EFFECTS OF REINFORCEMENTS ON THE PRESERVATION OF PAINTINGS ON WOOD PANEL

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In Figure captions, a Hamilton Kerr Institute treatment number (HKI.#) indicates photograph is by permission of the HKI. Unattributed photographs and all drawings are by the author.

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DECLARATION

ABSTRACT

To evaluate reinforcement design, this thesis combines observations on panel paintings, interviews with panel specialists, conservation records, and deformation analyses of constructed mock-ups of thinned panels bearing a selection of reinforcements. Reinforcements were reviewed, classified, and damaging effects discussed, with particular emphasis on the role of attitudes toward flattening of panel paintings. Mock-up surface deformations were then recorded during controlled changes in relative humidity (RH) using digital photogrammetry, moiré fringe analysis, and raking-light photography.

Results for unreinforced panels emphasised that wood movement causes deformations, not just in the transverse-grain direction, but in three dimensions, which must interact with reinforcement. A consistent pattern of overall panel warp was shown which decreases in rate and amplitude with increasing panel thickness, including considerable warp parallel to the grain, heretofore ignored.

Important results for reinforced mock-ups showed that during changes in RH, in-plane restraint by reinforcements such as laminates or battens fixed to the panel back causes bending in the opposite sense to that in which warp would occur in an unreinforced panel. For relatively rigid and sliding reinforcements, in-plane movement in the transverse-grain direction at the panel surface appears to be increased by restraining warp in a flat plane. Use of more flexible reinforcements should reduce associated stresses.

For cradled panels, a pattern of strain exists on the coated side which corresponds with cradle structure. Combining this information with recorded out-of-plane deformations and examples of panel paintings with cradled-related damages, "washboarding" and related deterioration were explained in more detail than before.

Reported twists or concave deformations soon after lamination with balsa and wax-resin adhesive/mortar are attributed to contraction during cooling and solidification of molten wax-resin.

Design improvements are suggested such as encouraging use of more flexible reinforcements. Marking their first application to art conservation and in particular to analysis of panel painting deformations, digital photogrammetry and moiré fringe analysis were shown to be very suitable techniques.

CHAPTER 1 INTRODUCTION

1.1 Overview

"The Greek term for worth is *aretē*...[which] demands not only moral convictions, good intentions, and a moral conscience but also the ability of adequate practical action...*[A]retē* presupposes *technē* [so that] the Greeks can speak not only of *aretē* of a human person but also the *aretē* of a tool. A weapon, a plow, and a house have *aretē* if they are fitted to the purpose for which they have been created. They must have a proper structure, their effect must not be impeded by unnecessary trifles, and they must show the highest degree of adequateness to their total purpose." [1]

Though many paintings in museums and private collections are on canvas, many others are on wooden panels. In Europe, panel supports were most important before the Renaissance after which textile supports became increasingly popular [2, pp. 229, 270]. However, panel supports continued to be used by some artists for particular reasons, such as for a desired surface texture, as in some Dutch still lifes of the 18th c. and in some of Stubbs' paintings. Panels were usually constructed by specialised craftsmen and were often reinforced at the back with various batten structures, depending on period and place of origin [3]. Some of these original structures are still intact.

The structures of many panel paintings have been altered since their execution, usually to repair splits or other damages or to return them to a flatter plane. Thinning of the panel followed by application of relatively rigid reinforcements, such as the cradle (described below), have often been used to help achieve flatness. The quality of such non-original reinforcements has varied widely, as shown by existing examples. Schießl [4] reviewed panel conservation in the Germanic countries, commenting that 19th century practices of flattening and cradling, according to publications dealing with restoration matters, were recommended to be done by specialised craftsmen. In the author's experience, some reinforcements have obviously been applied by skilled craftsmen while others have not. Despite skilled craftsmanship, which does not necessarily address the problems of panel restraint, damages have developed in many cases.

Today, many important collections turn to painting conservators to do such work. Research specifically directed at understanding panel painting behaviour and causes and effects of deterioration has also been mainly done by conservators, most quite recently, since the second World War. During this period, Richard Buck's research contributions are particularly notable. Some conservators are specialised in panel painting behaviour and devote their efforts toward using appropriate materials and techniques for repair and preservation. Their various approaches to panel reinforcement show that there are many schools of thought on what structures are appropriate.

Conservation ethical considerations have been directed more and more toward safeguarding the original material of painted panels as much as possible, including the wood support and original reinforcements, and minimising any further loss or alteration. This is partly because of the realisation by many museum professionals that alterations to the painting support can alter the appearance and preservation of the painted image. In 1948, focusing on the role of the support and the errors of past treatments, George Stout remarked,

"Apparently it did not occur to anyone in the practice of picture repair that the only value of a support in a complex construction was to carry a piece of design in paint and that anything done to the material underneath the ground and the paint would have some effect on the state and the character of the design." [5, p. 61]

For these reasons, effects of existing or proposed reinforcements should be understood and better reinforcements developed and promoted. The sixth directive of the 1995 Code of Ethics of the American Institute for Conservation of Historic and Artistic Works (AIC) states:

"The conservation professional must strive to select methods and materials that, to the best of current knowledge, do not adversely affect cultural property or its future examination, scientific investigation, treatment, or function." [6]

The International Council of Museums (ICOM) sanctions such professional codes of ethics for conservation [7]. Indeed, panel treatment policy in this century has been influenced more and more by the understanding of panel behaviour and the practice of panel reinforcement. This is partly due to the development of conservation as a discipline and to greater co-operation between conservators and custodians of artworks- owners, curators, administrators, etc.- especially in those major museums where policy is decided in concert. The importance of panel conservation and reinforcement in the scheme of things was underlined in 1955 [8] when the ICOM Commission for the care of paintings made it their third study area after cleaning and separation (called cleavage) of paint layers.

It is evident that faulty panel reinforcement has precipitated restoration of the entire painting in many cases. Cleaning before structural work is a practice adopted by most conservators. This author's experience has shown that it is important to do so, at least around splits and flaking, to allow for correct alignment and consolidation. However, minimising the repetition of restorations is now generally agreed as one of the most important ways of preserving paintings [9]. Therefore, reinforcements should be improved to decrease the chance of damages to both the panel and in turn the painting.

To preserve the original object in its entirety, thinning, flattening and other policies bearing on reinforcement have been progressively discouraged in some quarters and reinforcements have been continually changed and re-designed. There is ample evidence from publications and damaged panels that satisfactory designs have not yet been achieved or are not widely accepted. To summarise this situation, Plesters' annotated bibliography in Ruhemann's book [10], from 1968, comments somewhat dryly on a publication from the 1950's:

"A further attempt to evolve a safe and effective method of cradling".

She refers to modified designs based on the cradle, one of the most common non-original reinforcements applied to paintings.

Despite these efforts and the high cultural and material value of the objects, realisation of the importance of preserving painting supports has come slowly. This and lack of research have hampered development of panel reinforcements and understanding of their requirements. This should not be surprising. Conservation is a highly specialised field in which few people are specifically concerned with and trained for treating panel supports. An understanding of painting history and technique, conservation science and methods, structural/material mechanics, and wood science/craft are necessary to do related research. Unfortunately, few panel painting conservators have the training, financial support, and/or desire to seriously research methods.

1.2 Thesis Origin and Objective

A desire to improve panel reinforcement treatments prompted this thesis and related researches. While specialising in panel structural work at the Hamilton Kerr Institute (HKI), University of Cambridge, the author was confronted by panels which required repair and more appropriate reinforcement [11, 12]. Many panels had been thinned and restrained flat during past treatments. The majority of structural problems, such as unusual distortions, splits, and flaking paint, were caused mainly by faulty restraint of moisture-related panel movement by reinforcement structures. Thinner panels, especially larger ones, proved particularly difficult to reinforce safely. For example, Figure 1a shows deformations and splits in a relatively large panel due mainly to excessive restraint of panel movement by a number of different batten reinforcements (Figure 1b) applied over more than a century of repeated

a)

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Papers
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for Copyright
reasons

photo B.

Figure 1. A large Italian panel, dated 1537, damag with battens
fixed to the back: a) front, showing deformations a owing
several batten styles applied over the years. (Marco Palmezzano, "The Mystic Marriage of St.
Catherine", 2560X1805X20mm thick, private collection.) Photo b) Christopher Hurst.

restoration.

A preliminary literature search revealed that the effects of many common reinforcements such as cradles seemed poorly understood, unsuitable, or controversial in some respects (for example, [13]). The consensus of opinion was unanimous on certain desirable characteristics of some reinforcements, such as sliding battens allowing free in-plane movement across the grain. However, inconsistencies of thought and practice were evident because the same desirable characteristics were lacking in other reinforcements. For example, though balsa laminates do not allow free in-plane movement, they are accepted by many conservators who, on the other hand, would recognise a seized sliding batten as dangerous. Though accepted by many, just how the laminate is mechanically better than the seized batten has never been justified, to the author's knowledge, either in publications or verbally.

Also, many conservators are hesitant to remove damaging reinforcements because they are uncertain 1) how panels will react during and after removal, and in many cases, 2) what reinforcement, if any, is the best available replacement. This indecision and lack of knowledge about reinforcements has justified not treating many damaged panels which should have been treated and have instead continued to deteriorate.

To help clarify decisions, identify advantages and disadvantages of reinforcement types, and to recommend design improvements, research was done on panel paintings both with and without reinforcements. It was aimed mainly at thinner, weaker panels. These could be described numerically as those with a high ratio of cross-grain dimension to thickness (equivalent to what Buck called the "volume-to-surface ratio" [13]) The research involved searching conservation and wood science literature, visiting institutions and collections and searching conservation records to see a range of panels and to consult people involved with panel structural work.

These researches were an attempt to understand better how particular cases and attitudes toward reinforcement have changed over time. A database relating panels and their condition was assembled from the gathered information. Using this and the preliminary researches, a controlled-environment (CE) study on a representative range of panel/reinforcement mock-ups was made to examine their effects further, especially on thin panels. The majority of mock-ups were analysed using digital photogrammetry [14, 15]. Cradle effects were expected to require further study, so a separate pair of cradled and unreinforced panel mock-ups were also compared using moiré fringe analysis [16].

The objective of this thesis will be to show that these methods can be combined:

1. to increase understanding of panel/reinforcement behaviour,

2. to help make more appropriate decisions concerning application of non-original reinforcements, and

3. to identify areas for further research with greater certainty.

To the author's knowledge, this is the first time that such a combined study has been undertaken, incorporating a database to analyse panel deterioration, for example, as well as the first time that deformations of painted panels have been recorded over time with such methods. Following are some of the more important highlights realised from this research.

For unreinforced panels coated on one side, the pattern of warp movement in both the transverse and longitudinal-grain direction after a change in RH was shown to be consistent. In both grain directions, warp amplitude and rate were directly related to the rate of wood movement in-plane and decreased with increasing panel thickness.

In-plane restraint of wood movement by reinforcements fixed to the panel back was shown to cause bending in the opposite sense to which warp would occur in an unreinforced panel. This occurred even with balsa-wood laminates, which have been considered to "give" with panel movement.

For cradled panels, the pattern of strain on the coated side was shown to be remarkably similar to cradle structure. The development of "washboarding" was demonstrated and explained theoretically in greater detail than before. Possible causes of related damages such as splits and flaking paint were related to restraint of both in-plane and warp movement.

For cradles and other relatively rigid and sliding reinforcements, in-plane movement in the transverse-grain direction at the panel surface appears to be increased by restraining warp in a flat plane. Thus, reinforcements which conform to warp movement should reduce associated stresses.

Unexplained deformations of panel paintings soon after lamination with balsa, such as twist or concavity, were attributed to in-plane stress from contraction of wax-resin adhesive/mortar as it cooled from the molten state. More by chance than by design, evidence for this theory came from observations made during preparations for the CE study, which shows how important all observations can be during research.

1.3 Abbreviations and Terms

1.3.1 Museums, Institutions, and Inventory Numbers

(Painting inventory numbers are described in parentheses where appropriate):

AM- Ashmolean Museum, Oxford, England
CI- Courtauld Institute of Art, London, England (CI.No.#)

FW- Fitzwilliam Museum, Cambridge, England (FW.#)

GM- The J. Paul Getty Museum, California, U.S.A. (GM.#)

HKI- Hamilton Kerr Institute, Cambridge, England ("HKI.#" is a number of a treatment record residing at HKI)

LV- Louvre (LV.INV#, LV.MI#, and LV.RF#)

NG- National Gallery, London, England (NG.#)

NT- National Trust (NT.#)

RC- Royal Collection, England (RC.#)

SG- Statsgalerie, Stuttgart, Germany (SG.INV#)

TG- Tate Gallery, London, England (TG.NO# or TG.T#)

WC- Wallace Collection, London, England (WC.#)

1.3.2 General

In the text, first mention of common names of wood types are followed immediately by the latin name and attribution.

Following is a glossary of terms and abbreviations used:

BEVA (Berger ethylene vinyl acetate)- a commercialised thermoplastic adhesive containing synthetic wax and resins and solvent

bending- deformation due to stress from external forces applied to a section, such as to a longitudinal section of a beam or to a section perpendicular to the plane of a panel

c.- abbreviation for "century", as in "...a painting of the 17th c."

