed uppermost layers age and contract at faster rates than those underneath [68].

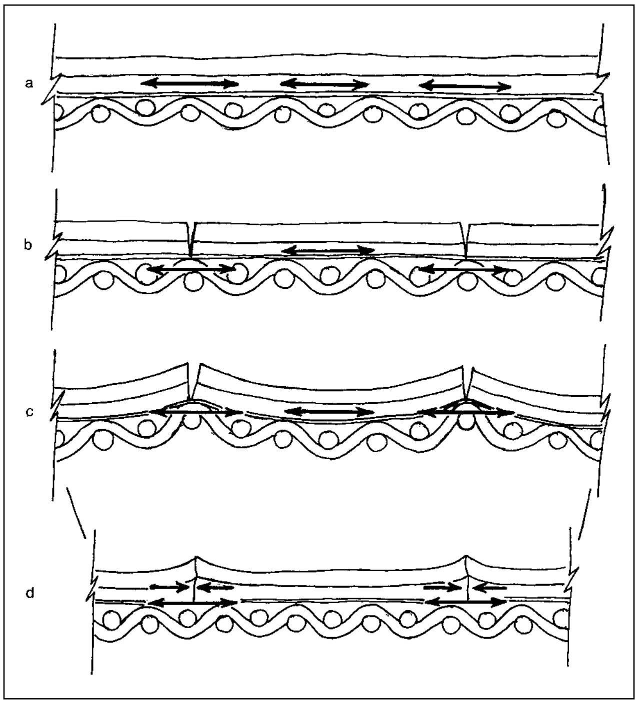

Fig. 1 Mecklenburg's Model for the Generation of Cupping in Canvas Paintings. (a) Prior to cracking of the ground and paint films. (b) Force relocation immediately after cracking of the ground and paint films. (c) Force realignment displacing all layers out of plane. Cupping. (d) Force locations in an unrestrained painting at low RH: glue in tension; ground and paint layers in compression. *(Reproduced with kind permission from M.F. Mecklenburg).*

Hedley

Hedley developed the relevance of Mecklenburg's work to conservation practice. He confirmed the painting's general response, which had been identified by Mecklenburg, and examined the behaviour of the entire painting rather than its individual layers, using environmental tests on uniaxial samples taken from naturally aged, nineteenth-century primed loose-linings [69]. The following results of tensile tests are from restrained samples.

Hedley found that the onset of canvas shrinkage was earlier than Mecklenburg had predicted – at around 78%RH. In biaxial tests, Young has since found that the onset of canvas contraction can occur even earlier, at 65%RH [40].

Hedley demonstrated that the painting's previous history of exposure to moisture was important in determining its response. In cycling RH conditions, the severity of canvas contraction decreased and the point at which shrinkage occurred shifted progressively from 78% to 80%RH. Similarly, sensitivity to stress build-up at humidities below 40%RH decreased on repeated exposures. In brief, the painting's initial exposure to damp or dry conditions gave the greatest response.

In cycling humidity conditions, Hedley observed a sudden tension release in the canvas at high RH. He attributed this to a phenomenon termed 'crimp transfer', where the weave geometry is permanently rearranged to give a more even distribution of crimp in the warp and weft yarns, and thereby producing a more isotropic response.

Hedley used earlier research [70, 71] to demonstrate that machine-manufactured textiles with tightly packed yarns and high weave counts were particularly prone to shrinkage. A high degree of crimp in the warp direction and tightly twisted yarns were important factors contributing to moisture-related shrinkage in textiles. He concluded that at high RH the swelling of discrete size layers, often applied as a cold gel in nineteenth-century prepared canvases, effectively acts as release layers for the overlying paint and ground, and therefore exacerbates the effects of canvas shrinkage [72]. Though Hedley showed that compact weave structures are an important consideration, this does not explain why some tightly woven canvases are insensitive to moisture-related damage or why some openly woven canvases are prone to this problem.

After removing an old glue lining from an early nineteenth-century painting, Hedley observed a pronounced increase in tension and stiffness in the painting after prolonged exposures (24 hours) to moisture (above 90%RH). This behaviour was explained by the regeneration of the old lining-glue remaining in the canvas. Karpowicz [73] has since noted that the increased tension in the above sample may have been caused by contraction of the glue after long exposures to high humidity. Karpowicz has shown that rabbitskin glue films contract in these conditions due to the release of locked-in stress, caused by restraint of the film during its initial drying. Therefore, shrinkage in unlined paintings after long periods at high RH may not be entirely due to canvas contraction but can be attributed to glue size layers.

