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FRONT COVER
Vincenzo Foppa, *The Adoration of the Kings*
(NG 729) (detail of Plate 1, p. 19)

TITLE PAGE
Attributed to Pedro Campaña, *The Conversion of the Magdalen*
(NG 1241) (detail of Plate 1, p. 55)

The Mechanical Behaviour and Environmental Response of Paintings to Three Types of Lining Treatment

CHRISTINA YOUNG AND PAUL ACKROYD

Introduction

THIS STUDY INVESTIGATES the mechanical response of canvas paintings before, during and after three different vacuum-lining processes with the following adhesives: glue-paste, wax-resin and BEVA 371. The purpose is to compare physical changes in a painting during lining and to assess the durability of a lined painting over a wide humidity range – 5%–85% relative humidity (RH) at ambient temperatures. Understanding the change in response of the lined painting will aid the assessment of a lining's ability to protect a painting from physical damage caused by changes in environmental conditions, in particular relative humidity.

Background

Since the nineteenth century, one of the principal reasons for lining has been to preserve and protect a painting from future physical deterioration, an entirely separate consideration from the actual repair of structural damage such as tears, flaking paint or raised and distorted cracks in the image. It is not unusual to find paintings lined in the nineteenth century, and indeed within the twentieth century, that show virtually no signs of damage and seem to have been treated for no obvious reason. It is probable, however, that these treatments were carried out as precautionary measures to prevent future degradation and to prolong the painting's life expectancy. Statements from numerous nineteenth-century restoration manuals testify to the importance of this aim. In 1854 Henry Merritt, for example, stated that 'it has only been by lining old canvases upon new that the chief pictures of the great masters now hang on our walls entire ... To line a picture properly, is to renew the lease of its existence for a century'.[1] It was this kind of justification that led to the lining of pictures purely as a matter of course, an attitude reflected in the literature of the time. J.M. Fielding in 1839, for instance, comments that 'In almost all cases, if the picture has not been already lined, it would be best that this should be done before any other operation takes place.'[2]

Nineteenth-century British glue-paste liners took the protective aspect of the treatment to extremes by producing excessively rigid supports, sometimes incorporating two lining canvases, with thick adhesive layers containing large amounts of animal glue, to render the picture solid and robust enough to withstand future hardship. It is fair to say that practitioners at this time acted on an empirical knowledge, but a more recent understanding of the mechanical functions of lining may lend support to the belief that a certain degree of stiffness in the lining may deter physical deterioration. In theory, a stiff, rigid support enables the transfer of tensile load away from the painting to the lining, thereby reducing the likelihood of mechanical failure through the development of cracks in the painting. It has been assumed that glue linings offer this kind of protection at ambient humidity and below but may be less effective in more humid environments.

The lining stiffness is one way to prevent mechanical damage in a painting. The other means of achieving this goal has been to protect the picture from climatic change by making it less hygroscopic. Hence, the aim of wax-resin lining, developed from the mid-nineteenth century, was to impregnate or embalm paintings in a non-hygroscopic material so as to render them completely inert. It has always been assumed that wax-based adhesives perform well in most environmental conditions, offering greater protection over a wide range of humidity, thereby restricting the development of stress and dimensional changes in paintings. The *Manual on the Conservation of Paintings*, published in 1940, with reference to wax adhesives, reiterates the idea that lining can have a preservative effect on paintings: 'Relining is often carried out as a preventive measure for paintings that are still in good condition, on the assumption that all canvas paintings will, sooner or later, have to undergo this treatment ... There is not much to be said against relining as a preventive measure, if it is properly executed...'[3] Confidence in the ability of wax-resin adhesives to safeguard against deterioration in paintings, combined with the seemingly perfect means of performing the operation through the introduction of the vacuum hot table from the late 1950s, again led to an indiscriminate use of lining. It is interesting to note Helmut Ruhemann's comment, written in 1968, some 120 years after Fielding had expressed his belief in the practice: 'Some restorers do not recommend lining unless it is urgent, others line every valuable picture that comes into their hands as a precaution – and now that modern methods have excluded practically all risks, there is little to be said against this'.[4] Despite the progress in lining technology there appears to have been no significant change in attitude at this time. Recent advances in lining have also lent credence to the belief that lining may preserve the longevity of the painting.

The reasons behind the introduction of BEVA 371 by Gustav Berger in 1968 were to supplant the use of wax-resin with an adhesive that also remained relatively inert to moisture, particularly when used with synthetic lining canvases, such as fibreglass or polyester sailcloth.[5] In effect, BEVA 371 is a synthetic wax and resin formulation, but unlike traditional wax-resin adhesives it is capable of providing a non-impregnating, strong nap-bond with the painting. In the early 1980s Berger sought to improve the protective abilities of BEVA linings by increasing their stiffness, incorporating interleaf materials, such as thick polyester sheets, sandwiched between the lining and the painting.[6]

More minimal forms of lining developed from the early 1970s, those employing acrylic dispersion adhesives have tended to avoid the term lining but refer to the process as the 'stabilization' of the painting. [7] Nevertheless, the implied intention, to ensure the permanence of the painting by making it resistant to future deterioration, is not dissimilar to that of traditional lining.

Since the early 1970s there has been a certain amount of disillusionment with lining, largely due to a progressive acknowledgement of the limitations and detrimental effects of most treatments. This has led to a dramatic reduction in lining activity, but many practitioners continue to have faith in its preventive aspects. The Canadian Conservation Institute Lining Project has provided much-needed data on some aspects of the mechanical properties of linings.[8] Berger has also examined the response of BEVA linings to temperature and humidity.[9] The aim of the present study is to examine the physical protection given to paintings by a selection of the above lining methods in tensioning conditions which simulate real situations, during the lining process and while on display.

FIG. 1 Modern copy of Velázquez's *Surrender of Breda*, before treatment.

Paintings for lining

The paintings used in the tests were a series of four previously unlined works by an unknown artist. They are copies of paintings by Velázquez in the Prado, Madrid (FIG. 1). The exact date of the pictures is unknown but, judging from analyses of the paint and ground and the types of commercially prepared canvas used, they were most probably made in the middle of the twentieth century.[10] As the paintings had aged naturally for approximately fifty years and had no intrinsic value, they were invaluable materials for comparative testing. Though they are by the same hand, not all of the canvases and their preparations are identical. Each canvas, however, has a plain weave pattern and has been commercially manufactured. Additionally, cross-sections through the paint, size and canvas layers show that there is a similar amount of proteinaceous size in each painting. Brief descriptions of their constituent materials and condition are given in Appendix 1. A piece from the copy of the *Equestrian Portrait of the Count-Duke of Olivares* was used in the glue-paste lining and another piece from the *Cardinal Infante Ferdinand* was lined with wax-resin. Two pieces from the *Surrender of Breda* were used for the BEVA 371 linings with linen and with polyester sailcloth, thus enabling direct comparisons to be made between both forms of this lining.

Samples for tests

Prior to testing, the paintings were prepared for lining. Once removed from their stretchers the reverses were cleaned and knots in the canvas pared away. The un-tensioned pictures were treated in a moisture chamber with the humidity controlled at between 72–78% RH and 20–22°C using a saturated salt solution for approximately 60 hours. They were then flattened on a low-pressure table at 40°C and 25 mbar pressure.

An area which showed minimal physical damage was chosen from each painting. A 330 mm-square sample was then cut from the painting and the corners removed to produce a cruciform-shaped sample that could be held in the grips of the testing apparatus. The distance between the grips in the two directions was 280 mm with a 270 mm central square section. The selected areas from the paintings are outlined in FIG. 1. After the load extension characteristics of the paintings had been established the cruciform arms were cut leaving 270 mm-square pieces of each painting to be used for lining. In effect, the painting samples simulated pictures that have had their tacking margins removed, a common practice during the nineteenth and early twentieth centuries.

Lining materials and adhesives

Fine linen canvas was employed in all three different types of lining [11] and, in addition, a BEVA lining was carried out with polyester sailcloth. The latter fabric required no initial preparation, but the linen was wetted and pre-stretched three times before use. This practice is commonly used in order to give the material a more isotropic response. A good deal of testing has already been carried out on these two lining fabrics and their mechanical properties are well established.[12]

A glue-paste lining was chosen for testing because large numbers of paintings in public collections have been glue-paste lined in the past, and the method continues to be widely practised, especially within Europe. Also, being a hygroscopic material, it was likely to provide an interesting comparison with the two non-hygroscopic adhesives. The glue lining adhesive consisted of one part refined gelatin and eight parts wheat flour (wt./wt.) with the addition of hydrogen peroxide as a preservative (2% by volume). This recipe contains relatively low quantities of animal glue and has been found to perform better than other formulations.[13]

A natural wax-resin adhesive was also selected, consisting of seven parts bleached beeswax, four parts dammar resin and one part gum elemi (wt./wt.). This was the wax-lining recipe used at the National Gallery from the early 1960s to the late 1970s. Although little practised nowadays, wax-lining was extensively used in the last century in some European countries and in North America. As the adhesive penetrates the bodies of both fabrics it is likely to produce a different pattern of behaviour to the other adhesives.

BEVA 371 was selected because it is probably the most widely used synthetic lining adhesive.

Lining procedures

Tests were initially carried out to establish the individual behaviour, tension versus extension, and tension versus relative humidity response, of the unlined paintings. The response during each stage of the lining process was also monitored and finally the behaviour of the lined painting was measured. Each lining was performed on a small portable suction table, specially adapted for the purpose of these tests.[14] The lining table and tensile tester set-up is described below under Equipment and the tests are described in detail under Test Methods. Where possible, the linings followed what were considered to be typical practical procedures. These are described below and are summarised in Appendix 2.

Glue-paste lining

A traditional hand-lining method was not chosen for the paste lining because the action of ironing would have interfered with the tension results recorded during the process. Instead, a low-pressure table technique, comparable with the wax-resin and BEVA 371 lining method, was selected. Although hand-lining methods are more commonly employed, glue-paste linings have been performed on vacuum tables by a number of practitioners.[15]

The painting was first faced with a dammar resin and beeswax adhesive in white spirit and Eltoline tissue. One thin coat of glue-paste was spread onto the back of the painting and made more even by rolling. The painting was then positioned centrally onto the lining canvas already tensioned in the tensile tester. The table surface had been previously covered with a release layer of polyester sailcloth. Vacuum pressure was applied at 25 mbar and the heat maintained at 40°C for 20 minutes, after which time the heaters were switched off and the lining left to dry for 90 minutes while maintaining 25 mbar pressure. Before further testing the facing was removed.