CAD- computer-aided design; refers to related software

CE- controlled environment

CCD- charge-coupled device; refers to video cameras here

compression set- in a material with visco-elastic properties, a permanent reduction in volume due to compressive stress and plastic deformation cupping- a common type of warp in which the transverse-grain section of a plank assumes a more or less regular curvature

deformation- any change in shape, whether from internal or external forces

dried or seasoned wood- wood which has been dried from a green moisture content to below its saturated moisture content (called the fibre-saturation point, about 28%) and then equilibrated to environmental relative humidity and temperature

EMC- equilibrium moisture content; the moisture content of wood when its vapour pressure is equal to that of the surrounding atmosphere

IBM- International Business Machines; computer maker

IRPA- Institut Royal du Patrimoine Artistique (located in Brussels)

lateral movement- wood movement of a panel in the general plane of the panel and in the transverse-grain direction

LRMF- Laboratoire de Recherches des Musées de France

MC- moisture content, the amount of moisture in a volume of wood expressed as a percentage of the weight of the wood when oven-dried

malrand, or barbe- the border of the preparation and paint layer of a panel painting where it shows the impression of a frame edge that was present when the preparation was applied

oven-dry weight- the weight (strictly speaking, the mass) of a volume of wood after it is dried to constant weight in an oven at 103+/-2C

PVA- a common type of wood glue usually consisting of polyvinyl acetate and dispersing agent(s) in water

RH- relative humidity; the amount of moisture in a volume of air expressed as a percentage of the amount of moisture the air would contain when saturated at a given temperature

sight size- the innermost dimensions of a frame which describe the area of painting visible from the front

SRMF- Service de Restauration des Musées de France; a body which administrates restoration in public museums in France

tented flaking of paint- paint which has detached from the layer beneath to form a tent-shaped bulge; the condition often indicates contraction of the underlying surface which has put the flaked layer under compressive stress

T- temperature

warp- a change in panel shape due to internal stresses caused by shrinkage or, as is generally the case in this thesis, wood movement; unless otherwise stated here, warp is understood to occur in the transverse-grain direction and is described when viewed from the front as convex, concave, etc.

washboarding- a cradled panel condition in which a transverse-grain section shows regular, serpentine undulations due to out-of-plane deformations which are directly related to the distribution of the fixed members; the painted surface resembles the corrugations in a washboard

wood movement- moisture-dependent expansion and contraction of dried or seasoned wood from internal stresses which arise from changes in moisture content due to changes in ambient RH wood shrinkage- change in dimensions of wood from the moisture content (MC) when green or freshly cut to MC at ambient conditions

CHAPTER 2 OVERVIEW OF PANEL REINFORCEMENT

2.1 Basic Panel/Reinforcement Behaviour and Definitions

It is important to outline current understanding of basic wood and panel painting behaviour under changing environmental conditions. Panels show decreasing deformations from wood movement as RH and temperature (T) become more stabilised. If RH and T are kept stable, panels would remain static and reinforcement would be a simple matter. However, many collections do not have adequate air conditioning and the environment may become unstable if active controls fail or when paintings are transported for exhibition.

Thus, reinforcements must strengthen panel supports which are not static but have inherent movement from internal stresses which arise from moisture-dependent expansion and contraction, called wood movement. Skaar, who lumps wood shrinkage and wood movement under the collective term "hygroexpansion", states that longitudinal-grain values are generally one or two orders of magnitude less than in the transverse direction [17, p.140]. Longitudinal shrinkage from green MC to dry wood MC, usually determined at 12%, is generally quoted as less than 0.1% [18, p.42]. Dinwoodie states that longitudinal-grain wood movement is considered insignificant for structural timbers [18, p.48]. This probably explains why reported values for longitudinal-grain movement are lacking. Therefore, to make a conservative comparison for the RH-range commonly quoted (90% to 60%), movement is about 10 times greater across than along the grain of most woods. Deformations from wood movement are therefore mostly associated with the transverse-grain direction. In literature on panel painting behaviour, only transverse-grain deformations have been considered.

For panels painted on one side, in-plane or lateral movement (Figure 2a) causes a degree of out-of-plane or warp movement (Figure 2b): the latter is linked to the

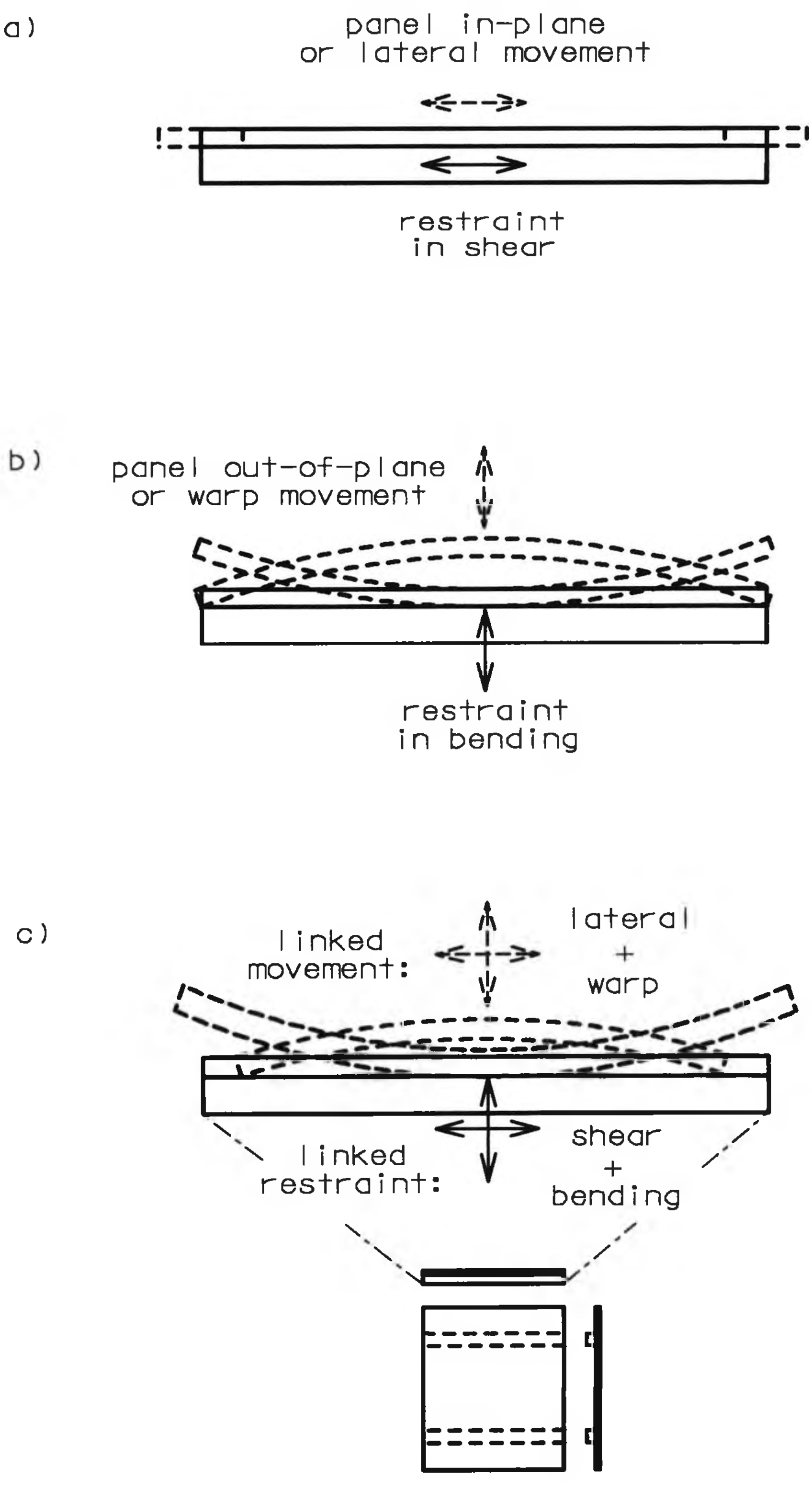


Figure 2. Movement and restraint in reinforced panels: a) in-plane, b) out-of-plane, c) combined.

former (Figure 2c). Buck called the latter [19, p.158] "temporary" warp, due to accompanying asymmetrical moisture gradients originating from the front and back surfaces. He distinguished it from more "permanent" warp due to creep and permanent set in the panel wood. The latter is usually manifested as a convex warp overall and is attributed to repetitions of the former, which cause a cumulative set in compression, more toward the panel back. Both temporary and permanent warp are usually associated with regular, approximately cylindrical curvature of the entire panel in the transverse-grain direction.

Reinforcements impose external stresses which restrain linked panel movements in two main ways: panel lateral movement is restrained in shear, that is, it is prevented from sliding over the reinforcement by being attached or by friction between the two (Figure 2a); warp movement is restrained in bending, that is, it is forced flatter, bent back on itself by the greater rigidity of the reinforcement (Figure 2b). Friction and therefore shear restraint are increased by warp restraint. Most reinforcements combine these two types of restraint to varying degrees.

Thus, linked panel deformations, generated by internal stresses, are opposed by corresponding linked external forces of restraint imposed by reinforcement (Figure2c). This interaction may cause more or less detectable elastic stresses and deformations (strain) in the combined structure which are not typical of unrestrained panel movement. This thesis makes qualitative inference of stresses from such deformations and other evidence such as warps, splits, flaking paint, and crack patterns.

Though the gradient effects described above have been considered most important for conservation, there are other causes of panel deformation. Changes in MC will also cause the planks to change shape depending on their grain orientation. Planks cut at a tangent to the annual rings of the tree (known as tangential cuts or flat-sawn planks) will tend to undergo greater warp ("cupping") during RH changes than those cut perpendicular to the rings (known as radial cuts or quarter-sawn planks). Thus, a plank will change dimensions and have a different warp after equilibrating to a change in MC. The rate of movement will vary through the plank so that a temporary warp, analogous to that described above for a plank coated on one side, is also associated with the effect of grain orientation. Also similarly, creep may occur during these changes, causing a permanent set warp in individual planks after repeated variation in MC. This is one reason why uncoated timbers show distortions with time. A different warp is visible in the planks of most panels due to these causes.

There may also be elastic stresses residing in panels due to both drying (or "seasoning") stresses incurred in the planks before panel assembly [18] and to internal stresses developed since assembly. If such stresses remain resident in planks, then any reduction in dimensions, such as thinning, could cause the panel to undergo deformations, usually visible as convex warp.

Finally, the author agrees with some others working with panel paintings [20] that the weathering which the exposed wood surface at the back undergoes over several centuries influences moisture response. This is because moisture gradients concentrate cyclic swelling and expansion at the exposed surface, as noted above regarding compression set. Thus surface wood fibres are initially compressed/crushed more than those toward the interior. After this compressive strain occurs, and while swelling under rising RH, the walls of the surface fibres do not contact each other as quickly as would unweathered fibres, nor would they have as much tensile strength across the grain while contracting under falling RH. Thus, the weathered surface layer buffers movement directly while absorbing effects of the moisture gradient at its steepest point. If freshly exposed by thinning, greater movement from RH changes could be expected.

This research is most concerned with temporary warp, which affects thinner panels in particular, and with warp changes due to the interaction of changes in MC with grain orientation. As indicated below, though problems with in-plane movement have been partly solved with low-friction sliding structures or mechanisms, warp is still a concern.

2.2 Assessment of Panel Paintings and Reinforcements

This is a sensitive diplomatic area for both conservators and museums who must answer to critics for their actions, including conservation treatments, sometimes with unwelcome publicity. The author has made every attempt to respect the trust of those who gave interviews and the institutions who gave permission to consult records.

2.2.1 Interviews

Visits were made to several public and private institutions and individuals in Europe and the United States (Appendix 1). Conservators treating panel problems were favoured when choosing destinations. Displayed and stored panels were examined, discussed, and photographs made if possible and/or requested. A questionnaire, designed to extract statistics concerning approaches to reinforcement, was abandoned as too formal because the researcher felt that some questions could compromise free discussion and because of language restrictions. Instead, concerns and experiences were discussed, with translation when necessary, and noted.

During discussions, most panel conservators expressed a keen interest in learning more about reinforcements, including their own choices. It was evident that few had had the opportunity to do the necessary research, mainly because of work commitments and funding limitations.

2.2.2 Surveys

As Schießl [4] has pointed out, collection/treatment records are a rich source of information on treatment trends and their consequences. Permission was obtained to consult treatment records at several institutions, including the Tate Gallery and the National Gallery, London, the Louvre's documentation department, Versailles, and the HKI. These records served as important reference material. Information from 453 panels was entered in a database format (page example, Appendix 2) from which comparisons of frequency of type of panel and reinforcement, effects, etc., could be made.

Abbreviations for collection inventory numbers for panel paintings cited in the text are defined in Section 1.3.1. Such citations are formatted thus: artist, painting title in italics, inventory number, and if appropriate to the discussion, dimensions (heightXwidthXthickness), shape, wood type and grain direction. An english translation is given after a slash mark (/) where names or titles in the text were taken from a source document in another language.

2.3 Review of Reinforcements

It is neither possible nor is it the purpose of this thesis to give a complete historical and technical description of panel reinforcements. A summary of the more common types is given with reference to publications, examples in collections, and comments from conservators. Changes and deteriorations from the original state will be noted for each type. Of particular interest historically is the gradual allowance for greater freedom of panel movement and the changing attitudes underlying reinforcement policy.