Using Thermomechanical Analysis and Dynamic Thermomechanical Analysis to determine the glass transition temperatures of paint and ground films as a function of temperature and humidity, Hedley *et al.*[74, 75] found that the softening temperatures decreased and the plasticity of the samples increased on absorbing moisture. The optimum conditions for softening these films were found to be around 38°C and 94%RH. These results were obtained using Mecklenburg's paint samples (10 years old), and nineteenth-century examples of an oil ground and blue paint layer. Different paints exhibited different degrees of response depending on their medium content, pigment type and previous exposures to cleaning solvents. Leaching of low molecular weight components in oil films with propan-2-ol and propanone produced stiffer responses.

Michalski

Michalski [66] was less optimistic about the possibilities of plasticising aged oil paint layers and made a number of observations based on data available from a range of sources.

He observed that increased plasticity in the painting is dependent on a complex interaction of time, temperature and humidity. Raising temperature and humidity affects the paint film's glass transition behaviour, altering its properties from a glassy to a rubbery material, and ideally to a material that exhibits rubbery flow in order to ensure the permanent removal of distortions. Achieving this state may require long exposures to heat and moisture. The rate at which a force (e.g. the application of pressure during treatment) is exerted upon the painting is an important consideration; slowly applied pressures are likely to achieve a more plastic response than rapidly applied forces.

The glass transition behaviour of paints is dependent on their medium content, film thickness, pigment particle size, the pigment's effect on the drying of the oil medium and previous solvent treatments. Therefore, rubbery flow is difficult to achieve in thick, aged films with low medium contents and relatively small pigment particles that form tough, rigid films on drying. This description typifies paints containing lead white, common to most paintings predating the early twentieth century. Practitioners can testify to the difficulties in treating distortions in these layers.

Michalski drew attention to the fact that aged oil paints are cross-linked polymers, held by primary chemical bonds, and therefore alterations to their mechanical properties may not be easily achieved. He stated that: Overall, oil paint is leathery over a wide range of conditions' [66, p.228], ranging from 0-100°C, and that the true glass transition region for oil paints is likely to be between –30°C and 0°C. This suggests that it is difficult to attain rubbery flow in aged paints and that attempts to treat distortions in these layers are unlikely to achieve permanent results.

It has been assumed that the restraining effect of lining supports may prevent the reappearance of deformations, but Michalski, as discussed above, demonstrated that this restraint may be short-lived due to the effects of stress relaxation. Additionally, if one extrapolates from Mecklenburg's model for stress realignment, then a flattening treatment without a subsequent lining may lead also to the recurrence of distortions. After a successful moisture/flattening treatment the painting may be returned to a situation similar to that shown in Figure 1b, but on re-stretching the raised cracks are likely to reappear, as illustrated in Figure 1c. In short, the above research suggests that moisture/flattening treatments for serious paint layer deformations are unlikely to achieve permanent success and that some evidence of their presence may return in time – whether followed by a lining or not.

The impact of research on practice

Conventional methods of introducing moisture to paintings (e.g. direct applications of water to the reverse or indirect applications with dampened interleaves placed beneath the picture) are crude and often lack quantitative control. The research highlighted a need for precise control of moisture dosage in order to avoid canvas contraction, while maximising the potential for plasticising the paint layers.

In the early 1980s Albano [76] constructed an inflatable moisture chamber built over a vacuum hot table. Moist air, produced and regulated by an evaporative humidifier, was blown into the chamber and circulated above the exposed picture with the intention of increasing plasticity in the paint film. After humidification the painting could be heated and dried under vacuum pressure.

Similarly, in the mid 1980s Willard [77] manufactured a multipurpose table incorporating a perspex dome over the work surface in which moist air could be circulated simultaneously from above and below the painting. Both Willard and Hacke [78] attempted to control moisture dosage with low-pressure tables containing in-built humidification systems. Though the former managed to achieve even distributions of moisture across the work surface, both tables had limited success in controlling high humidities for any length of time, especially at temperatures above ambient.