Wax lining

The wax lining was also carried out using a vacuum hot-table procedure rather than a traditional hand-lining method. The lining was performed in three stages: firstly, the lining canvas was impregnated with adhesive, secondly, the painting was impregnated in the same manner, and finally the lining was carried out. Saturating the lining canvas and painting separately with wax-resin prior to lining not only provided an even adhesive layer but also ensured that the entire laminate, both lining canvas and painting, was thoroughly impregnated.

Throughout the three stages the table surface was covered with silicon-coated Melinex to prevent the canvases from sticking to the metal plate. The adhesive was first melted and brushed onto the linen lining canvas tensioned on the tensile tester. The canvas was covered with Melinex and the vacuum established at 25 mbar throughout. The heaters were then switched on and the adhesive layer was made more even by rolling. After a temperature of 70°C was achieved the lining canvas was then cooled for two hours to ambient conditions.

The back of the painting was brushed with the molten wax-resin. It was not held in the tensile tester during this operation but was subsequently tensioned face up over the vacuum table and covered with Melinex. Pressure was maintained at 25 mbar, and while being heated, the surface was rolled. Once the temperature had reached 65°C the picture was cooled for two hours.

The painting was then lined having been placed onto the lining canvas that was tensioned on the tensile tester. Heat was applied until a bonding temperature of 65°C had been reached, and then cooled for two hours. Pressure was regulated at 25 mbar throughout.

BEVA linings

The linen canvas was placed under tension in the tensile tester and was first sized with a thin coat of the warm adhesive diluted in white spirit (one part BEVA 371 gel: four parts white spirit, v/v). Once this coat had dried three subsequent coats were applied, consisting of two parts BEVA: one part white spirit, allowing time for drying between each coat.

The preparation of the BEVA lining onto sailcloth was carried out in the same manner except that the sailcloth was not given an initial sizing. Throughout the preparations of the lining canvas and the actual linings the table surface was protected with a sheet of silicon-coated Melinex.

Both BEVA linings were carried out following identical procedures. The prepared lining canvases

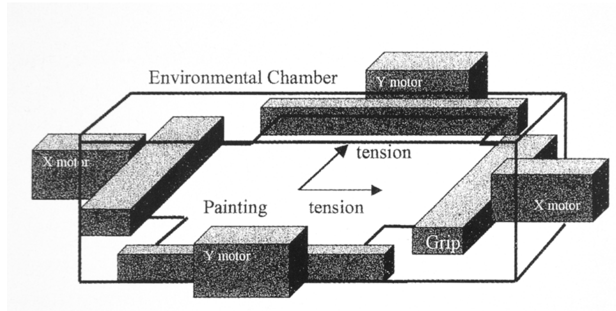


FIG. 2 The tensile tester with integral environmental chamber used for the tests before and after lining.

were tensioned on the tensile tester and the painting samples placed on top of the dried adhesive films. A covering sheet of Melinex was put in position, the pressure was then applied at 25 mbar and the heating switched on until a bonding temperature of 70°C was attained. Thereafter, the linings were allowed to cool on the testing rig for two hours.

Equipment

The biaxial tensile tester

The tests were performed on a biaxial tensile tester fitted with an integral environmental chamber developed specifically for investigating the mechanical behaviour of canvas paintings and the effectiveness of structural conservation treatments (see FIG. 2). The tensile tester measures the load and extension in two directions simultaneously, in these tests the weft and warp of the material. The tensile tester consists of ball and screw translation stages each driven by a stepper motor via a gearbox. There are stepper motors in both the weft and warp directions and tensioning of the canvas is achieved by displacement of the stage. A load cell in each axis measures the in-plane tension and compression. The stages are attached to grips which, for these tests, have rubber faces to prevent damage to the paintings. The translation of each stage is measured by a linear variable differential transformer, from which the extension is calculated. The control and data acquisition is controlled by a 16-bit data acquisition board.[16]

The environmental chamber and conditioning unit

The grips of the tester are enclosed within an insulated steel chamber fitted with a glass lid. The conditioning unit consists of a chiller for dehumidification, an ultrasonic humidifier for increasing the air moisture content, and a ceramic heater element for heating. The air within the chamber is exchanged with the unit via tubes and fans. Manual valves control the air flow. Two Vaisala SM50Y temperature

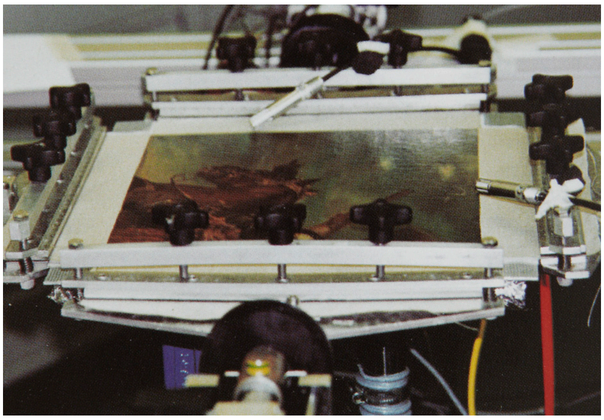


FIG. 3 The testing set-up with the small vacuum table and tensile tester used during lining.

and humidity probes are positioned inside the chamber: one underneath the sample and one on an inside wall of the chamber. These probes send signals back to the programme controlling the environmental conditioning unit and tensile tester. The environmental chamber can be programmed to increase the relative humidity within the chamber at a specified rate in discrete steps, or to remain constant.

Testing arrangement

For the tests, before and after lining, the tensile tester was used with its environmental chamber, with the RH and temperature sensors positioned as described above. For tests on the lining preparations and during the actual lining, the tensile tester, without its chamber, was bolted to a separate frame. On a support frame below the tester, a small vacuum hotplate was placed underneath the central area of the sample (see FIG. 3). The front face of the 330 mm-square vacuum plate was positioned in-line with the centre of the grips. It was found that, with the vacuum at 25 mbar, the plate would not provide adequate temperature for the wax and BEVA linings. The temperature also varied from the centre to the edge of the plate. Additional heating was provided, by placing four 150W compact halogen flood lamps directly beneath the plate, facing upwards onto its back face. This provided an even temperature up to a maximum of 80°C at the top of the plate with a pressure of 25 mbar applied across its surface. The temperature of the plate and painting face were spot-checked using thermocouples. In practice, it was impractical to have the Vaisala probes close to the surface of the painting or lining because they obstructed the application of adhesive and the rolling of the linings. Instead, the probes were taped to the top of the grips. This gave an indication of the temperature and humidity in the vicinity of the painting during the whole process and helped in identifying when equilibrium had been achieved with the ambient conditions.

Test methods

Two main tests were performed on the lining supports, the unlined paintings, and the lined paintings. These were:

a. Measurement of the biaxial (warp and weft) tension resulting from extension at constant humidity and temperature. Three cycles of tensioning then untensioning the samples were performed.

b. Measurement of the biaxial tension due to step changes in relative humidity as a function of time.

During the preparation of the linings and adhesion of the lining to the painting the procedure was monitored by:

c. Measurement of the biaxial tension as a function of time.

All these tests are described in detail below.

Tests on paintings before and after lining

Test a(i)

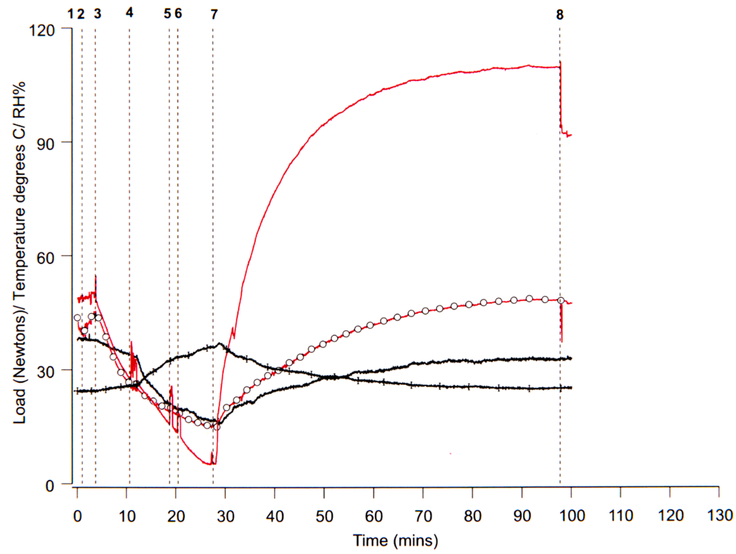
The cruciform painting sample was first positioned in the grips of the tensile tester with the warp direction in the x-axis and weft-direction in the y-axis of the tester. The lid of the environmental chamber was closed and the sample was left to reach equilibrium at 55% RH for two hours. (Ambient conditions varied from 45% to 55% RH in the room in which the paintings were stored.) The painting was tensioned and then un-tensioned in the warp and weft directions from 5N to 100N back down to 5N by equal displacement of the grips. This cycle was repeated three times.

Test a(ii)

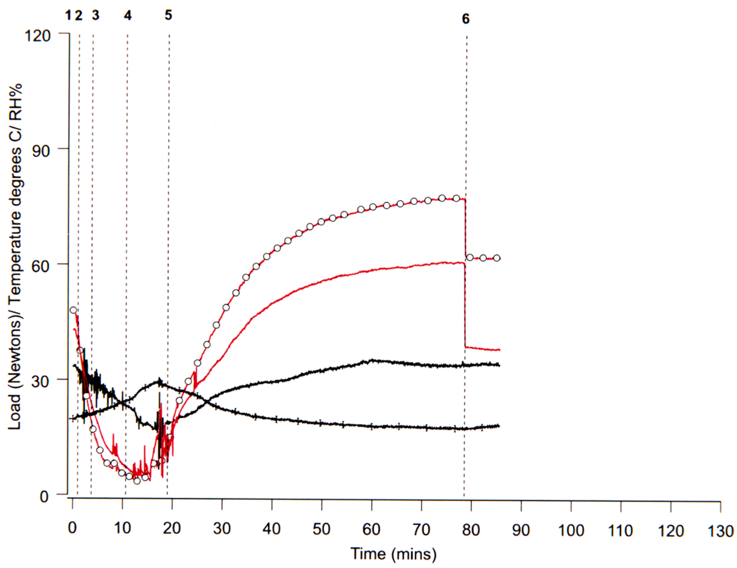
The painting was re-tensioned to 20N in the warp and weft and then conditioned to 5% RH. The tension in the warp and weft direction, the relative humidity and temperature were measured during conditioning of the sample. Test a(i) was then repeated at 5% RH.