Across the grain, panels show the greatest deformations from wood movement and are weakest so that the perpendicular-grain dimension could be expected to show some relation to the need for reinforcement. Most panels have been painted with the grain direction vertical, if viewed with the painting upright. Therefore, with a sufficiently large number of examples, panel width can be used as an approximate index of size in the perpendicular-grain direction.

Table 1 shows that size has indeed influenced the likelihood of a panel being constructed with an original overall reinforcement or not. Of panels still with original backs, smaller ones tended to have been constructed without overall reinforcement, most of them northern paintings on oak of the 16th and 17th centuries. This indicates that though important, size cannot be considered the only factor because panels of that provenance are known for their quality of materials and fabrication [21], often consisting of radially-sawn planks which have therefore remained relatively flat.

Size also appears to have influenced whether the original structure later required treatment, as shown by the back having been altered. It can be seen that of 453 recorded panels, larger ones were more likely to have been altered while smaller ones retained their original backs. Though important for panels, size is not the only factor which determined whether paintings were treated. For example, works by more popular artists have tended to receive more attention and have therefore been restored more often than less popular works, some of which have remained relatively untouched [22].

PANEL WIDTH	**TOTAL**	**BACK ALTERED**		**BACK ORIGINAL**		
				TOTAL	**UNREINFORCED**	
(m)	#	#	%Total	#	#	%Original
<0.30	88	24	27	64	51	80
0.30 -0.60	189	59	31	130	98	75
0.60- 0.90	94	45	48	49	33	67
>0.90	82	46	56	36	16	44

Table 1. Alteration and reinforcement of some surveyed panels according to size as indicated by their width.

2.3.1 Unreinforced Panels

It can be assumed that most panels were constructed to provide flat surfaces for painting and were intended to remain flat. In general, temporary and permanent deformations are more pronounced in panels with exposed backs than in those coated on both sides. In thinned examples, the author has observed warp changes within minutes of a change in ambient RH [11, p.62]. In collections, such movements usually escape visual detection unless some record of the panel shape is made at intervals (eg. tracing the contours at an edge). However, observant individuals have remarked that certain panels in collections can serve as a danger signal of RH changes, warping visibly in relation to the inner frame edges [23]. It is then assumed that other panels in the collection may be put at risk of damage from excessive restraint from whatever cause. Panels with tangentially-cut planks, even of original thickness, would be particularly prone to temporary warp, as would larger, thinner panels [12].

Unaltered panels with exposed backs often show a permanent and more or less convex warp usually attributed to compression set. Such warp was noted in most panels surveyed (for example, Figure 3), regardless of origin and quality of construction. Examples included: Anthonis/Anthony Moro, *Le Nain du Cardinal Granvelle/The Dwarf of Cardinal Granvelle*, LV.INV1583; Anthony Van Dyck *Tête de Viellard/Head of an Old Man*, LV.MI916; Willem Claesz Heda, *Nature Morte au Gobelet D'Argent/Still Life with Silver Gobelet*, LV.INV1319; Lambert Doomer, *Le Pont-Neuf à Angers/The Pont-Neuf (New Bridge) at Angers*, LV.RF3733; Bartholomew van der Helst, *Les Syndics de Saint Sebastien D'Anvers, 1653/The Syndics of Saint Sebastian of Antwerp, 1653*, LV.INV1332.

Tangentially-sawn planks or regions of planks showed greater permanent warp, suggesting that they were more prone to movement and subsequent compression set at the back. This can cause reinforcement difficulties, especially

Figure 3. Permanent convex warp of a 16th c. Italian panel of original thickness. (Raphael, "Sainte Famille" called "La Petite Sainte Famille" 1518-19, Louvre INV.605.) Photo Laboratoire de Recherche des Musées de France (1983).

of large, thinned panels with horizontal grain in which such warped planks are located near the bottom. The warp increases buckling stresses from the weight above and because the panel rests on its bottom edge, any temporary warp will be magnified toward the top where the panel has more freedom of movement [12].

Panels painted on both sides are generally accepted to represent the most stable condition with regard to both temporary and permanent warp. Their relatively flat state and good condition have been noted elsewhere [8, p. 153]. Coatings reduce total moisture exchange and if both sides are coated, and in rare panels the edges as well, exchange occurs as relatively symmetrical gradients from opposite sides.

A more symmetrical set appears to occur through the section of such panels so that though warp is less likely, in-plane deformations can be observed. This was shown by a permanent reduction in transverse-grain dimensions noted in some paintings, such as some northern European paintings, generally on oak and in original grooved frames, where a "malrand" (or "barbe") no longer contacts the original frame edge. Wooden frame perimeters, which are cut in the longitudinal-grain direction, are more dimensionally stable than are panels in the transverse-grain direction.

Some out-of-plane deformation from such set is also usually visible. Both in- and out-of-plane deformation are shown by an extremely well-preserved painting of *St. Luke* by Simone Martini (Figure 4) in which, though the subject is painted on one side only, the back and edges retain original imitation-porphyry coatings of painted gesso. Compression set has caused the panel to contract over the centuries and to disengage from the original frame.

2.3.2 Original Reinforcements

Original reinforcements are those applied when the panel was constructed, usually before application of the ground and paint layers. It is useful to start with original reinforcements to understand how reinforced panels were intended to look, how they have aged, and why they have been altered. Most have been relatively rigid batten structures located at the panel back and either fixed or sliding in the transverse-grain direction. Out of 50 recorded panels with original reinforced backs, all had batten reinforcements. Since nearly all panel paintings can be assumed to have been created as flat images overall, most original reinforcements must have had a dual role: 1) to reinforce the panel structurally and 2) to maintain its flatness.

When original reinforcements were applied to small paintings, especially those on a single thick plank, maintaining the initial flatness of the panel was apparently the main purpose because structural reinforcement would seem to have been unnecessary. For example, many small icons which were built to be portable are in this category and were battened anyway. Icon

a) b)

Figure 4. Permanent set in a 14th c. Italian panel with original coatings on all sides: a) front, and b) back, with resulting gaps at panel edges. (Simone Martini, "St. Luke", The J. Paul Getty Museum GM.82.PB.72.) Photo permission of The J. Paul Getty Museum.

construction, however, has had a strong ritualistic tradition which may have surpassed mere structural needs:

"C'est le respect de la tradition et l'application méticuleuse des procédés techniques qui garantissent la relation avec la transcendance." [It is respect for tradition and meticulous application of technical procedures that have guaranteed the relation with transcendance.] [24]

Castelli and Ciatti [25] examined the evolution of Florentine and Tuscan reinforcement methods from the 13th through the 16th c. and in light of modern Florentine conservation techniques. Reinforcements evolved from rigid battens and/or frame-like structures fixed to the panel with nails, to sliding battens inset in grooves cut into the panel back with the frame separated entirely, then finally to battens shifted to the back panel surface to slide through retainers which were nailed and/or glued in place. Similar concurrent developments in northern Europe saw the frame separated from the panel structurally and functionally in the 15th c. [21]. In general, the shift throughout Europe was thus away from restraint in all three dimensions toward restraint of warp movement only.

(a) Fixed Battens and Frame-like Structures

Fixed batten reinforcements were usually of relatively large-section timber and sometimes of a wood type denser than the panel wood, underlining their dual role of reinforcement and flattening. Battens were sometimes disposed diagonally, in a cross or as part of a "Z" pattern, or were part of a peripheral frame structure. Both are found in some 13th c. Italian panels ([25, p. 143; 26], and Spanish panels into the 16th c. [3, pp. 79-82]. The author has noted twists in many fixed-batten panels. Disposed diagonally, battens would help resist the development of twist [27].

Commenting on the mechanical suitability of poplar for panels, Castelli and Ciatti [25] noted that its relative softness and flexibility allowed some freedom for nails in early fixed-batten structures, as did the use of square-section nails set into circular-section (drilled) holes [25, p. 145]. Softer panel woods such as poplar and pine would tend to deform around attachments to relieve some stress from in-plane and out-of-plane deformations during panel movement.

While most early Italian and northern panels were assembled from dried (seasoned) planks so that panel deformations were less likely afterward, some Spanish panels were not (Figure 5). The author had the pleasure of examining virtually unaltered panels from a 15th c. Spanish retable [28] of softwood, probably pine, reinforced with battens of sweet chestnut (*Castanea sativa* Mill.). It is an example where effects of timber shrinkage on warp (section 2.1) could be distinguished at the unplaned back to help deduce the construction order. Discussions with the conservator [20] revealed the order as: relatively unseasoned planks nailed centrally through their front sides to transverse battens; seasoning and warping of the planks; wedges set between battens and panel to rigidify; luting of joints between the planks with wood inserted at the front; planing of the front; bridging of the joints at back and front with plant fibres and gesso; application of preparation and paint layers to the front.

Thus, compared to most Italian 13th and 14th c. panels and nearly all later examples, where planks were seasoned first and then solidly glue-joined, planks of this retable were seasoned after being nailed to the battens. An example of seasoning after construction is unusual and of considerable interest historically and because original effects could be mistaken for deteriorations due to later deformations. Structurally and materially similar to many early Italian panels (poplar and pine woods have roughly similar elastic moduli [29, pp. 19, 45; 30, p. 67], the retable planks sustained considerable warp during shrinkage with little or no splitting. However, splits, disjoins and twists had developed since construction that are typical of planks reinforced by such fixed-batten structures.

Figure 5. Original fixed battens on a 15th c. Spanish panel: Detail, transverse-grain edge at one side showing a split (top), a disjoin beneath an original fibre/gesso layer (middle), and a cupped warp in the lower plank, shown by the shadow along the batten at left.

(b) Sliding Battens

Sliding batten structures were usually applied parallel to each other and perpendicular to the panel grain direction. Battens on Italian panels of the 16th c. [25] were typically of dovetailed cross-section and tapered lengthwise to slide in a similarly shaped channel or groove cut into the panel back (Figure 6a). Like fixed battens, they were usually more rigid than the panel by being thicker and/or of a more rigid wood type. Therefore, it can be assumed that in-plane panel movement, perpendicular to the grain, was permitted in such panels though they were intended to remain flat.

A few exceptions were examined where battens appeared to have been purposefully made more flexible. For example, two relatively thick oak panels, described as "Durer school" [31], had two relatively thin original battens. They were in good condition structurally.

Some panels with more rigid sliding battens have survived relatively intact, such as in Figure 6b. In contrast there are virtually unaltered panels, as in Figure 7, which show damage apparently from batten restraint. The illustrated panel had split with the grain and toward the middle, most evident where the back was exposed between the battens.

The location of these splits suggests that restrained warp was involved, probably combined with restrained panel movement along the battens. In Figure 2, a regular warp in either direction would cause the panel to contact first at the midpoint and ends of the batten. If the batten did not bend with the panel, then warp would effectively be restrained (ie. bent) around a fulcrum at the panel middle so that bending stresses would be concentrated there. If a convex warp, tension stress would develop at the back surface. Friction between panel and batten would impede contraction of the panel across the grain, increasing tensile stress and the chance of fracture, probably from the back. Marette [3, Plate 56] shows similar original

a)

b)

Figure 6. Original sliding battens in two Italian panels: a) a batten end (Fra Angelico and Domenico Veneziano, "Le Couronnement de la Vierge", 1435, Louvre INV.314), b) a smaller panel in very good condition (Raphael, "La Vierge à l'Enfant avec le Petit Saint Jean-Baptiste", called "La Belle Jardinière", 1507, Louvre INV.602.) Photos Laboratoire de Recherche des Musées de France (1964, 1956, respectively).

battens on Da Vinci's *Sainte Anne, Vierge et Enfant Jesus* Louvre INV.776, where the panel joints have probably been affected by this kind of batten restraint.

Splits in the Boateri panel were also more evident in the exposed areas at the back, between the battens. This was also true in many examples with altered backs and with non-original reinforcements in which a large proportion of panel back was left exposed. Areas of exposed panel would undergo more rapid moisture exchange and could therefore be expected to undergo greater and more rapid wood movement than wood beneath battens. Resulting shear stresses, along the batten edges and between the regions of differing transverse-grain movement, may help to initiate splits.

Larger panels especially show reinforcement problems [12]. Figure 8 shows a panel which retained three original sliding battens set into dovetail-sectioned grooves. A number of repaired breaks can be seen through a thick non-original coating, which was probably applied to slow moisture exchange.

A large painting by Pesellino (Figure 9) shows original sliding battens similar to those in Figure 8. Similarly, the panel evidently developed sufficient permanent convex warp from compression set to impede it's lateral movement along the sliding battens. Friction from restrained bending probably combined with tension stress at the panel back to cause breaks at the joints, which were evidently weaker than the wood. Once disjoined, each plank became more free to assume a more or less convex warp. This warp reaction could also be expected with split planks.