A more sophisticated use of moisture chambers improved humidity control [79]. Chambers can be simply constructed using a metal or plastic frame covered with polythene and, apart from a dew point analyser recommended for accurate RH monitoring, the material costs are cheap. Humidities are raised gradually using saturated salt solutions at ambient conditions, enabling larger amounts of moisture to be absorbed into the painting than at elevated temperatures, and can be reliably maintained for long periods, sometimes days, in order to achieve equilibrium conditions in the paint layers. During humidification, paintings are normally pre-stretched onto looms, partly as a precaution against canvas contraction, but also to facilitate their quick and easy removal from the chamber to a preheated low-pressure table for subsequent flattening and drying. Though humidification processes are controllable, drying treatments with suction tables are haphazard and may desiccate the painting, particularly when heat is employed. There is a risk, as Mecklenburg [53] has shown, that size layers become increasingly brittle and vulnerable to damage in dry conditions.

Schaible [80] produced another effective means of moistening paintings that took advantage of diffusion theory and combined the intentions of the moisture chamber with traditional humidification methods using dampened interleaves. The loomed painting is positioned over an open-celled foam sheet, beneath which is placed a damp cloth. The picture is then surmounted by a small, transparent, semi-permeable chamber. Diffusion theory shows that a moisture gradient is established from the saturated conditions in the damp fabric and will progressively decline through the painting and chamber. Humidity can be varied by altering the permeability of the cover-sheet and can be monitored by a hygrometer inside the chamber. After humidification, the picture is transferred rapidly to a low-pressure table.

Hedley *et al.* [81] maximised the possibility of correcting paint film distortions while reducing the risk of canvas shrinkage by introducing moisture directly to the paint rather than to the canvas reverse. Aqueous gels were locally applied onto the paint surface through polyester mats and covered with a transparent membrane to prolong exposures. Heat and pressure could then be supplied with a hot spatula.

Piper Hough and Michalski [82] have investigated a number of methods to prevent cupping in a simulated modern painting, for example, localised reinforcements with thin, stiff, stainless steel strips, polyester threads coated with heat-cured epoxy and glass filaments embedded in the same epoxy resin. These were attached directly behind the cracks at the canvas reverse using BEVA 371 film. Preliminary tests have shown promising results though further work is in progress to determine whether the strips will create raised distortions in the image over time. By comparison, a moisture/flattening treatment, without reinforcements, was less effective in deterring the reappearance of cupping.

There have been few developments in moisture/flattening treatments over the last decade, but there has been a move away from using moisture as the sole means of plasticising deformations and many conservators have returned to a combined use of agents – heat, moisture and, occasionally, moisture and solvents [10]. The lack of new developments also reflects a greater tolerance of raised cracks in the paint film and, perhaps, a pragmatic appreciation of the difficulties of achieving permanent results.

Conclusion

The year after the Greenwich Conference, at the 4th Triennial Meeting of the ICOM Committee for Conservation in Venice, Percival Prescott called for a moratorium on lining to allow time for an assessment of new developments. This was largely ignored and the proliferation of new lining materials in the 1970s and 1980s was not accompanied by a proper evaluation of their physical effects on paintings. It is only recently, now that lining has become less popular, that there has been research into the long-term behaviour of linings, and this remains incomplete. It is hoped that a wider use of alternative treatments to lining, brought about by the concerns of minimalism, will not follow the same trend – and that questions over their long-term performance will be addressed. Informed decisions on the longevity of conservation processes are hampered by the paucity of empirical and scientific data, especially regarding most alternative treatments to lining. Staniforth [83], in the context of conservation budgets for the National Trust in Britain, has estimated that a minimal treatment may last twenty-five years whereas a full conservation treatment, that would include lining, could last a hundred years, so long as good environmental conditions are maintained. With the present lack of technical information, however, it is difficult to say which will offer the least degree of physical hardship to a painting over a hundred year period – a likely series of minimal treatments or a single highly interventive lining. In all conservation practice, the principles of minimalism can conflict with aspirations for preserving the object’s physical condition and aesthetic appearance; satisfying all these competing objectives, without some degree of compromise, can be a difficult equation to balance.

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Author

Paul Ackroyd received a BA Honours in Fine Art from the University of Trent in 1979. He studied the Conservation of Easel Paintings at the University of Northumbria at Newcastle and was awarded a post-graduate diploma in 1982. From 1982 to 1986 he was a student conservator at the Tate Gallery, London, receiving Diplomas in Easel Paintings Conservation from the Courtauld Institute of Art in 1985 and the Tate Gallery in 1986. He was a Leverhulme Research Fellow at the National Gallery, London, where he has worked as a paintings restorer since 1987.