Test b(i)

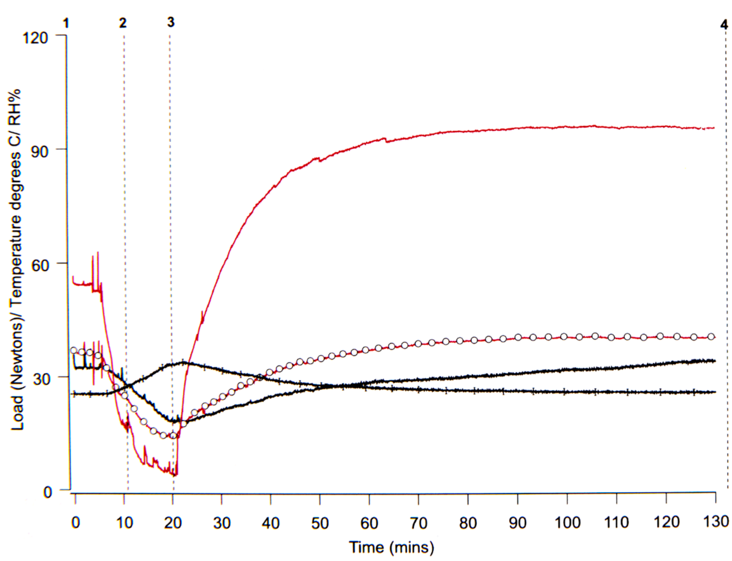
The painting was re-tensioned to 100N in the warp and weft. The relative humidity in the chamber was raised in 10% increments from 5% RH to 65% RH for the paintings and 85% RH for the lining supports. Each RH value was maintained for three hours. The tension in the warp and weft direction,



a. Lining canvas
1. Initial loads
2. Liquid wax applied
3. Heat on
4. Temperature 47°C
5. Temperature 63°C
6. Rolling
7. Temperature 74°C. Vacuum on. Heat off
8. Vacuum off



b. Painting
1. Initial loads. Liquid wax applied
2. Heat on
3. Temperature 63°C
4. Vacuum on. Heat off
5. Temperature 28°C
6. Vacuum off



c. Lined painting
1. Initial loads. Place painting on top. Heat on
2. Temperature 52°C
3. Temperature 78°C. Vacuum on. Heat off. Rolling
4. Vacuum off (200 mins.)

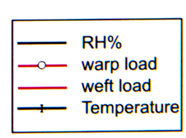


FIG. 4 Wax-resin lining process: a. lining canvas, b. painting, c. lined painting.

the relative humidity and the temperature were measured throughout the conditioning of the sample. The lid of the chamber was removed to allow the sample to return to equilibrium with the ambient conditions.

Tests during preparation and lining

Where possible the preparations of the lining canvases and the linings themselves were performed on the tensile tester, effectively using it as a loom. All processes, including application and rolling out of the glue, the vacuum and the response of the sample itself, were measured throughout the various procedures by the load cells sensing changes in tension. All lining canvases and paintings in the tensile tester were initially tensioned to 40N in warp and weft. After the painting samples had been cut to 270 mm squares they were carefully positioned in the middle of the lining fabrics that had been centred on the vacuum plate. The lining preparations and procedures are described above and are summarised in Appendix 2.

Results

Tension response during lining

FIGS. 4–7 include the curves for temperature and RH% values just above the surface of the canvas and provide an indication of the conditions close to the painting. The temperature values given in the 'listing of events' are from the thermocouple placed temporarily on the painting surface. Tension in the graphs is expressed in Newtons (N).

The wax-resin lining process

FIGS. 4a, b and c show the change in tension in the warp and weft directions during each of the three stages of the wax-lining process for the lining canvas (4a), painting (4b) and final lining (4c). Each process causes similar tension changes as the adhesive melts or solidifies during the application of vacuum pressure. Rapid solidification of the liquid wax occurs once it has been applied to the lining canvas. On heating, the wax starts to melt again causing a reduction in canvas tension (FIG. 4a); this occurs throughout all the stages of the wax lining as the adhesive begins to melt at around 40–45°C. Over a 22-minute period the tension is lowered from 50N and 45N, to 16N and 6N in the warp and weft directions respectively. There are two mechanisms that contribute to the tension reduction. Firstly, there is thermal expansion of the canvas caused by the direct application of the hot liquid wax. Secondly, lubrication by the liquid wax of the yarns in the linen canvas reduces friction at the points where the yarns cross over one another in the weave. This enables the yarns to move easily, thereby allowing a relaxation of the stresses created during the pre-wetting and pre-stretching process and possibly some residual stress induced during manufacture. On cooling, with the vacuum on, there is an initial and immediate increase in tension that is associated with a visible and rapid solidification of the wax. Both tension response and fall in temperature are approximately exponential. As room temperature is reached, after 75 minutes, tension stabilises to 48N in the warp and 100N in the weft. Tension is reduced by approximately 10N when the vacuum pressure exerted on the painting is removed.

As the wax-resin, applied to the reverse of the painting, melts there is a similar decrease in tension, from 48N and 43N before wax application to 5N and 7N in the warp and weft respectively (see FIG. 4b). This occurred more quickly than for the lining canvas, taking only 11 minutes because the painting was heated more rapidly. The tension eventually stabilised to 61N in the warp and 78N in the weft after approximately 70 minutes.

FIG. 4c shows the tension response during the final lining process. The initial peaks in tension occur as the painting is placed on top of the prepared lining canvas tensioned in the tester. As heat is applied and the adhesive (wax-resin) melts, the tensions drop from 38N and 53N to 14N and 4N in warp and weft respectively. Tension stabilises at 40N in the weft and 95N in the warp after approximately 70 minutes. This large discrepancy between the warp and weft final tension, when compared to the preparation of the painting, is probably because the behaviour of the lined painting was dominated by the characteristics of the lining support rather than that of the painting.

For all of the above stages there was an increase in tension once the wax-resin had solidified. This is caused by a combination of contraction of the wax-resin with decreasing temperature and an associated locking of the canvas weave which will reduce residual creep.

Glue-paste lining process

FIG. 5a shows tension change in the warp and weft directions during the lining operation. A new piece of linen without adhesive was tensioned and the painting, with the wet paste having been applied to

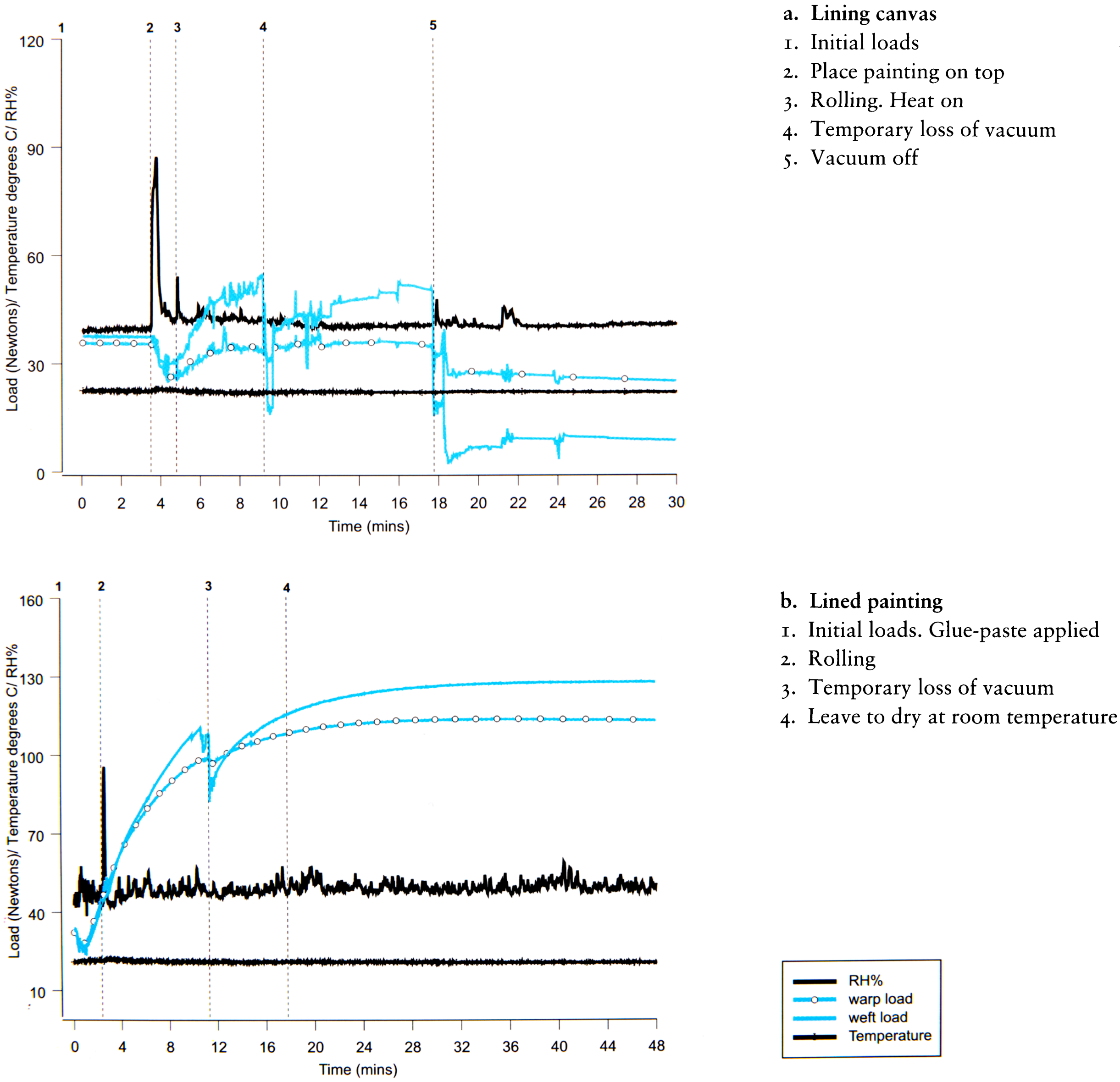


FIG. 5 Glue-paste lining process: a. lining canvas, b. lined painting.

its reverse, was positioned on top of the lining canvas. An initial decrease in the tension of 11N in the warp and 6N in the weft was observed. After rolling the surface and application of heat the tension reached 34N in the warp and 54N in the weft. (Although a temporary loss of vacuum occurred, the tension stabilised at around these values.)