In some cases, original sliding battens have simply fallen out of the groove, such as in "Portrait of a Man With a Watch" by Maso da San Friano, in the London Science Museum (HKI.1743). There, one of two battens had begun to detach from a relatively shallow groove. Interestingly, the battens appeared to have been planed thinner since the panel was constructed, perhaps to make them more flexible

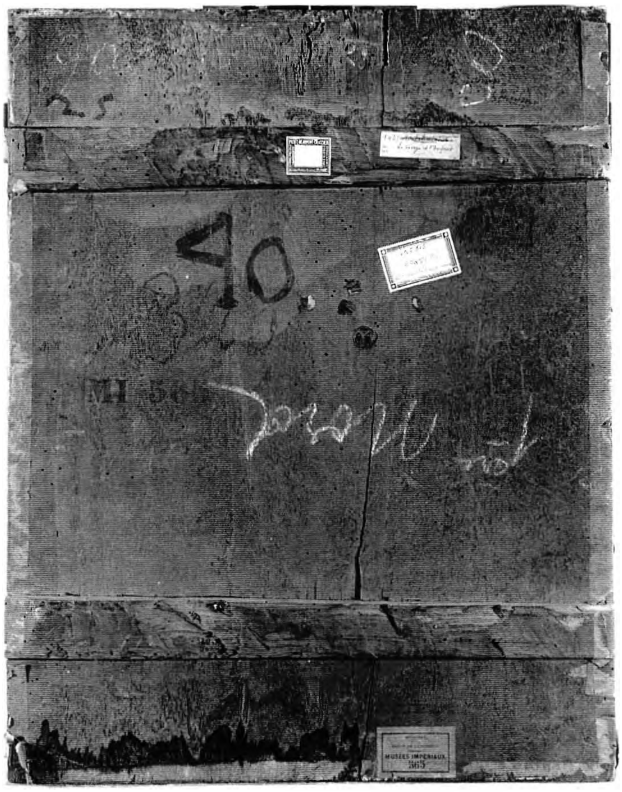


Figure 7. Splits in a panel with original sliding battens (Jacopo Boateri (active Bologna, 1500), "La Vierge et L'Enfant Avec un Saint Franciscain", Louvre MI.565.) Photo Laboratoire de Recherche des Musées de France (1971).

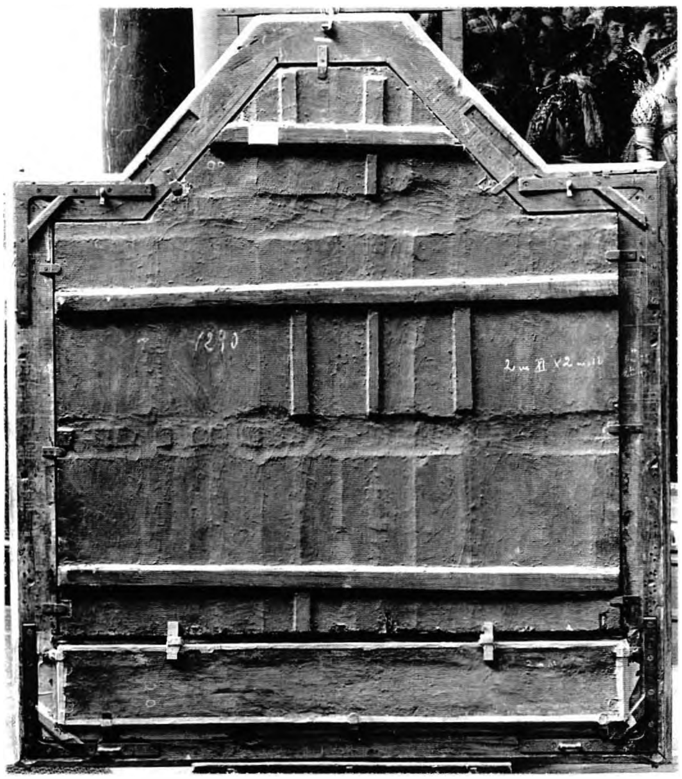


Figure 8. Back of a large panel with three original sliding battens remaining. (Fra Angelico and Domenico Veneziano, "Le Couronnement de la Vierge", 1435, 2090X2060X30-50mm estimated thickness, Louvre INV.314.) Photo Laboratoire de Recherche des Musées de France (1964).

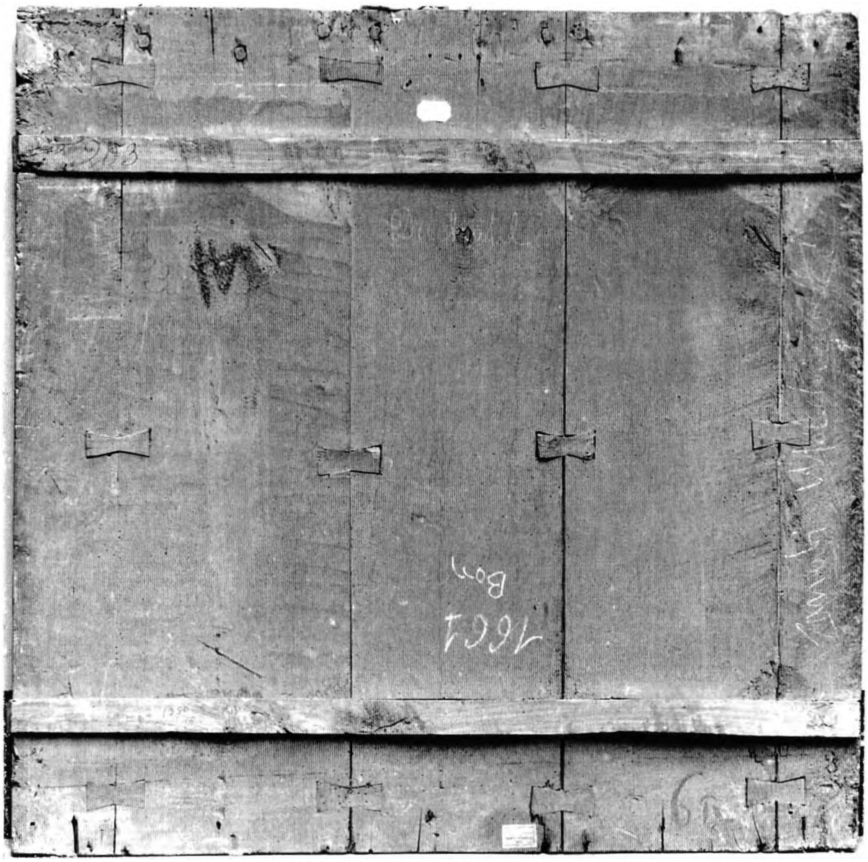


Figure 9. Back of a large panel with original sliding battens showing disjoins. (Pesellino (Francesco di Stefano) (Florence, 1422-1457), "La Vierge et l'Enfant entre Saint Zanobie(?), Saint Jean-Baptiste, Saint Antony Abbe, et Saint François", 1764X1731X30-50mm estimated thickness, Louvre MI.504.) Photo Laboratoire de Recherche des Musées de France (1967).

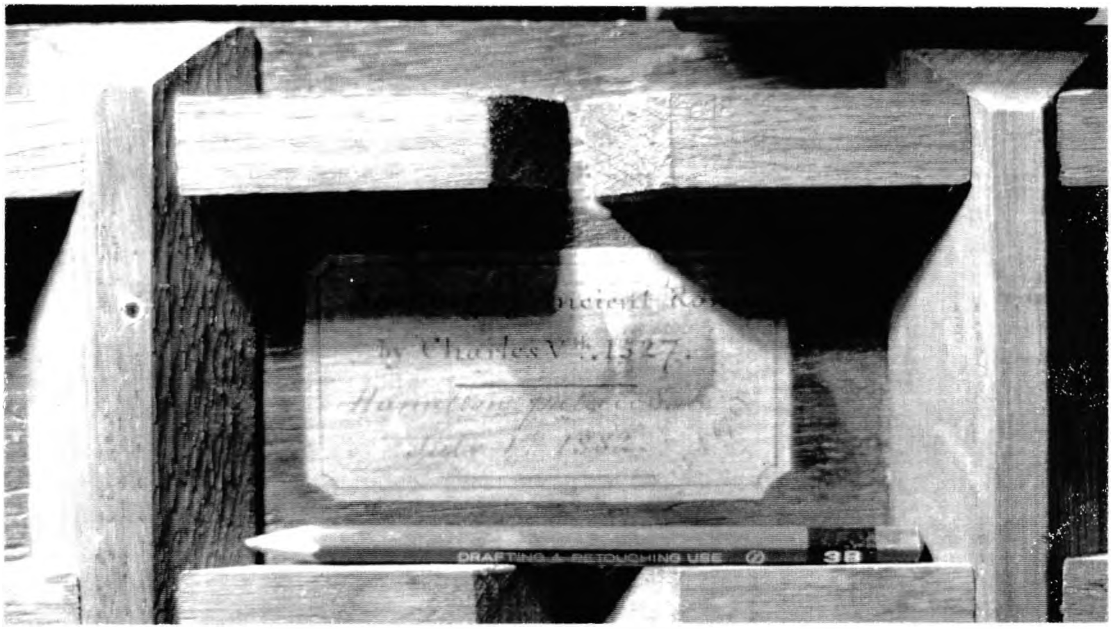


Figure 10. Detail of what is probably a 19th c. "Italian cradle". A paper label from an Italian exhibition is dated 1882. It's position between the sliding battens indicates it was applied after the battens.

to conform better to warp. There was no other structural damage.

There are many panels with original battens either missing or, as stated in accompanying condition records, removed or altered because of warp restriction or damages. Examples noted were Raphael, *Pope Julius II*, NG.27; Garofalo, *The Vision of St. Augustine*, NG.81; Michelangelo, *The Entombment*, NG.790; Carlo Crivelli, *The Virgin and Child With Saints Francis and Sebastian*, NG.807; Domenico Ghirlandajo, *La Visitation/The Visitation*, LV.INV297; Bernardo Pinturicchio *La Vierge et L'Enfant entre Deux Saints/Virgin and Child between Two Saints*, LV.MI574 ; Giorgio Vasari, *L'Annonciation/The Annunciation*, LV.INV732; Paolo Zacchia, *Portrait d'un Jouer de Viole/Portrait of a Viola Player*, LV.MI610.

Castelli and Ciatti [25, p. 147] note that through the second half of the 15th c. and into the 16th c. in Siena, battens were sometimes laid against the panel back and slid within metal or wooden "bridges" (called "retainers" in this thesis) distributed at regular intervals across the panel back and attached with nails and/or glue. Thus when originally constructed, rather than being engaged continuously for their entire length and more within the panel plane, battens were shifted to bear on the back surface and were retained at discrete points of attachment. Treatment record photographs show, for example, that the *Martyrdom of Saint Sebastian* by Antonio and Piero Pollaiuolo (2nd half 15th c.), NG.292, originally had such battens.

A much smaller proportion of oak panels from northern Europe show evidence of original batten reinforcements. Even panels up to 1m or more across the grain were often not reinforced at the back, though most were intended to have a perimeter frame of some sort. Overall reinforcement was perhaps less necessary because, regarding flatness, the generally radial cut of the planks preserved a relatively flat plane, and regarding strength, oak panels were relatively strong and rigid with joints often strengthened by dowels. Dovetailed grooves cut into the panel were seen in a few larger examples and oak battens sliding through iron retainers nailed into the panel were noted in a large painting by Rubens (*Adoration of the Kings*, Kings College Chapel, Cambridge, England) [12].

(c) Perimeter Frames

Mention will be made of original rigid, grooved frames found in many northern panels. Many such panels were coated on both sides and their edges chamferred to slide with minimum contact in the frame grooves. Besides set warp developed over time, repeated varnishing and other interventions have fixed many of these panels at points in the grooves, causing deformations and splits. Some others, painted on one side only, have developed enough set convex warp to cause binding in the frame grooves.

2.3.3 Non-original Reinforcements

This discussion must respect the requests of those who created or applied some of the designs presented. Some individuals to whom the author spoke preferred not to have photographs published, so only a verbal description is given. Though such suppression fits with old guild practice, it is counter to open discussion and advancement of better designs. Publications are cited, but some of the designs discussed here have either not been published or the author could not locate any publication.

(a) Fixed Battens

There are many panels which have had non-original battens of wood or metal glued and/or nailed or screwed to them. The panel by Palmezzano (Figure 1) is a good example. Deformations, splits and disjoins are commonly associated with such treatments. In some cases, battens have become partially or completely detached. Numerous examples with attributed damages may be noted among the treatment records examined: Hans Memling, *Donateur Présenté par Saint Jean-Baptiste/A Donor with Saint John the Baptist*, LV.RF886 (split); Ecole Flamande/Flemish School (end of 16th c.) *Diane et Actaon/Diana and Acteon*, LV.RF1941-9 (disjoined, split); Pinturicchio, *Saint Catherine With a Donor*, NG.693; Buonconsiglio, *Saint John the Baptist*, NG.3076 (splits); Rembrandt, *Paul in Prison*, SG.INV746 (disjoins, front concave warp), Studio of Joos Van Cleve, *Adoration of the Magi*, FW.1784 (concave warp, disjoins), Frans Floris, *Faith, Hope, and Charity*, NT. Kingston Lacy No.69 (disjoins), Giovanni Bellini, *Saint Jerome*, AM (splits, saddle-shaped warp).

The small panel by Bellini (266X217X6mm thick) had been thinned and had two oak battens glued across the grain. The panel had split and assumed a saddle-shaped warp. The warp decreased considerably after the battens were removed. Many of the deformations present in the panel painting by Palmezzano (Figure 1) also greatly decreased after the fixed reinforcements were removed [12].

At the Kollektief in Amsterdam, the author examined a 17th century oak panel (600X400X5mm thick), thinned and with three later battens glued across the grain, which had split between the battens but not over them. The panel also had a slight concave warp across the grain. Splits appeared to have resulted from the panel being fixed in all directions over the battens, with relatively little restraint between. The conservator had thinned the battens to about half their original thickness, during which the panel had warped more concavely. This was a typical example of more disturbing panel behaviour which can occur during removal of reinforcement structures.

Another oak panel of three planks (Cornelius Johnson or Janssen, *Penelope Noel*, Corsham Court, HKI.896) had hardwood battens glued to the back of the two vertical joints, with the grain. The panel was warped convex both with and across the grain, with a bulge between the battens and paint losses over the joints. It became much flatter after the battens were removed.

(b) Sliding Battens

Most non-original sliding battens found on panels are variations on the later Italian style of original batten described above which bears on the panel back and is intended to slide between retainers that are attached to it. Brachert [32, p. 8] described typical rigid designs used in Germany which he notes were derived from Florentine designs. Schießl [4] says that one of these, the "Italian cradle", also mentioned by Wehlte [33, p. 577; 34] and Straub [35, p. 156], was derived from Secco-Suardo, an Italian restorer of the late 19th c., and he attributes the first published German reference to a description by Tony Roth in 1949 in [36]. The journal *Museum* [8, p. 161] shows an example of a similar design applied in the 18th c. to a 16th c. Venetian panel in the Louvre. Figure 10 shows an example that was probably applied in the 19th c.. Wehlte [34] also showed a modified design, based on rigid T-shaped cross-section wooden battens, in which the top flange of the "T" was held against the panel back by wooden retainers on both sides.

John Farnsworth [37] discussed his experiments using relatively thick test panels bearing these two designs and another reminiscent of that used for Duccio's *Maestà* [38], except the battens he used were made of rectangular-section aluminium (Figure 11a); both panels and battens were therefore relatively rigid. During changes in RH, panel lateral movement seized in all three designs, especially the T-shaped batten type (Figure 11b). Disjoins and/or splits have been reported in some panels with this type of rigid wooden batten, such as: Monogrammiste de Brunswick (Jan van Amstel?) *Montée au Calvaire/The Road to Calvary*, LV.RF773 (disjoins), Garofalo, *Saint Catherine of Alexandria*, NG.3118 (split), Garofalo, *Holy Family*, SG.INV157 (split).

Straub [35] also illustrated an Italian variation on such retainers, developed by Carità at the Istituto Centrale in Rome [39]. Each retainer consisted of a wooden block to either side of regularly-spaced slots cut in a rectangular-section batten of metal (usually stainless steel). The batten was oriented with its larger sides perpendicular to the panel plane. A spindle bridged each set of blocks and supported a roller bearing in the slot between, allowing a very low-friction sliding batten system. Warp movement was not accommodated by this system.

A major treatment on Duccio's *Maestà* was published in 1959 [38, pp. 29-36], though illustrations of the reinforcement appeared in 1955 in the journal *Museum* [8, p. 172, 173]. The former included a detailed description of the reinforcements, and principles behind their construction, used to support the *Scenes from the Life of Christ*, fourteen previously-thinned predella panels of the altarpiece. The reinforcements were intended

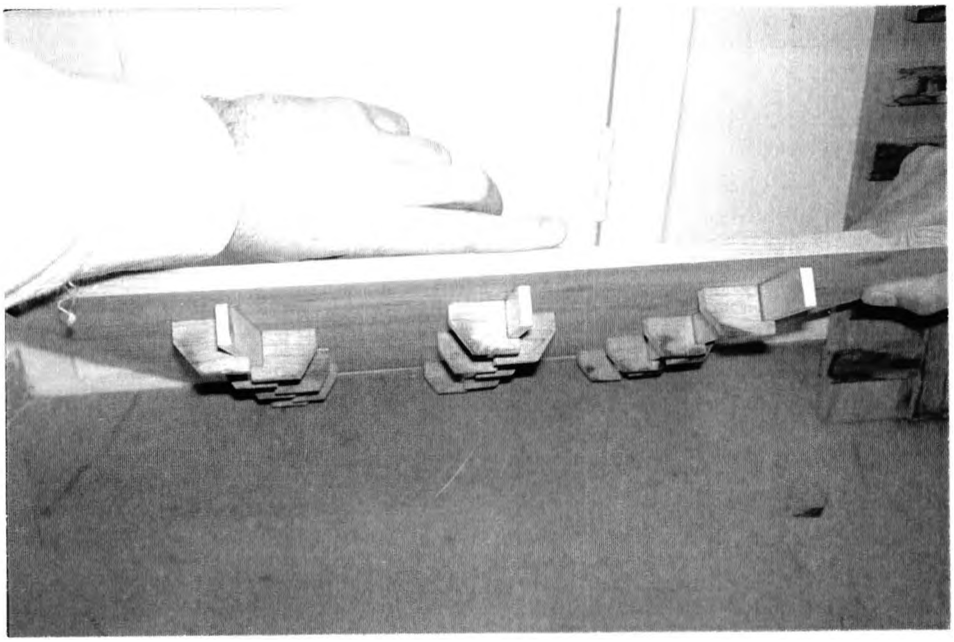
"...a mantanere piane le assi, consentendone tuttavia i movimenti generati dal mutare delle condizioni ambientali, sopratutto dalle oscillazioni dei valori di umidità relativa" [...to keep the boards flat, whilst allowing them to move with changes in environmental conditions, most of all from fluctuations in RH level] [38, p. 29].

The design was based on calculations made by aeronautical engineers

"...per renderle e conservarle piane. In relazione alle dimensioni delle tavole saranno stabiliti i criteri per scegliere le più opportune dimensioni delle aste, la loro distanza, la forma della sezione, la natura del materiale" [...to render and conserve [the panels] flat in relation to criteria for choosing the most effective/best dimensions of the battens, their distance, the section shape, and the nature of the material out of which they were made.] [38, p. 31].

The moduli of elasticity of the panels were estimated in the transverse-grain direction using wood samples and by applying a beam formula. The bending force necessary to restrain any expected warp was then calculated using the

a)



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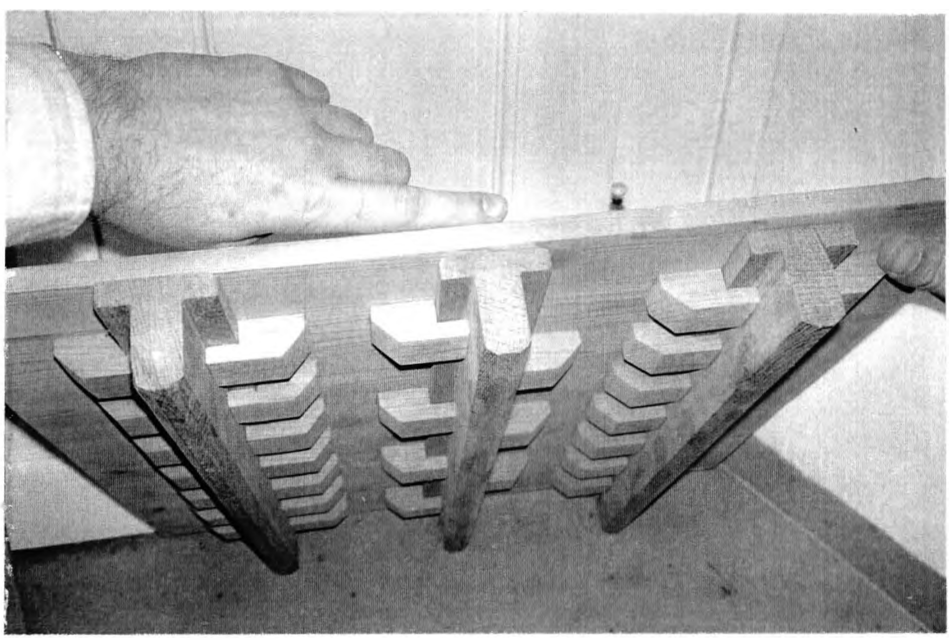


Figure 11. Panel/reinforcement mock-ups used to test sliding batten designs, from Münster, Germany: a) rectangular section aluminium battens, b) wooden T-section battens, similar to those used by Wehlte.

panel dimensions, and the smallest rectangular section was calculated for steel battens of known elastic modulus which would restrain an estimated panel warp. The steel battens, with their largest face perpendicular to the panel plane, were slid through U-section guides of silver-plated brass which were glued to retainers of wood which were glued to the panel back. These were intended to act as low-friction retainers, similar to those proposed by Carità [39], but with a sliding mechanism instead of a roller bearing.

It is explicitly stated [38, p. 31] and evident from the calculations and subsequent design that the aim was to prevent out-of-plane movement:

"Scopo del presente lavoro è quello di stabilire le più opportune caratteristiche delle aste di irrigidimento che si fissano alla faccia posteriore delle tavole dipinte per renderle e conservarle piane." [The aim of the work in hand is to establish the most appropriate characteristics of reinforcing battens which are fixed to the backs of the painted panels to render and to conserve them flat.]

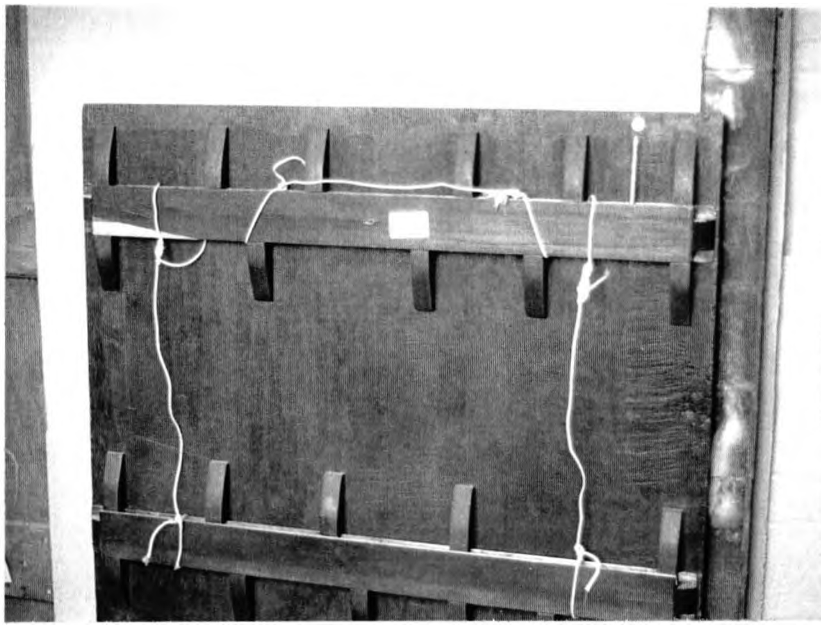
A flexible lattice published by Carità [40] (see section 2.3.3 (e)) in 1954 attracted attention in France, referred to briefly as a "parquet souple" (flexible cradle) in a treatment proposal [41] from 1965 for Palmezzano's *Le Christ Mort* in the Louvre. The proposal mentions some of the first work of Claude Huot, who made some important contributions to development of panel reinforcements in France. Encouraged to improve methods by Germain Bazin, then Conservateur en Chef de la Restauration des Peintures (chief curator in charge of painting restoration), Huot [42] returned to Paris in 1965 from a period of study at the Istituto Centrale in Rome. He was deeply impressed by designs then being developed at the Istituto and adopted the principle of rigid battens sliding on roller bearings, with some modifications (Figure 12a). Preferring wooden battens over the stainless steel ones proposed in Rome, he attached U-section metal rails (usually brass) to both sides of the batten in which the roller bearings could slide ("traverses munies de rails laiton avec taquets à galets"). The retainers or cleats (*taquets*) were not sprung to allow for warp.

During Huot's work for French museums over the following years, the "chassis cadre" (literally, "support frame"), a type of perimeter frame reinforcement, was also developed (Figure 12b). Sometimes it also employed retainers with roller bearings [43, p. 25]. The author saw similar sliding frame-like structures in Florence. In panels judged to have a significant set warp, the transverse-grain members, while remaining rigid, have been shaped to conform to panel curvature, usually by sawing them to form a regular curve. Battens have also been similarly shaped.

Kolch [44, p. 61] noted that aluminium battens of T-shaped section were used to rigidify balsa laminates as early as 1939. As battens, aluminium T-section sliding between wood retainers have been used for several years at the Institut Royal de Patrimoine Artistique in Brussels (Figure 13) [45]. Rubens' large *Deposition From the Cross* is a recently published example [46]. There, the oak-wood retainers allow in-plane movement only. They are apparently intended to break under excessive stress from bending or friction because the size of the batten section would appear to allow very little bending. The conservator indicated that attempts were being made to find different methods than aluminium T-section, possibly using more flexible and stable materials like carbon fibre composites. In Denmark, a conservator at the National Museum indicated that the studio there had used aluminium T-section in the early 1960's but had later stopped [47].