FIG. 5b shows tension change in the warp and weft directions during the application of glue-paste to the lining. The sample was used for comparison in the environmental tests. As the glue-paste is applied to the lining canvas there is an initial but small loss in tension of 10N in both warp and weft, followed by a steady rise in tension as the adhesive dries in room conditions. Tension stabilised at 113N in the warp and 127N in the weft after 40 minutes.

The increase in tension on drying of the glue-paste results from the contraction of the glue and, as with the wax-resin, a locking of the canvas weave.

BEVA and sailcloth lining process

FIGS. 6a and b show tension change in the warp and weft directions during the two stages of the BEVA/sailcloth lining process. As the first layer of BEVA was applied to the sailcloth there was an immediate loss of 10N in both weave directions (see FIG. 6a). The tension then stabilised at 37N in the warp and 45N in the weft as the solvent in the BEVA evaporated. Further applications of BEVA had a negligible effect on the tension in either weave direction. The prepared sailcloth was then re-tensioned and the painting positioned onto the lining fabric (FIG. 6b).

As the lining was heated an immediate reduction in tension from 38N and 35N to 15N and 7N occurred in the warp and weft respectively. This tension loss occurred as the BEVA softened at around 45–50°C and continued until a temperature of 70°C was reached, at which point the lining was then cooled and the vacuum applied. The tension rose as the BEVA solidified and stable values of 25N in the warp and 43N in the weft were attained after 40 minutes.

BEVA and linen lining process

FIGS. 7a and b show tension changes in the warp and weft directions during the two stages of the BEVA/linen lining process. As the BEVA sizing layer was applied to the linen there was a loss in tension of 23N in the warp and 12N in the weft (see FIG. 7a). It is difficult to distinguish between tension lost due to the application of the BEVA from that caused by creep, as both occurred simultaneously in the linen. Subsequent application of coats of BEVA produced smaller tension changes in the order of 10N in both warp and weft.

Once the lining canvas had been prepared it was re-tensioned and the painting positioned on top (FIG. 7b). As heat was applied, tension in the warp and weft reduced at a slower rate than that seen in the prepared lining canvas on its own because the vacuum slowed the rate of heating. After the picture surface had reached 70°C, the lining was cooled, producing a rise in tension, which stabilised after 40 minutes from 5N to 30N in the warp, and from 10N to 100N in the weft.

Interestingly, the BEVA/linen and wax-resin/linen lining processes result in a lining that has a large difference in the warp and weft tension when compared to the glue-paste/linen process. It is possible that this has occurred because these lining processes allowed a complete crimp redistribution, which was locked in when the adhesive solidified, rather than it being the sole action of the adhesive contracting. However, it is unclear why this should be the case.

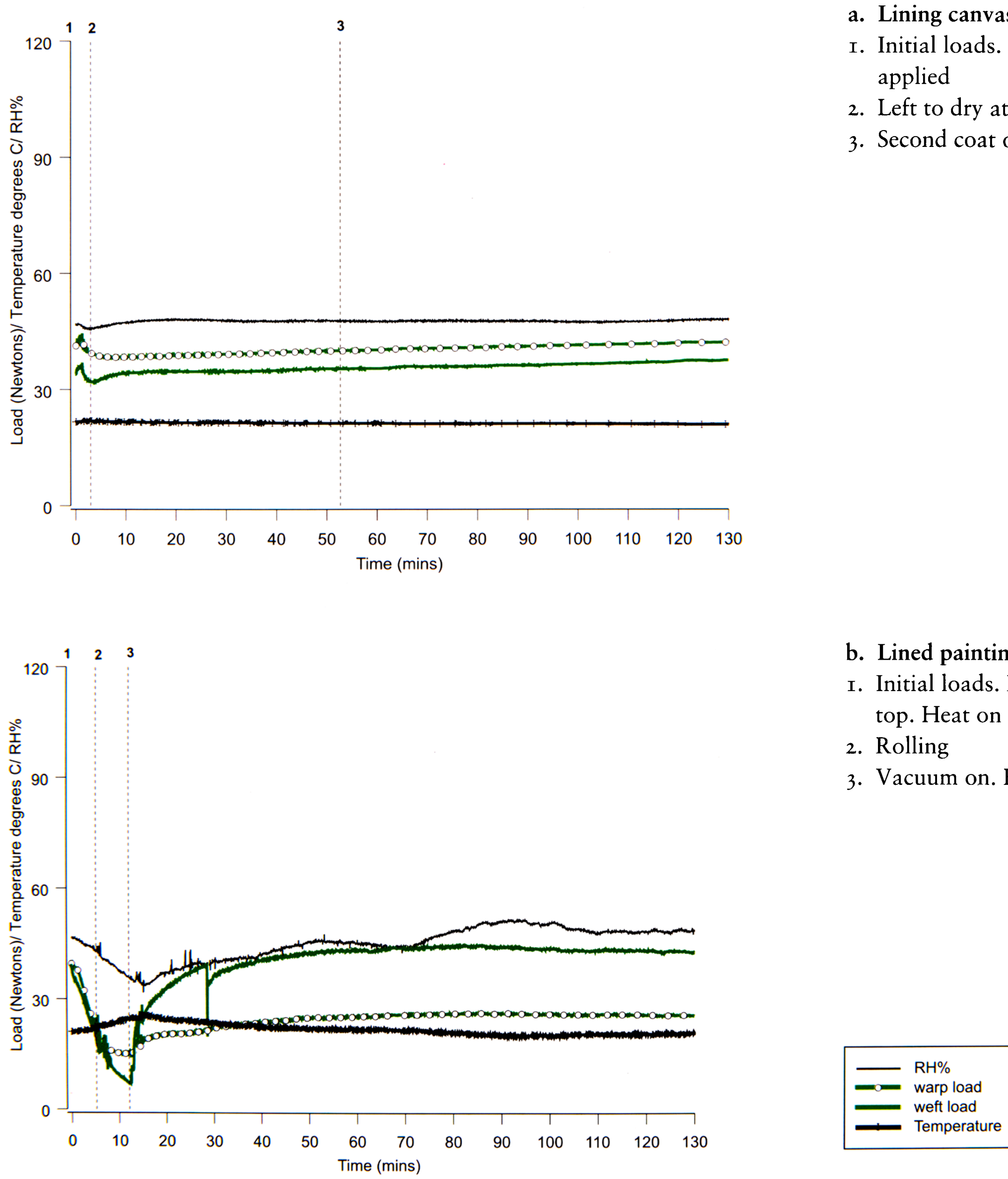
Comparisons of stiffness before and after lining

Measurement of the thickness of the materials, using a micrometer, before and after lining show that the overall thickness after lining was less than the combined thickness of the lining and painting before lining. Hence, during the lining processes the materials had been compressed (see Appendix 3). This is because the pressure induced by the vacuum and the impregnation with adhesive altered the weave structure and packing of the yarns in the canvas. Calculations in terms of stress (force per unit area) are meaningless in this instance because the area of painting or lining canvas under tension cannot be accurately defined. Thus, comparisons have been made in terms of the tension experienced by each painting (all the same size) and the strain (extension compared to the original length). The biaxial tension versus strain, and the tension/RH versus time, have been compared for the unlined paintings, the lined paintings and the prepared linings.

FIGS. 8a–d shows the graphs for the unlined painting, the prepared lining and the lined painting. Each graph gives the tension versus % strain, for both weft and warp on the third cycle between 0–100N at 55% RH at 20°C. The steeper the gradient of the tension versus strain curve the stiffer the material. The stiffness in the 50N–100N tension region has been calculated at the third cycle for the paintings before and after lining at both 5% RH and 55% RH. These values are summarised in Appendix 4.

By comparing the gradients of the curves it is evident that in all cases the painting is stiffer than its associated lining. All the paintings produced strains in the region of 0.08% to 0.16% for a biaxial tension of 100N. The linings, on the other hand, produced strains above 0.23% for the same tension. All the lined paintings produced strains somewhere in between those of the lining materials and the unlined paintings with values in the region of 0.12% to 0.27%.

On first consideration it might be assumed that lining these paintings would produce a final composite that is stiffer than the painting on its own, since the tension is shared between both lining and painting. Furthermore, the amount of material under load in the lined painting has increased even though the measurable loading area has not. However, in these tests on the lined paintings, only the lining canvas was held by the grips and, therefore, the tensioning configuration is equivalent to a lined painting without its original tacking margins which could be attached to its stretcher. Consequently, the combined in-plane tensile stiffness is not as high as one would expect because there has not been complete load transfer through the adhesive layer. In other words, the lining and painting do not act as a continuous solid. The adhesive and the adjacent weave form a relatively flexible layer between the two and consequently high shear strains must be occurring at the interfaces with the adhesive (FIG. 9). Although the lining procedure has produced a composite with greater flexural stiffness this does not necessarily mean that the tensile stiffness has increased. If the painting and lining were gripped together, as is the



a. Lining canvas
1. Initial loads. BEVA 371 size layer applied
2. Left to dry at room temperature
3. Second coat of BEVA 371 applied

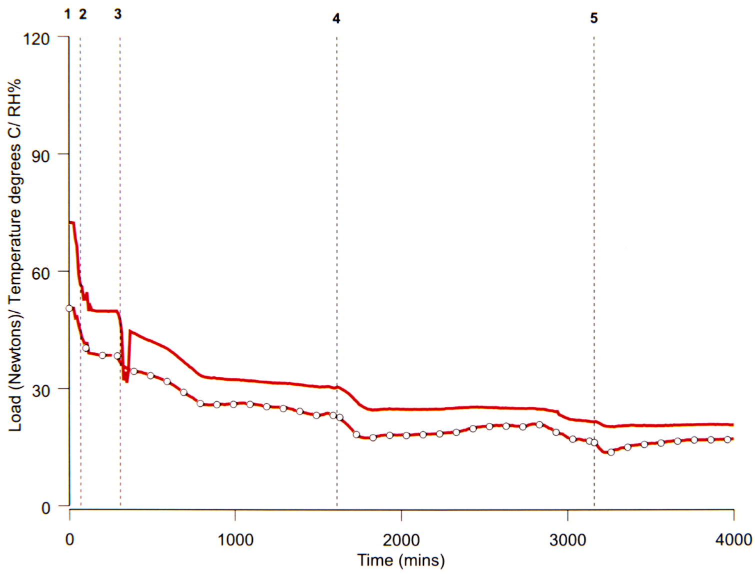
b. Lined painting
1. Initial loads. Place painting on top. Heat on
2. Rolling
3. Vacuum on. Heat off

FIG. 6 BEVA/sailcloth lining process: a. lining canvas, b. lined painting.

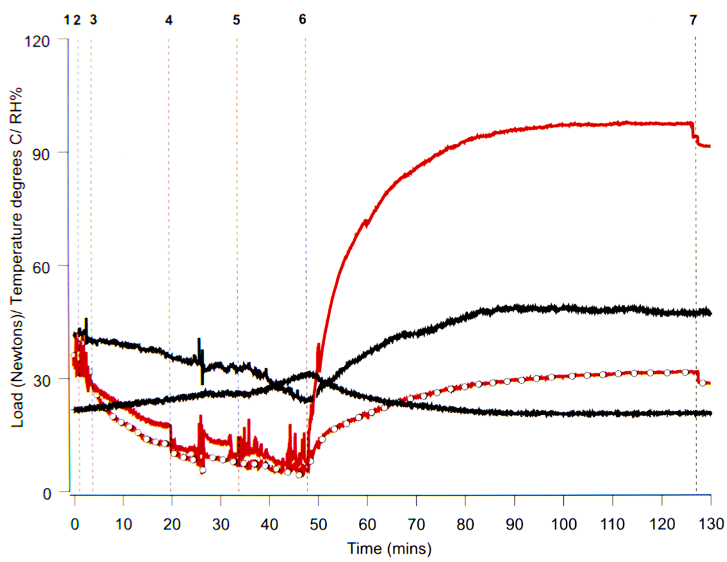
case in a lined picture stretched with its original tacking edges intact, then an increase in tensile stiffness should be evident. Indeed previous research using uniaxial tests support this belief,[17] but further confirmation is needed under biaxial conditions. If the lining adhesive produced a relatively flexible bond between the lining and the painting, then the painting will be free to expand and contract, to some extent, with changing humidity.

Relative humidity response before lining

The load response is similar for the three paintings; all lose tension as the RH increases from 5% RH to 55% RH. The change in RH from 55% to 64% RH, however, produces two different types of response: samples from the *Cardinal Infante Ferdinand* and the *Equestrian Portrait of the Count-Duke of Olivares* continue to lose tension, while the two samples from the *Surrender of Breda* gain in tension (see FIG. 10). This initial drop then rise in tension with increasing RH has been demonstrated in previous uniaxial and biaxial tests on canvases with proteinaceous size layers.[18] The phenomenon occurs because of the expansion and loss in stiffness in the size layer with the uptake of moisture, resulting in a corresponding loss in tension. This is followed by the subsequent swelling of the canvas yarns, causing canvas contraction and an increase in tension. Weave counts for *Cardinal Infante Ferdinand* and the *Portrait of the Count-Duke of Olivares* are 15–16 yarns/cm while those for the *Surrender of Breda* are 22–23yarns/cm. It is the higher weave density of the latter canvas that



a. Lining canvas
1. Initial loads
2. BEVA 371 size layer applied
3. First coat of BEVA 371 applied
4. Second coat of BEVA 371 applied
5. Third coat of BEVA 371 applied



b. Lined painting
1. Initial loads
2. Painting placed on top
3. Vacuum on. Heat off
4. Temperature 37°C.
   Vacuum turned down
5. Temperature 52°C
6. Temperature 75°C. Heat off.
   Vacuum increased. Rolling
7. Vacuum off

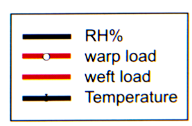


FIG. 7 BEVA/linen lining process: a. lining canvas, b. lined painting.

accounts for an earlier onset of tension increase that is associated with canvas shrinkage.[19]

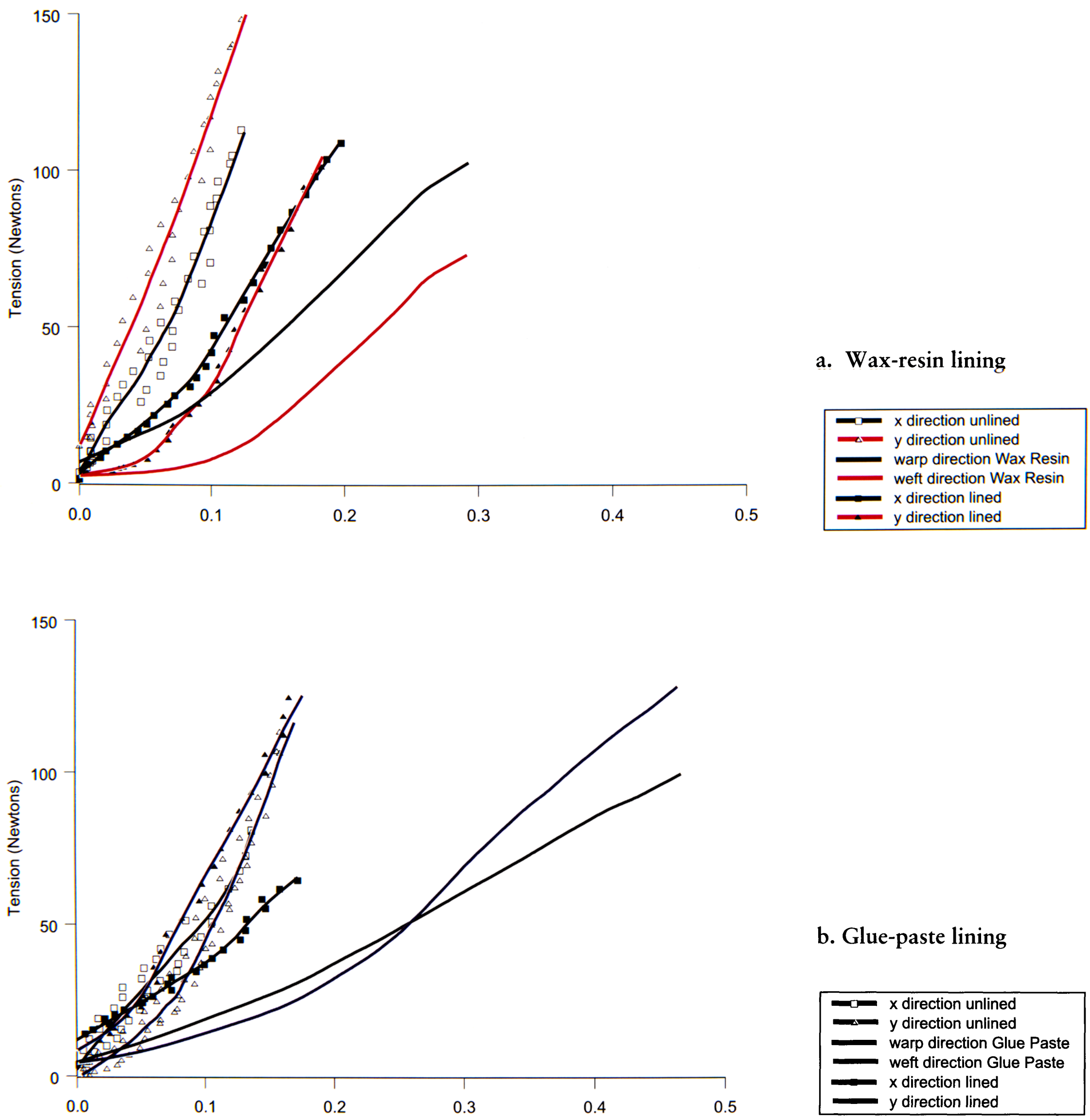
Relative humidity response after lining

As stated previously, in these tests the nature of the interface between lining and painting allows some expansion and contraction of the painting which is independent of the lining. Thus, the measured tension by the tester is an indirect measure of the tension induced in the painting with changing humidity.

During the tests on the lined paintings the external ambient RH was above 50%. This created difficulties in controlling the conditions within the environmental chamber and meant that the initial RH increase from 5% to 55% RH was not performed in discrete steps. Instead, RH in the chamber rose exponentially to 55% RH followed by 10% increments to 85% RH. Therefore, in comparisons with the paintings, where step-like changes in RH were achieved, the data will be discussed in two regions: 5%–55% RH and 55%–85% RH. FIG. 11 shows the tension response and RH versus time for all the lined paintings. For comparison FIG. 12 shows the tension response and RH versus time for all the prepared linings on their own.

The 5%–55% RH region

On tensioning to 100N all the prepared lining canvases crept immediately. The lined paintings also crept but at a much slower rate. In practice, a lined painting will creep after re-stretching on its stretcher and may require further tensioning after a day or



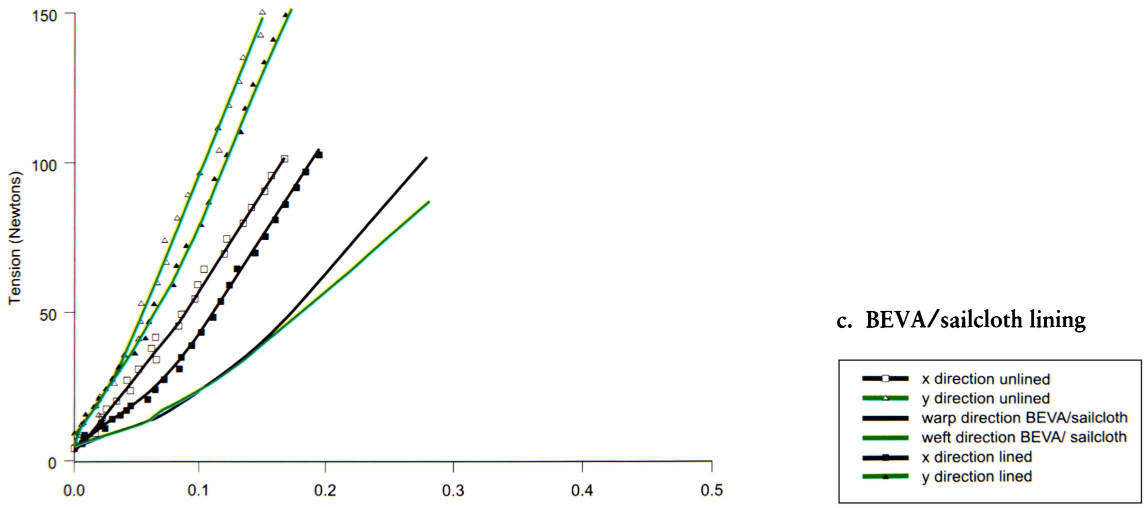
FIGS. 8a and b Relative stiffness of the unlined paintings, prepared lining materials and the final lined paintings.