Though not in the form of sliding battens, aluminium tubing was also used, as early as 1935, to rigidify early balsa/wax-resin laminates [44, p. 23]. Tubular metal battens running through wooden retainers glued to the panel have also been used (Figure 14). During interviews, some panel specialists disapproved of such sliding battens, recounting panels which had split and had to be treated again as a result [48]. They blamed excessive friction

a)



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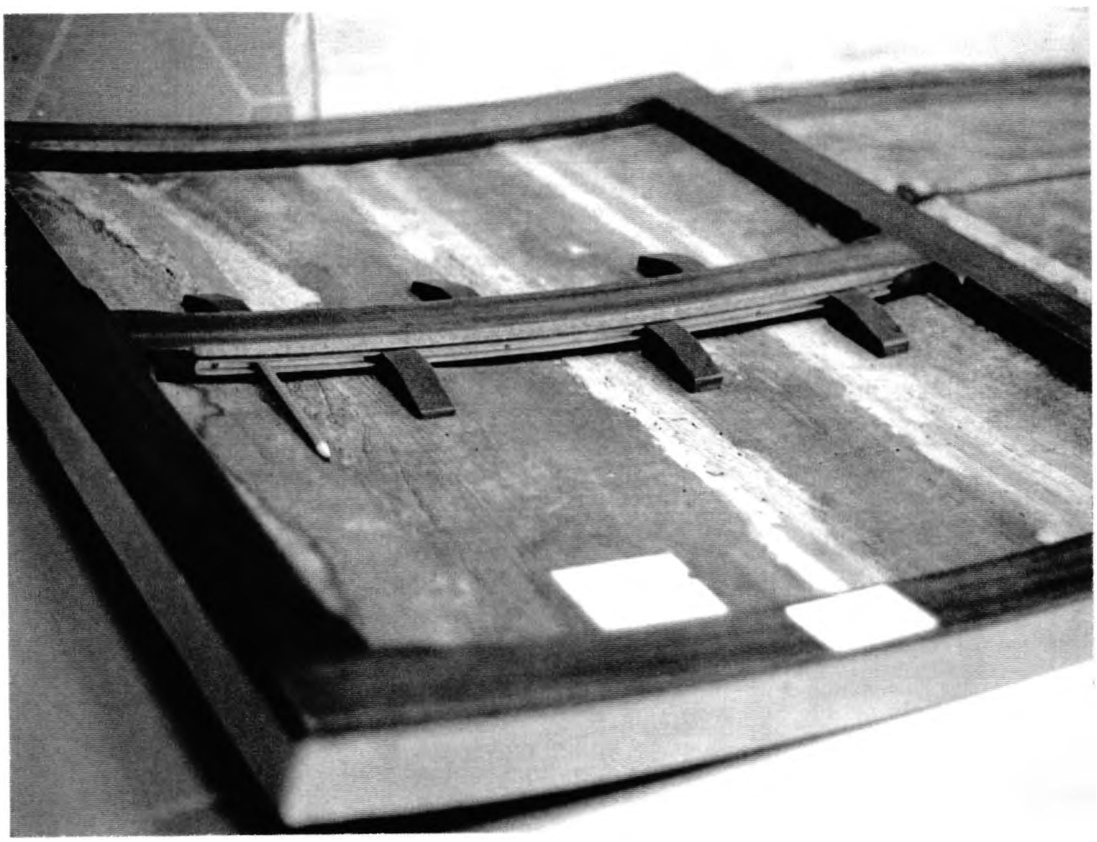

Figure 12. Rigid reinforcements which slide on roller-bearings: a) wooden battens with metal U-section runners on a thicker panel, b) a "chassis cadre" with cross member on a thinner panel in which the members lying across the panel grain are cut to approximate permanent warp.

between the tubing and retainer holes. One conservator noted that aluminium has significant sliding friction [49], a possible cause of excessive restraint since freshly cut aluminium surfaces oxidize quickly.

The author found a few aluminium batten treatments dating from the 1960's in treatment records: Pesellino, *La Vierge et l'Enfant Entre S. Zanobie(?), S. Jean-Baptiste, S. Antony Abbé, et S. François/Virgin and Child With Saint Zanobius (?), Saint John the Baptiste, Saint Anthony Abbot, and Saint Francis*, LV.MI504, applied 1968/69 (A 1978 photo of the front in raking light (LV.Neg24542) shows warps and losses); Maître de Saint Barthelemy, *La Descente de Croix/Descent from the Cross* LV.INV1445, applied 1966; the same reinforcement was considered in 1966 for Paolo Zacchia's *Portrait d'un Musicien/Portrait of a Musician* Louvre MI.610, but apparently was not applied. Lack of examples and of current use suggests that this style of batten has not stood the test of time.

A 1965 record entry [50] of a treatment by the Istituto Centrale del Restauro, Rome, concerning reinforcement of a large walnut panel (Josse Lieferinxe, dit le Maître de Saint Sébastien/called the Master of Saint Sebastian, *Le Calvaire/Calvary*, LV.RF1962-1) proposed rectangular-section stainless steel battens turned on edge, as for Duccio's *Maestà*, sliding through retainers of trapezoidal section glued to the panel back, similar to tubular aluminium battens. Again, the battens were spaced some distance from the panel back. Apparently the Istituto did not propose a roller bearing retainer system, which Carità [39] had developed 10 years earlier.

Regarding the possible development of excessive friction in these latter two designs, spacing of the battens from the panel back may be an important factor. This is due to the radial relationship between the arc of the warp, the projection (length) of the retainers, and the displacement of the retainer ends in the plane of the panel. For a convex warp (Figure 15), such as under dry conditions, the

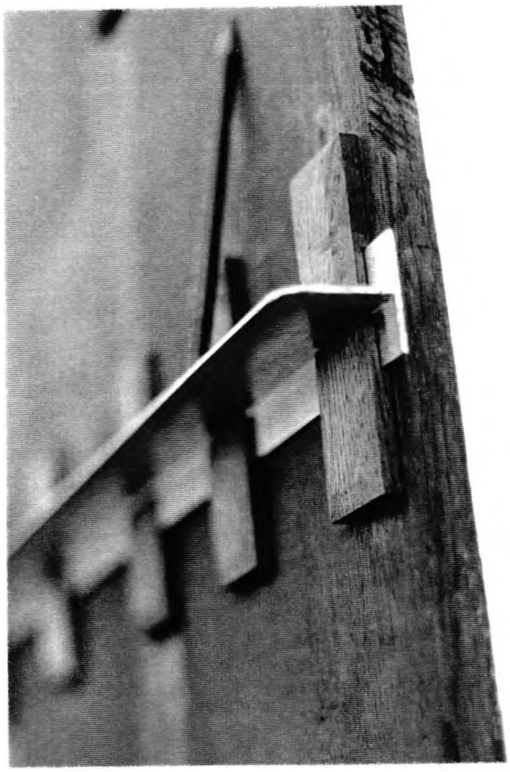

Figure 13. A T-section aluminium sliding batten.

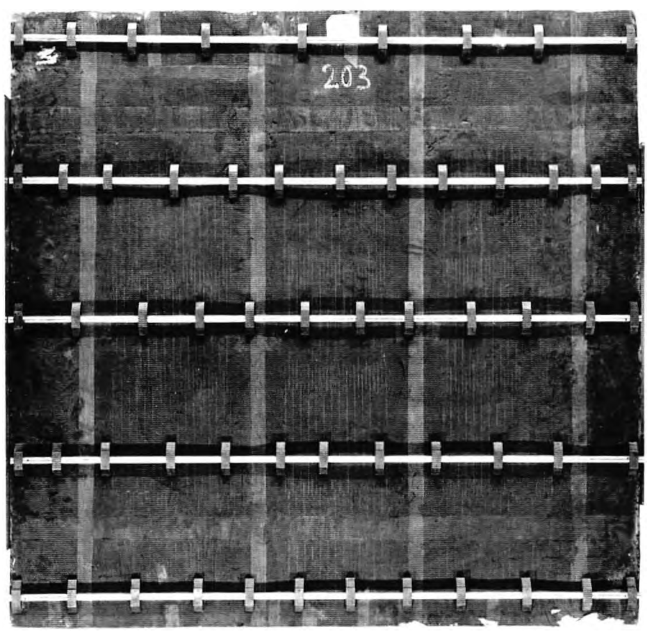

Figure 14. A large panel with tubular metal sliding battens (Pesellino (Francesco di Stefano) (Florence, 1422-1457), "La Vierge et l'Enfant entre Saint Zanobie(?), Saint Jean-Baptiste, Saint Antony Abbe, et Saint François", 1764X1731X30-50mm estimated thickness, Louvre MI.504.) Photo Laboratoire de Recherche des Musées de France (1975).

retainers would rotate toward the arc center. If they project only a short distance from the panel, their displacement will be small, so they will be less likely to contact the batten and develop friction than if they project a greater distance. Once engaged with the batten, restraint is transmitted to the panel via the retainer. A bending moment is applied to the batten at the extreme end of the retainer, and a reacting moment at the retainer base. The moment arm is equal to the projection of the retainer, or more correctly, the distance of the outer batten surface from the panel back. Therefore, longer retainers increase 1) the force and speed at which pressure is applied at the retainer extremity, causing greater friction and binding, and 2) the torque applied to the panel at the retainer base, causing deformations and splits. A close tolerance between the batten and retainer holes would increase this tendency. These observations could have important implications for sliding batten reinforcements in general, including cradles. One conservator felt that the high cradle design is more dangerous because mechanical movement is intensified [51].

Bünsche [52], working in Berlin in 1976, described in detail the treatment of a large spruce panel using T-section aluminium battens sliding between sprung retainers. Combining Carità's [39] roller-bearing retainers and Wolters' [53] work on flexible reinforcement, the design is notable because it attempts to account for both in-plane and, to a small degree, warp movement. However, considering the amount of flattening done with moisture (humidity) before reinforcement application and the relatively small tolerance for warp in the design, it is this author's opinion that the panel must have undergone considerable bending stress after equilibration.

For many reasons, new approaches are not necessarily adopted or developed in conservation. Many real improvements have died with their creator. It is therefore important to note where continuity of enquiry into reinforcements has fostered progress. A good example is the

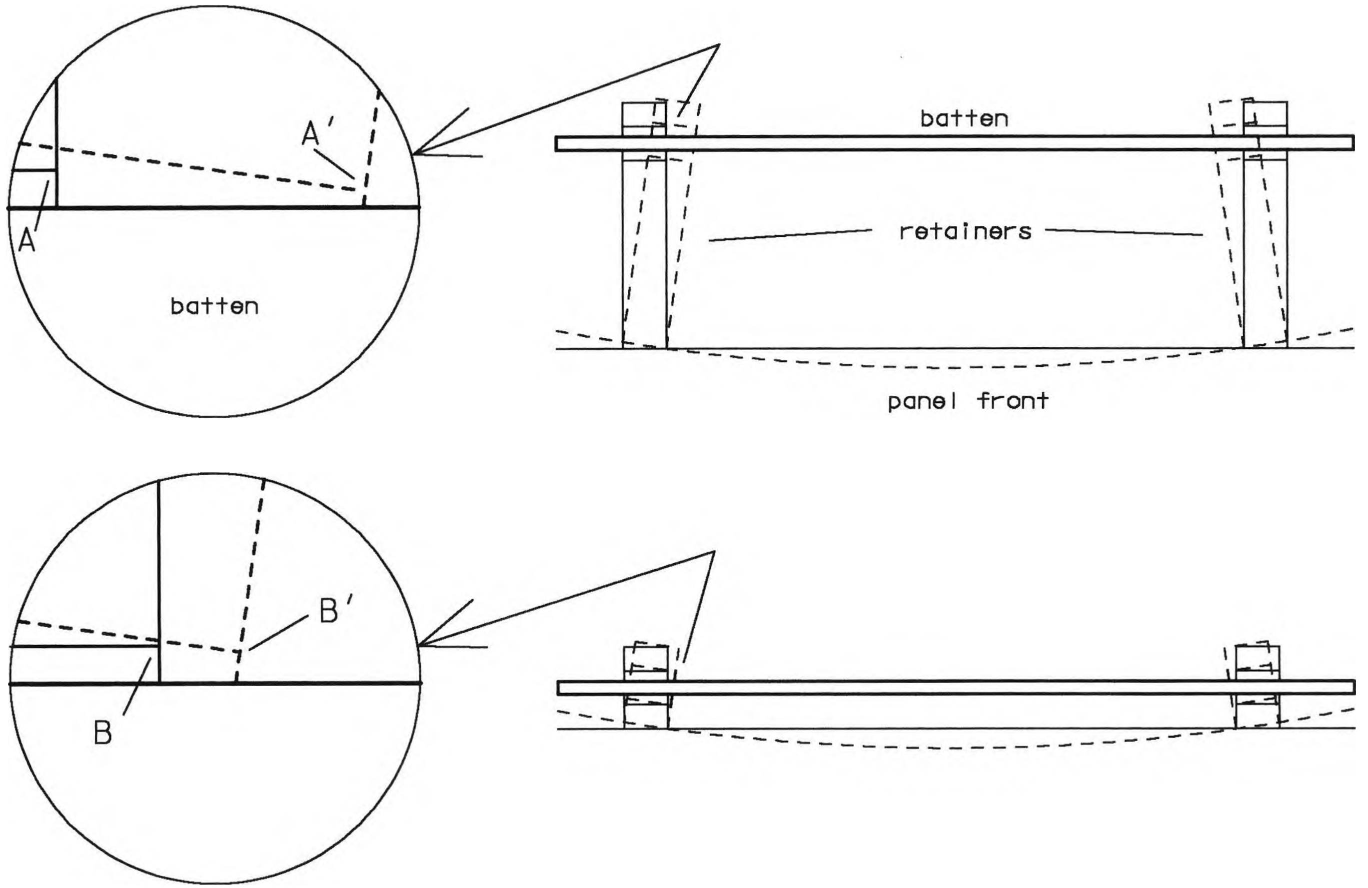

Figure 15. The effect of moving battens away from the panel back. The panel, face down, is shown before (solid lines) and after a convex warp (dashed lines). For battens retained further from the panel back (above), the contact surface moves a greater distance down and across (from A to A', detail at left) than it would for battens retained closer to the panel back (below and in detail, from B to B'). Thus battens retained further from the back will impede panel movement more easily.

work done on a variety of more recent batten and sprung lattice designs developed during the 1980's and 1990's at the Opificio delle Pietre Dure in Florence, some of which have been published in their journal *OPD Restauro* [54] and elsewhere [55]. These systems use rigid wooden battens and one of a number of different retainer designs which usually are sprung to allow for some warp.

The retainers have similarities with Carità's use of a low-friction sliding mechanism [40], but his later use of roller bearings [39] (rolling friction is considerably less than sliding friction) have not been pursued with these designs. Panel movement in-plane is generally met by slotted attachment while out-of-plane movement is provided for by some form of spring mechanism. For the latter, coil springs are usually used in conjunction with machine screws, but flat spring-steel plates have also been employed (Figure 16). Because bearings are not used, much of the research and development has been directed toward reducing friction between the batten and retainer and between the batten and panel surface, Teflon (polytetrafluoroethylene) or cheaper nylon (polyamide) elements sometimes being used.

The use of rigid battens means that the springs must accommodate out-of-plane movement. Again, the situation described in section 2.3.2 *(b)* for the Boateri panel would apply. The greatest deflection would be at the panel middle during a convex warp and at each edge during a concave warp. Warp restraint would be in proportion to the panel's deflection from the batten, greatest in the middle and diminishing to zero toward the batten ends. Thus bending stresses would be greatest toward the panel middle (Figure 2b,c). Under a convex warp, unsprung retainers would tend to contact a rigid batten only at the center, where all the restraining tension would be transferred to the panel surface at one point. The use of springs means that all retainers bear a part of the deflection tension which is transmitted to the panel at their joining surfaces. A coil-spring at the panel middle would have to undergo the

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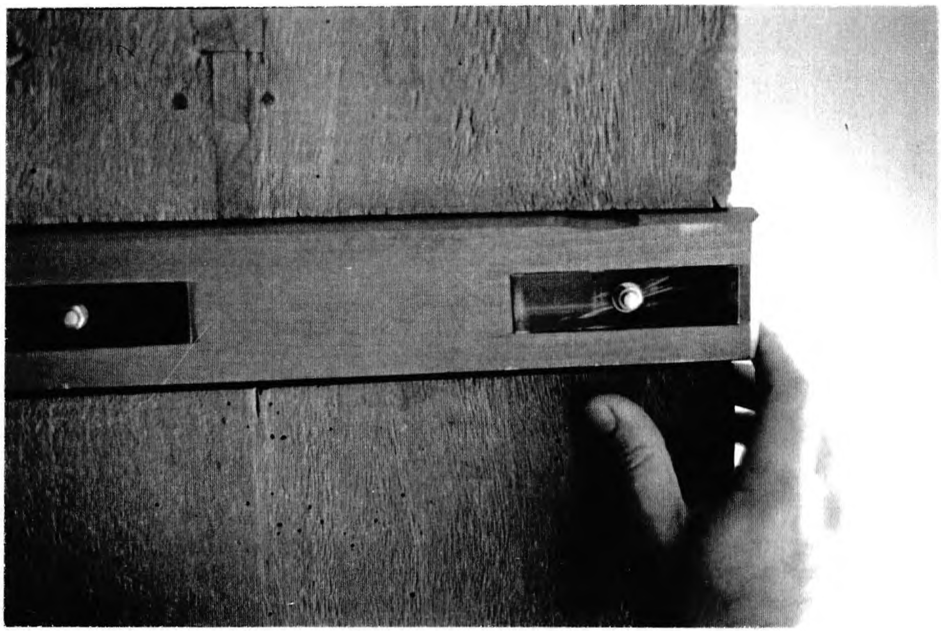

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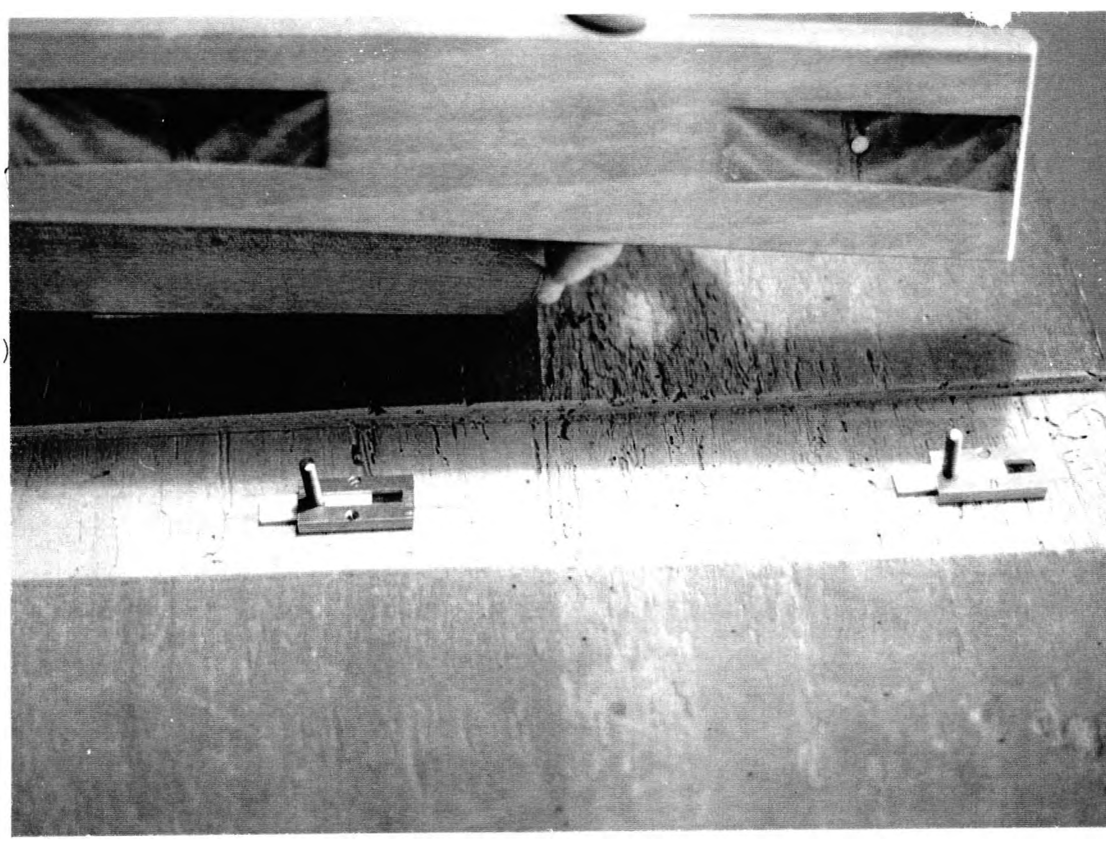


Figure 16. A rigid sliding batten with retainers sprung to allow for warp movement: a) batten with flat spring-steel rectangles in place and bolted into groove in panel back, b) batten removed, showing outer face with depressions for springs, brass retainers screwed to panel, and sliding mechanisms consisting of bolts trapped in low-friction plastic strips.

greatest extension and would transfer the tension of restraint to the panel at the central point of attachment.

One conservator [56] had adapted furniture drawer runners consisting of ball-bearings in metal cages, running as independent units between inner and outer U-section metal channels (Figure 17). An outer channel was embedded in a wooden batten and fixed with screws. Short lengths of inner channel were screwed in line and at intervals across the panel back. A ball-bearing cage was then fitted to each small section as the batten was slid in place. The cages were prevented from sliding free by stops screwed to each end of the short channels. This system was mechanically similar to other low-friction sliding battens with roller bearings (above). The conservator, who had engineering training, believed that only in-plane movement, not warp, need be accommodated by reinforcement, and that minimum friction was most important.

Figure 17. A rigid batten sliding on ball-bearing runners: the batten with outer track and ball-bearing cages is shown at the top, with below, sections of inner track which would be screwed to the panel back.

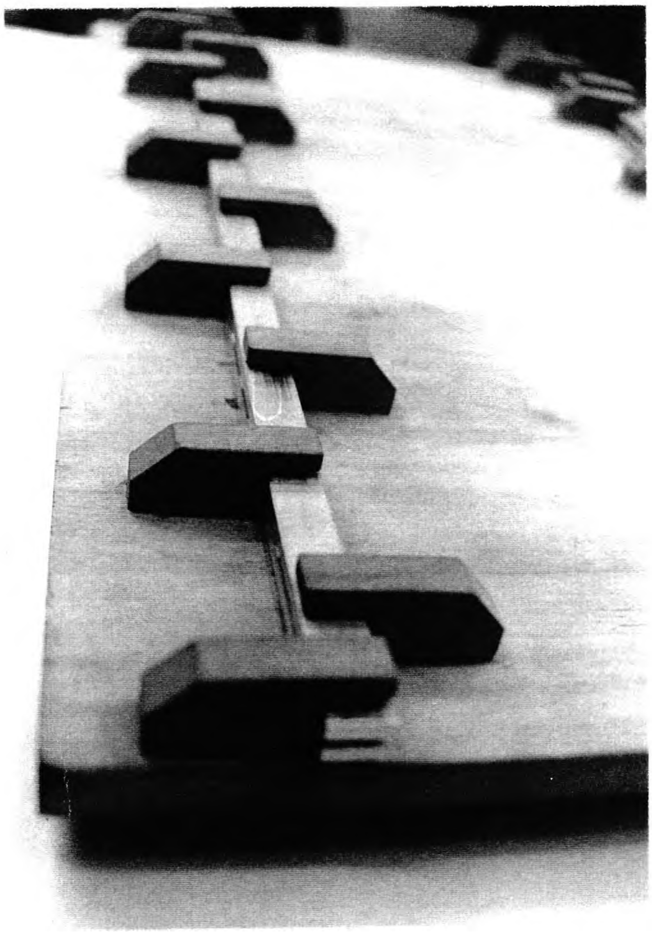
The author was shown batten systems developed at the Vatican Museum conservation studios [57]. The author was unable to locate any publications of these designs, so one type is shown in Figure 18. These consisted of flexible metal battens of small section relative to the panel thickness sliding through low-friction retainers with teflon contact surfaces. Rather than doubling the thickness of the battens for stronger panels, they were simply layered double with teflon spacers between them. The retainers were not sprung. Warp movement was accommodated by elastic bending of the relatively flexible battens. Batten flexibility is apparently judged empirically according to the apparent strength of the panel.

Giovanni Marussich, who has worked in Florence at the Opificio delle Pietre Dure and at the studios of the Palazzo Pitti [58], has applied a consistent batten design (Figure 19) to panels in the United States as well, notably at the J. Paul Getty Museum in California and at the Boston Museum of Fine Arts [59]. Again, the design is based on the later Italian style of original batten described above (section 2.3.2 (b)) which bear on the panel back and are intended to slide between retainers attached to it. Like the Vatican design (above), the panel's strength is judged empirically and the battens made relatively flexible by adjusting their section, both width and thickness.

The author examined an early-to-mid-16th c. painting on paper marouflaged to an oak panel with battens very similar to Marussich' style [51] and also similar to the Italian cradle (Figure 10) which Schießl [4] attributed to Secco-Suardo. The panel was in good condition.

Individual efforts have contributed much to reinforcement development. Working independently, and sometimes somewhat original and advanced in their thinking, certain individuals have designed and built reinforcements which share characteristics of later designs developed elsewhere. For example, at the Statens Museum for Kunst in Copenhagen,

a)



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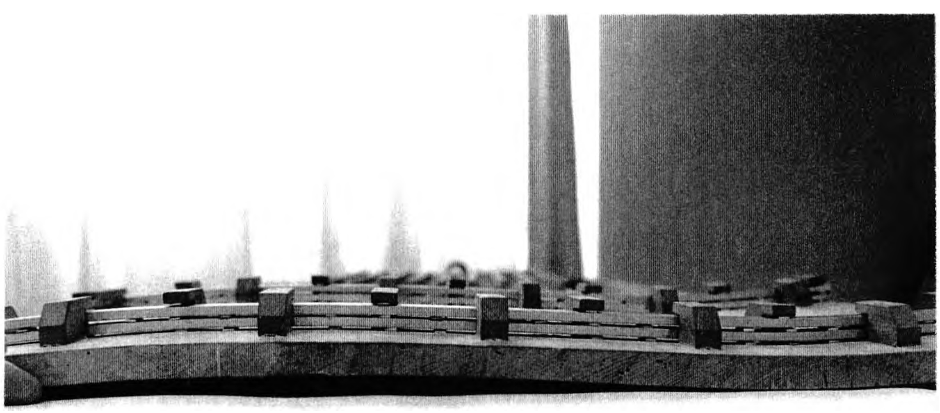


Figure 18. A model showing sliding flexible metal battens: a) viewed from the batten ends and b) from a transverse-grain edge showing the two layers of batten bent to conform to the panel curvature.