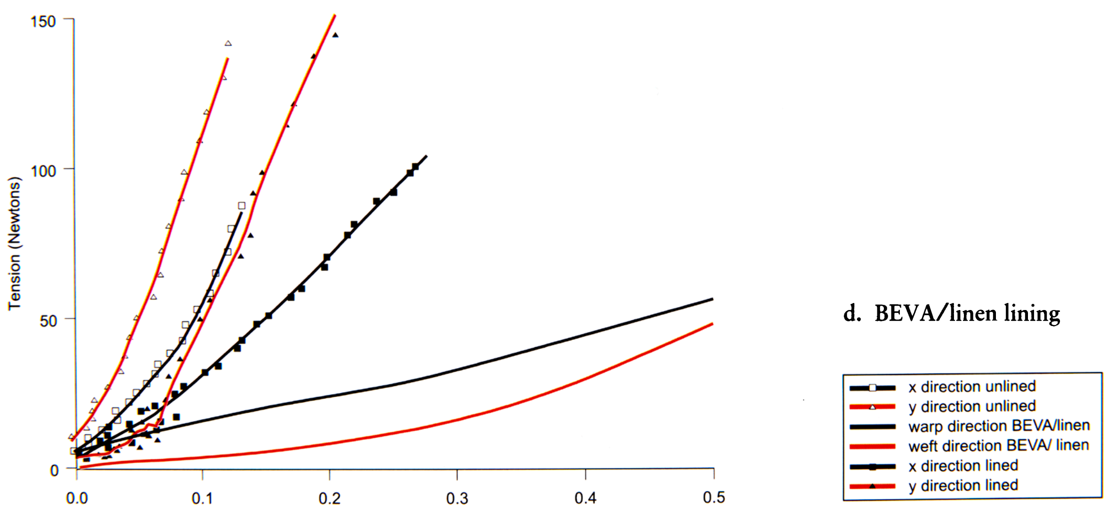
two. Due to time constraints it was decided that creep could not be avoided in the load versus RH tests.

For the wax/linen and BEVA/linen (FIG. 11) it is impossible to distinguish between the initial tension loss due to creep in the linen from that caused by increasing RH. There is a very similar loss in tension for the BEVA/sailcloth resulting from creep, but this is also due to moisture uptake in the sailcloth. The response of sailcloth to moisture, although relatively small compared to linen, has been measured previously[20] and warrants further investigation. For the glue- paste/linen there is a more rapid loss in tension than that associated with the creep of the linen alone. Additionally, the glue-paste/linen has a similar response to that of glue-sized linen, suggesting that its behaviour is associated with the glue-paste absorbing moisture, which allows the canvas to relieve stress to a point where it becomes slack. The glue-paste lining, as expected, is the most sensitive to increases in moisture content within this humidity range.

The 55%–85% RH region

In the 55%–85% RH region discreet step increases in RH% were achieved. The tension curves corresponding to those increases show similar step responses. The initial rise in tension and stabilised value are different in each case.





FIGS. 8c and d Relative stiffness of the unlined paintings, prepared lining materials and the final lined paintings.

Wax-resin/linen

In this RH region the painting lined with wax-resin and linen shows practically no response to increasing humidity (FIG. 11). This is expected since the lining canvas and painting were completely impregnated with the adhesive. A thorough impregnation was only achieved during the final lining process and prevented the canvas from absorbing moisture.

Interestingly, the wax/linen lining canvas on its own does respond (FIG. 12). Tension increases as the RH is raised from 65% to 85% RH, but at a reduced response rate when compared to BEVA/linen.[21] This demonstrates that wax impregnation, even though incomplete, has a greater effect on retarding the humidity response of linen than a non-impregnating lining with BEVA.

BEVA/linen

The BEVA/linen lined painting (FIG. 11) shows the greatest response to moisture over this RH region, increasing in tension from 58N and 48N at 55% RH to 92N and 108N at 75% RH in the warp and weft respectively. As BEVA does not fully saturate the linen lining canvas, moisture is able to penetrate the yarns from the reverse. Thus, at high humidity (above 65% RH) canvas shrinkage will occur for a high yarn count, machine-woven canvas. As discussed above, the painting itself showed a tendency to shrink between 55% and 75% (see FIG. 10). The BEVA/linen lining on its own also started to increase in tension rising from 55N and 71N at 55% RH, to 77N and 83N at 75% RH, in the warp and weft respectively (FIG. 12). Therefore, as the RH increased,

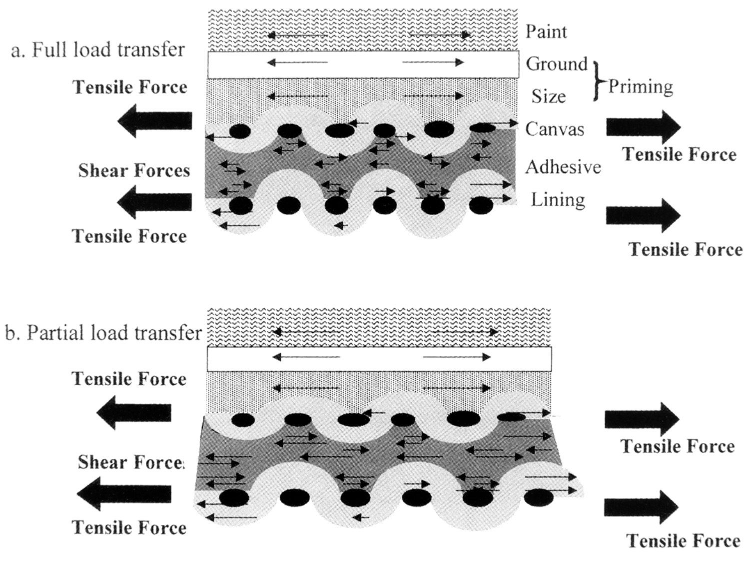


FIG. 9 Tensile load transfer.

the whole composite, painting and lining canvas, attempted to shrink (FIG. 11). There was a slightly slower response to RH change for the prepared lining canvas and the final lined painting than for the painting on its own. This indicates that the BEVA does provide a certain amount of protection against moisture even though the painting has not been saturated with adhesive. But, at 85% RH this is not sufficient to prevent severe canvas shrinkage. It can be concluded, therefore, that the BEVA/linen combination produces the least dimensionally stable lining at humidities where canvas shrinkage is likely to occur.

Glue-paste/ linen

The glue-paste/linen lined painting only started to increase in tension at 85% RH. This surprising lack of tension response at high humidity can be explained by the fact that the degree of tension increase will depend on the initial tension in the lined painting immediately before canvas shrinkage takes place. The glue-paste lined painting was at a considerably lower tension than the BEVA/linen lined painting before the onset of canvas contraction because the former lining had lost a great deal of tension as the moisture softened the glue. The BEVA/linen lining, on the other hand, maintained some tension because the adhesive is less sensitive to moisture. A painting similar in size to the samples used here would typically require a tension of around 20–60N at 55% RH to maintain it in a reasonably taut state for display. (The tension response of the BEVA/sailcloth lined painting at high humidity is therefore representative of normal loading conditions.) Ordinarily, the glue-paste lined painting would have been stretched onto a stretcher to produce a tensioned flat painting under loads of around 20–60N at 55% RH. It therefore follows that with the onset of shrinkage in the lining canvas at around 65% RH there would be a greater increase in tension in the glue-paste lining than that presented in FIG. 12. Similarly, higher increases in tension would be expected than those seen in FIG. 11 as the RH falls from 65% RH. To confirm this idea, the glue-paste lined painting was re-tensioned to 50N at 55% RH and the RH% was increased in 10% RH steps to 85% RH. Surprisingly, the tension decreased as the relative humidity increased without showing any increase in tension even at 85% RH. Without further investigations, it is only possible to conclude that the expected tension increase did not occur because the lined painting had already been put through a high relative humidity cycle, which might have changed the strain distribution within the painting composite.

BEVA/sailcloth

The BEVA/sailcloth lining on its own showed a decrease in tension with increasing RH (FIG. 12). The painting itself had shown an increase in tension (FIG. 10). Therefore, the painting canvas and the sailcloth are moving in opposition to one another as humidity is raised. It can be seen from FIG. 11 for the 65% RH–85% RH region that the influence of the canvas shrinkage of the original painting has overridden the opposing expansion of the sailcloth and, to some extent, the restraint of the lining and adhesive.

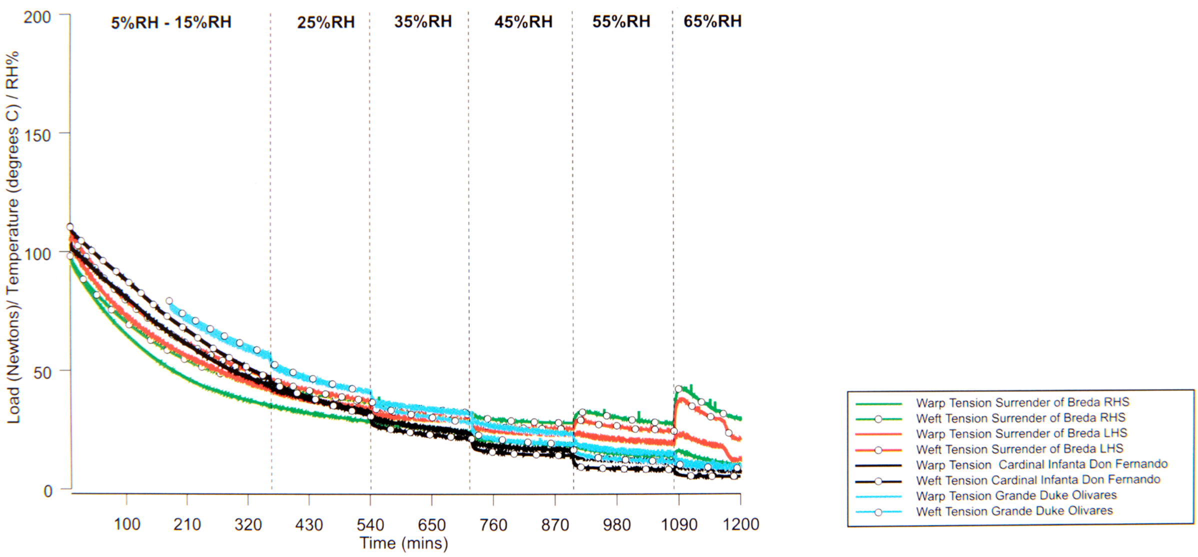


FIG. 10 RH response of the unlined paintings.

Conclusions

The speed at which the unlined paintings, lining materials and some of the lined paintings responded to moisture is extremely rapid. Even the fastest change in humidity produces an immediate tension response, although reaching equilibrium took at least three hours. The onset of canvas shrinkage at 65% RH in the *Surrender of Breda* canvas is earlier than the predictions made by previous research.[22] There were no visible signs of flaking or blistering of the paint and ground in any of the paintings even though they were exposed to 85% RH. However, some paintings may flake during exposure to these conditions, depending on their condition and history. These observations have some significance for the conditions recommended for loan and display. It would be unwise to extend the recommended upper humidity parameter to 65% RH as canvas contraction may occur in certain paintings, even though there was no actual sign of physical damage in these tests. It has been suggested that 'the key to setting safe limits of RH fluctuation is to avoid stresses that exceed the yield point for a specific environment and that would produce plastic or irreversible deformation'.[23] However, damage can occur through fatigue failure of the materials, as the tension is repeatedly altered, according to the fluctuating environmental condition. Given the fast response times of canvas paintings to humidity changes, even low amplitude, low-frequency deformations (below the materials' yield point) caused by humidity could result in fatigue in the long term.

Comparative measurements of the behaviour of different lining types during each process have not been attempted before and the results were particularly interesting. Increased tension in the glue lining as the linen lining canvas contracted was to be predicted but the large decrease in tension during the wax-resin and BEVA linings due to the melting or softening of the adhesives was unexpected. The final loads in the paintings after lining tended to be higher in the weft than in the warp direction. In practice the loading conditions can be adjusted and made more even during the subsequent stretching of the painting onto its stretcher. But equal tension in both warp and weft would be desirable immediately after the lining. Tension changes in the lining fabric during the process will undoubtedly result in alterations to the shape and structure of its weave. In turn, these movements in the yarns may have some influence on the overlying painting, for example they may contribute to textural alterations in the picture surface. It is possible that tension change may be avoided in the actual lining if the lining materials were not held under tension, as is sometimes practised in some wax-resin and BEVA lining procedures.

The protection against humidity change offered by the various linings varied considerably. The wax-resin lining proved to be unaffected by humidity change and this therefore supports the long-held view that such treatments render paintings almost inert. This state is only achievable when the entire composite is thoroughly impregnated so that a discrete layer of adhesive is visible at the back of the lining. Beeswax, however, is sensitive to relatively small

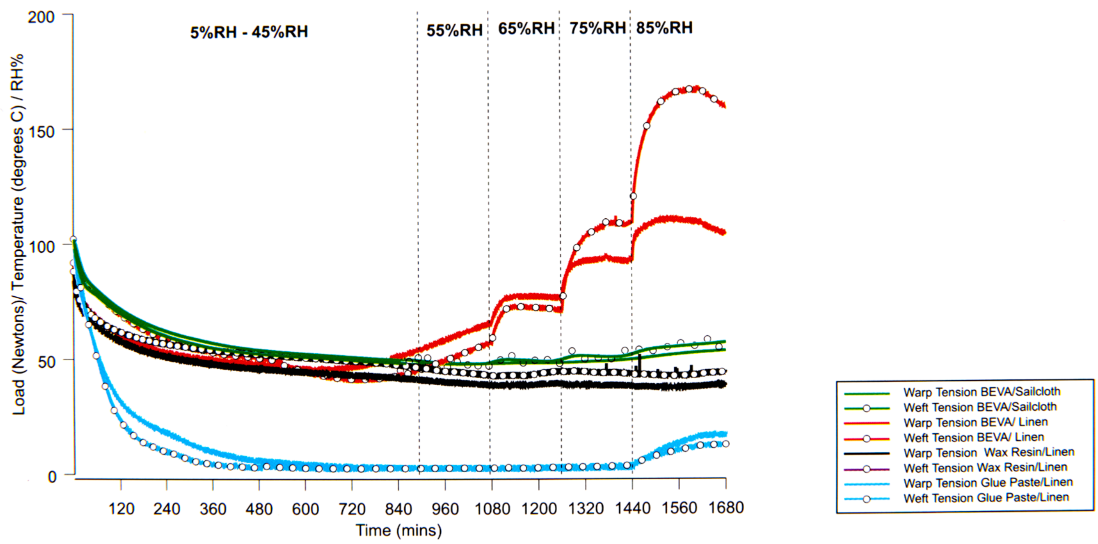


FIG. 11 Response of the lined paintings between 5 and 85% RH.

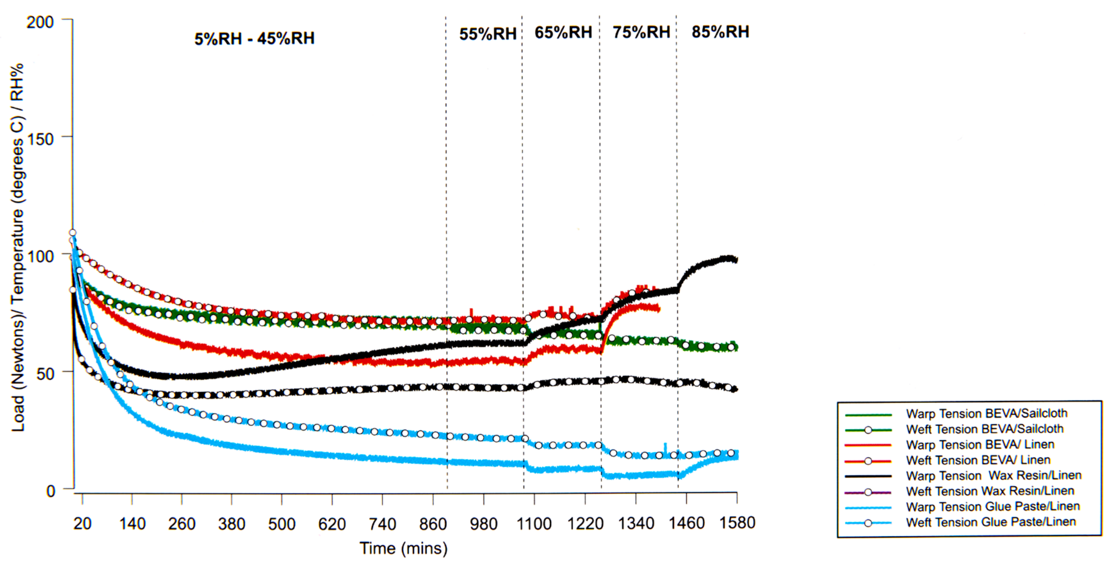


FIG. 12 Response of the prepared linings between 5 and 85% RH.

changes in temperature, and since it is usually the largest constituent of wax-resin formulations, the adhesive is unlikely to be completely inert to climatic change. The effect of temperature on the materials was outside the scope of the present study but needs further investigation.

In contrast, the BEVA/linen lining was particularly sensitive to moisture. This appeared to have only a moderate effect in protecting the lined painting from humidity change. The initial thin sizing of the linen with dilute BEVA might be effective as a moisture barrier if the canvas could be totally impregnated with the adhesive.

The BEVA/sailcloth lining appeared to offer better protection to the painting than the BEVA linen lining, but less than the wax-resin. This finding does not amount to a vindication of wax-resin lining, which results in an irreversible and, to many, an unacceptable impregnation of the painting.

Predictably, the glue-paste lining was the most responsive to moisture at low RH; below 40%, the glue lining is stiff and may enable the transfer of stress from the painting to the lining support. Consequently, if the painting had been initially placed under high tension at around 55% RH and then conditioned to a low RH, the lining adhesive will form a brittle layer, which could lead to its eventual failure. Response times in the glue-lined painting are rapid and tension loss sudden. Therefore, in most gallery-controlled environments glue-paste linings may offer little long-term protection to paintings. It is often the case that glue-paste recipes contain larger quantities of animal glue than the particular adhesive tested here and, therefore, it is likely that many glue-lined paintings on display in museums and galleries could respond more vigorously than the results shown here. Performance of this type of lining could be improved by applying a beeswax moisture barrier to the reverse of the lining.

The protection provided by a lining through its ability to transfer tensile stress away from the picture to the lining support is more complicated than first expected. This highlights the need for further work in this area. Many liners have assessed the stiffness of their linings by tapping the surface of the stretched picture. It is not necessarily the case that this measure of flexural stiffness corresponds to the lining's tensile stiffness. In paintings where the tacking edges have been removed there is likely to be only a partial transfer of stress from the picture to the lining. The situation may be different for paintings where the tacking margins are intact. This issue is particularly relevant to paintings glue lined in the nineteenth and early twentieth centuries when it was common practice to remove the tacking margins.

There are many avenues for further research based upon the work reported here. In particular, understanding how the shear strains build up in the adhesive interface and how they influence the mechanical properties of the final lined painting.[24] Tests performed at the Courtauld Institute of Art and Tate Modern have demonstrated the fast response of paintings to changes in relative humidity even when within specified gallery conditions. This emphasises that the need to determine the exact role linings play in reducing and protecting paintings from mechanical deterioration induced by environmental parameters is still pertinent.

Acknowledgements

Stephen Hackney, Roger Hibberd, Alan Phenix, Marika Spring, The University of London Central Research Fund, The Leverhulme Trust, NERC, The Commission for the Great Exhibition of 1851, Conservation Department Tate Gallery, Mechanical Engineering Department Imperial College.

Notes and references

1 Henry Merritt, *Dirt and pictures separated: in the works of the old masters*, London 1854, p. 14. A number of other statements supporting the importance of lining as a preventive measure include: 'This [lining] is one of the most important proceedings to secure a picture from farther injury. It is performed with great ability by many persons in London, and at very moderate charges,' Henry Mogford, *Handbook of the preservation of pictures, containing practical instruction for cleaning, lining, repairing and restoring oil paintings*, eighth edition, Winsor and Newton, London 1876, p. 39. Also ' The relining of paintings is often an excellent precaution for their preservation', John Thomas Gullick and John Timbs, *Painting popularly explained: including fresco, tempera, encaustic, miniature, oil, watercolour, missal, painting on pottery, porcelain enamel &c.: with historical sketches of the progress of the art*, Kent and Co, London 1859, p. 315.

2 J.M. Fielding, *On painting in oil and watercolour*, London 1839, Chapter 10, p. 139.

3 *Manual on the Conservation of Paintings*, International Institute of Intellectual Co-operation, Paris 1940, 1940 translation, p. 212.

4 Helmut Ruhemann, *The cleaning of paintings: problems and potentialities*, London 1968, p. 153.

5 Gustav A. Berger, 'Formulating adhesives for the conservation of paintings', *Preprints to the IIC Congress*, Lisbon 1972, pp. 613–30.

6 Gustav A. Berger, 'Some conservation treatments in the light of the latest stress measurements', *Preprints to the ICOM Committee for Conservation, Eighth Triennial Meeting*, Sydney 1987, vol. 1, p. 134.

7 *Recent lining methods and related processes*, Handbook to a slide collection for teaching, Getty Conservation Institute and the Royal Danish Academy of Fine Arts, Copenhagen 1992. New methods for lining are generally referred to as 'stabilisation' processes.

8 S. Michalski and D. Hartin, 'C. C. I. Lining Project: Preliminary Testing of Lined Model Paintings', *Preprints to the ICOM Committee for Conservation, Eleventh Triennial Meeting*, Edinburgh 1996, vol. 1, pp. 288–96.

9 Gustav A. Berger and William Russell, *Conservation of paintings: research and innovations*, Archetype Publications Ltd, London 2000.

10 Analyses of the paint and ground materials were carried out by Marika Spring in the Scientific Department of the National Gallery.

11 The linen lining canvas used in the tests was a fine, medium-weight fabric manufactured by the Ulster Weavers, 44 Montgomery Rd, Castlereagh, Belfast. The fabric has, on average, 19–20 threads per cm in the warp direction and 15–16 threads per cm in the weft.

12 Christina Young, *Measurement of the biaxial tensile properties of paintings on canvas*, PhD Thesis, Imperial College, University Of London, 1996, Chapter 10, pp. 174–92.

13 Paul Ackroyd, 'Glue-paste lining of paintings: an evaluation of the bond performance and relative stiffness of some glue-paste linings', *Preprints to the UKIC Lining*

and Backing Conference, 1995, pp. 83–91. Nineteenth-century glue-paste adhesives tended to be formulated with larger proportions of animal glue. For example, Mogford recommends a recipe consisting of 'equal parts flour and glue', see Mogford, cited in note 1, p. 10.

14 A portable low-pressure suction device manufactured by Willard Developments Ltd was adapted and used to perform the linings.

15 Bent Hacke, *En utraditionel metode til vacuum rentoileringaf tempera maleri på lærred (An untraditional method of lining tempera paintings on canvas under vacuum pressure)*, Meddelelser om Konservering, edited by Nordisk Konservatorforbund, 1964, pp. 2–10. Other publications on glue-paste lining treatments using low-pressure tables include: *Recent lining methods and related processes*, cited in note 7, and Anthony Reeve, Paul Ackroyd and Ann Stephenson-Wright, 'The multi-purpose low-pressure conservation table', *National Gallery Technical Bulletin*, 12, 1988, p. 10.

16 A full description of the testing equipment is given in Christina Young and Roger Hibberd, 'Biaxial tensile testing of paintings on canvas', *Studies in Conservation*, 44, Number 2, 1999, pp. 129–41.

17 Ackroyd, cited in note 13, p. 88. In uniaxial conditions the stiffness of painting samples lined with glue-paste increased when compared to the stiffness of the lining materials tested on their own. This indicates that when both the painting and lining are both gripped and tensioned there is a transfer of load from the painting to the lining support.

18 This initial fall then rise in tension with increasing RH for canvas with a proteinaceous size layer has been demonstrated by G. Hedley, 'Relative humidity and the stress strain response of canvas paintings: uniaxial measurements of naturally aged samples', *Studies in Conservation*, 33, 1988, pp.133–48; and by Christina Young, 'The characterization and physical properties of 19th century primed loose linings', forthcoming publication.

19 Young, cited in note 18. The results reported here are consistent with other tests performed on nineteenth-century primed loose linings. The point at which the rise in tension occurs after an initial loss varies from 65% to 85% RH, depending on the nature of the canvas. If the RH% is increased to 95% there is a corresponding increase in tension but the maximum change occurs between 75% to 85% RH. From the results in this study it is therefore reasonable to assume that the Velázquez copies, if subjected to an RH greater than 65%, would all produce a tension response similar to some nineteenth-century primed loose linings. The speed of the response in the Velázquez copies is also consistent with previous tests.

20 Christina Young, 'Towards a Better Understanding of the Physical Properties of Lining Materials for Paintings: Interim Results', *The Conservator*, 23, 1999, pp. 83–91.

21 Hedley, cited in note 18. In uniaxial conditions the impregnation of a primed nineteenth-century loose lining with plain unbleached beeswax decreased its rate of moisture absorption but did not completely prevent it from responding. These findings, although for pure beeswax rather than wax-resin impregnation, are consistent with the results in this study.

22 Hedley, cited in note 18.

23 D. Erhardt and M. Mecklenburg, 'Relative humidity re-examined', *Preprints to the IIC Congress,* Ottawa 1994, pp. 32–8.

24 Further tests on lined paintings are planned using optical interferometry, to monitor the strains in the top surface of the painting compared to the strains in the lining resulting from changing the tension. Also, shear tests on lining adhesives with the associated lining material at different RH will give important background information. Additionally, direct measurement of the change in flexural stiffness of the painting using three-point bend tests, compared to the change in tensile stiffness, will help to understand the detailed function of the lining. All information from the above tests can be incorporated into an analytical model to calculate shear strains within the lined painting. Further work is also required to investigate the low RH response in controlled conditions for longer equilibrium times and different initial tensioning conditions. Direct measurement of the moisture transport through the lined painting and the associated thermal gradient requires the development of new sensors that can be incorporated into the composite.

Appendix 1. Brief descriptions of the paintings used for testing.

Painting	Canvas	Mean weave count	Sizing	Ground	Paint	Condition
Surrender of Breda	Plain-weave linen (unidentified)	22–3 yarns per cm in both directions	Proteinaceous layer	Lead white tinted with small amounts of earth colours.	Oil medium identified. Earth colours identified.	Evidence of previous exposure to water at the reverse, and cleavage of some areas of paint and ground at the front.
Cardinal Infante Ferdinand in Hunting Dress	"	15–16 yarns per cm in both directions		Lead white and barium sulphate. Medium unidentified.	Oil medium (unidentified). Lead white and Prussian blue identified.	Evidence of previous exposure to water at the reverse, and cleavage of some areas of paint and ground at the front.
Equestrian Portrait of the Count-Duke of Olivares		15–16 threads per cm in both directions		Lead white tinted with small amounts of earth colours. Medium unidentified.	Oil medium (unidentified). Vermilion identified.	No evidence of previous water damage.

Appendix 2. Summary of the lining preparations and procedures.
(Those procedures which are in italics were NOT performed on the rig.)

Glue-Paste (1 step)
Lining and Painting:
Tension lining canvas in tester. *Apply glue-paste to painting*. Position painting on top of lining. Smooth with roller. Apply 25 mbar pressure (and maintain until the composite is dry). Heat to 40°C for 20 mins. Leave to dry on tester. Remove from tester.

Wax-Resin (3 step)
1. Lining
Tension lining canvas in rig. Brush liquid wax onto lining canvas. Smooth with roller. Apply 25 mbar pressure (and maintain throughout). Heat to 70°C for 20 mins. Leave to cool on rig (2 hrs). Remove from tester.
2. Painting
Brush liquid wax on painting. Position painting in tester. Heat to 65°C for 10 mins. Smooth with roller. Apply 25 mbar pressure (and maintain throughout). Heat to 65°C for 20 mins. Leave to cool on tester (2 hrs). Remove from tester.
3. Lining and Painting
Tension lining in tester. Position painting on top of lining. Apply 25 mbar pressure (and maintain throughout). Heat to 65°C for 20 mins. Leave to cool on tester (2 hrs). Ready to test on tester.

BEVA 371 (2 step)
1. Lining
Tension linen lining canvas on tester. Size linen with brush coat of hot diluted BEVA gel (4:1 white spirit:BEVA). Leave to dry (4/6 hrs). Brush a further 3 coats of hot BEVA (1:2 white spirit:BEVA) onto the linen allowing 4/6 hrs drying time between each application. Leave on tester.
2. Lining and Painting
Position painting on top of lining. Apply 25 mbar pressure (and maintain throughout). Heat to 68°C for 20 mins.
Leave to cool on rig (2 hrs). Ready to test on tester.

Appendix 3. Thickness measurements of the paintings and lining materials before and after lining.

Painting	Lining	Before Lining	After Lining
Surrender of Breda LHS	BEVA/linen 0.60 mm	0.96 mm	1.00 mm
Surrender of Breda RHS	BEVA/sailcloth 0.44 mm	0.98 mm	0.73 mm
Cardinal Infante Ferdinand in Hunting Dress	Wax-resin/linen 0.93 mm	0.55 mm	0.97 mm
Equestrian Portrait of the Count-Duke of Olivares	Glue-paste/linen 0.51 mm	0.98 mm	0.90 mm

Error +/-.3 mm

Appendix 4. Calculated stiffness for each painting before and after lining.

Painting	Lining 5%RH–55%RH	Before Lining 5%RH–55%RH	After Lining 5%RH–55%RH
Surrender of Breda LHS	BEVA/linen	10.4/7.6	22.8/10.4
Surrender of Breda RHS	BEVA/sailcloth	14.8/10.0	14.4/10.0
Cardinal Infante Ferdinand in Hunting Dress	Wax-resin/linen	9.2/8.8	14.0/11.2
Equestrian Portrait of the Count-Duke of Olivares	Glue-paste/linen	12.8/9.4	25.4/12.0

Error +/-.3 mm