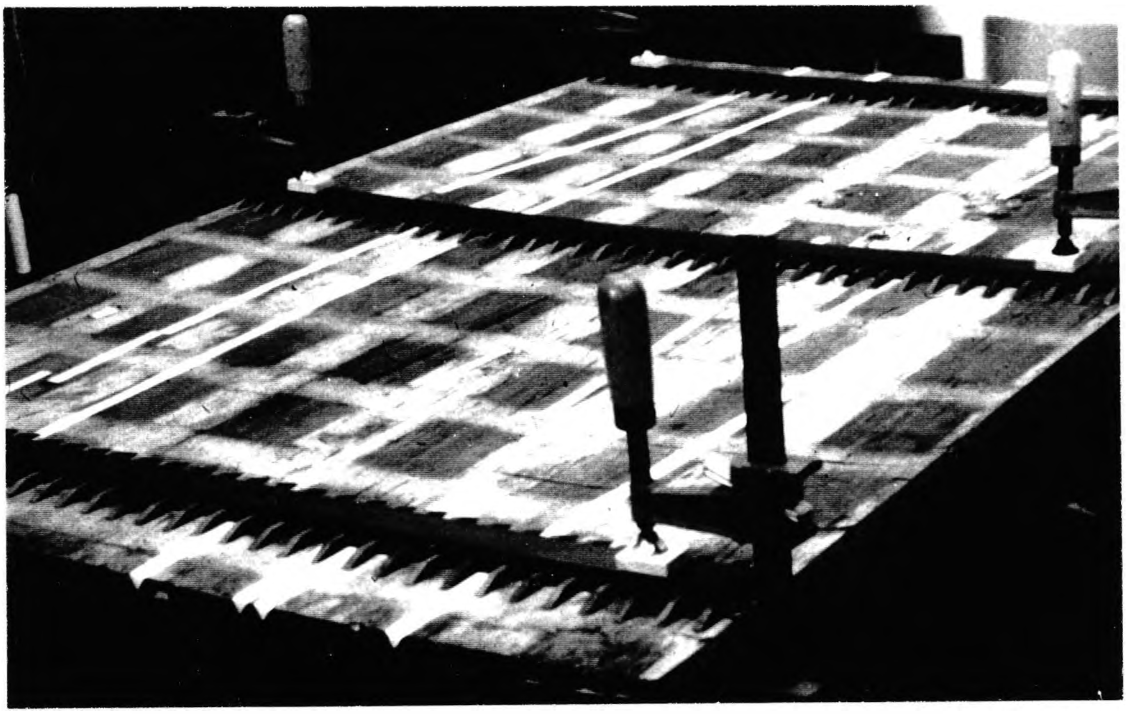
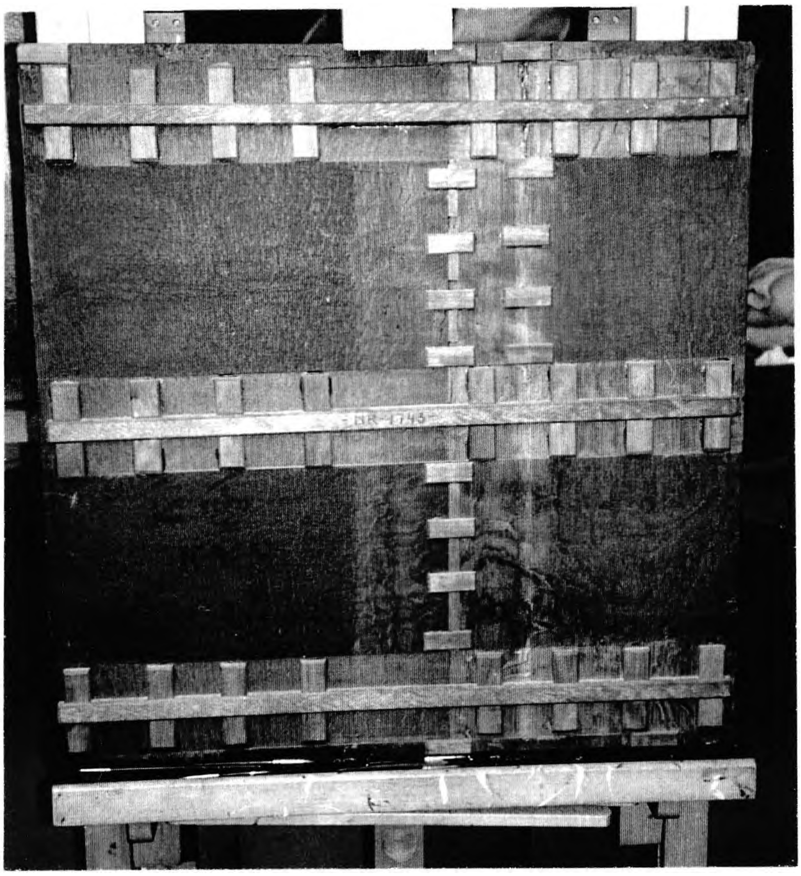


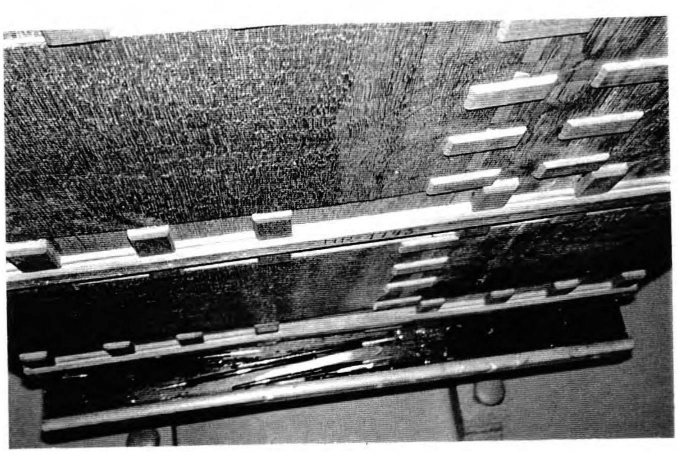
Figure 19. Flexible wooden sliding battens. (Photo courtesy The J. Paul Getty Museum, Malibu, U.S.A.)

the author examined a flexible batten design dating from the 1940's [47] and applied to a 17th c. oak panel (Figure 20). The design originated with a carpenter employed at that time by the museum who had "had his own opinions". The battens were grooved on each edge (Figure 20b,c), but the grooves did not continue across the middle third of the batten's length (Figure 20b). Wooden retainers were glued to the panel with tongues engaged with the groove. The discontinuous grooves served to stop the batten from sliding out. The reinforcement was obviously carefully considered.

Von Reventlow [49] used his idea of a perimeter frame with "cable suspension" (see section 3.5.3), as it will be called in this thesis, for independent battens which he felt conformed better to local distortions and especially panel twist than would the rigid perimeter frame. Each batten was made from a hollow-section aluminium bar to either side of which was stretched a wire cable with adjustable tensioners. The wires and tensioners were borne by specially machined wooden or metal bosses attached to each end of the bar. Like the frame, the panel slides on



a)



b) c)

Figure 20. Flexible wooden sliding battens on a panel in Copenhagen: a) panel back, b) view from above showing grooves which stop near panel middle, c) batten viewed from one end.

retainers glued to the panel back. To the author's knowledge, these designs have not been published.

In one panel treated by the author, non-original sliding battens were made more flexible by making transverse-grain cuts part way through their thickness and at closely spaced intervals (called kerfing or kerf-cutting) on the side next to the panel back. The battens, too rigid and too tightly fitted, had seized and caused splits and disjoins.

The batten material partly determines the batten's mechanical properties. Most original rigid battens are local woods, either relatively dense types such as oak or sweet chestnut, or larger sections of less dense woods such as pine or poplar. Metal or wood have been used in most non-original battens. Exotic hardwoods have been used for appearance, durability, and workability (such as mahoganies (*Swietenia macrophylla* King and *Kaya* spp.) and utile (*Entandrophragma utile* (Dawe & Sprague) Sprague)), notably in French designs. An Italian conservator has used mansonia (*Mansonia altissima* A. Chév.), probably for its fine, straight grain, a structure which also gives it consistent mechanical and working properties and pleasing appearance.

(c) Cradles

The cradle (Figure 21) was apparently first developed in 18th c. France by Hacquin [60] and has flourished under a craft-based approach. The noun "parquetting" is found in 19th c. English references to panel treatments, meaning cradle or cradling in this context. It is from the french "parquetage", still used specifically to denote cradle application, and derived from the general term for the act of applying planks or pieces of wood to a surface. The cradle consists of a lattice of more or less evenly spaced fixed members, glued parallel to each other and to the panel grain, in which channels are cut next to the panel to allow a regularly-spaced set of transverse sliding members to pass. (Laurie [61, p. 60] gives an admirably frugal description: "Strips of wood, slotted out at intervals, are glued on the back the way of the fibre, and cross-pieces are slipped into the slots.") Sometimes the channels were not cut through to the outside (perimeter) edge of the outer two fixed members to prevent the sliding members falling out. This has generally been called a "blind" or "closed" cradle in English-speaking countries.

Of 160 surveyed panels with non-original reinforcements, 108 were cradled. It has been the most popular non-original reinforcement used on panel paintings.

Two basic styles have been described: the "low" cradle (*parquetage á plat*) and the "high" cradle (*parquetage du champ*), which Schießl [4] says was introduced in the 1930's. Members of the former had their largest faces parallel to the panel plane and usually covered a larger proportion of the back. Members of the latter were turned with the edges parallel to the panel plane, presenting a smaller area of contact. This was done to decrease the glued surface area of fixed members, particularly across the panel grain, and to decrease friction of the sliding members, which were also comparatively more rigid stood on their edges. Spacing of the members was not reduced so the high cradle usually covered a smaller proportion of the panel surface. Cradles surveyed ranged between the two styles, which are illustrated together in Straub [35, p. 155].

Cradle application typically involved surfacing the back flat or, more often, thinning the panel to allow for easier flattening. For example, Keyselitz [62, p. 75], discussing a modified 19th c. cradle design from Vienna, says that thinning to 5mm was typical for panels as large as 1500X3000mm wide. Kühn [63, p. 7] emphasised the cradle's flattening function: "For any type of cradling to be effective [at flattening], the thickness of the panel must be considerably reduced." The survey done in this thesis showed that of 26 thinned and reinforced panels surveyed, with transverse-grain dimensions 165-1210mm and mean 570+/-280mm, thickness was from 2-5mm and mean 4+/-1mm.

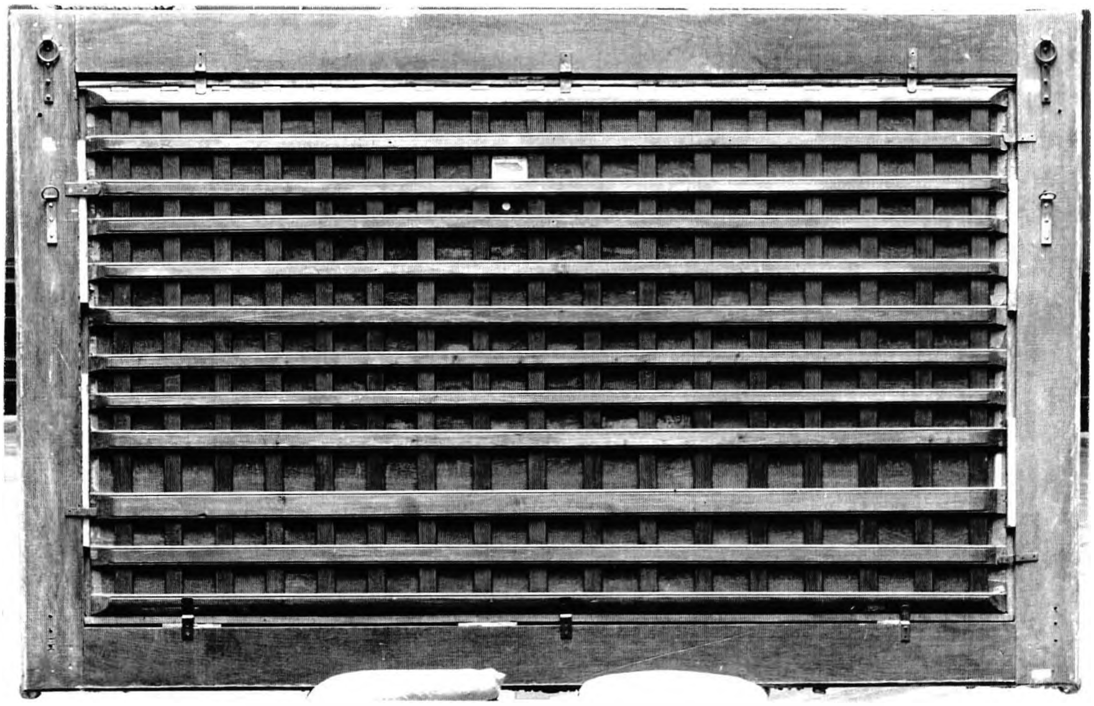


Figure 21. A cradle on a relatively large oak panel (Peter Paul Rubens, "The Village Celebration" or "La Kermesse", 1490X2610X7mm estimated thickness, Louvre INV.1797.) Photo Laboratoire de Recherche des Musées de France (1980).

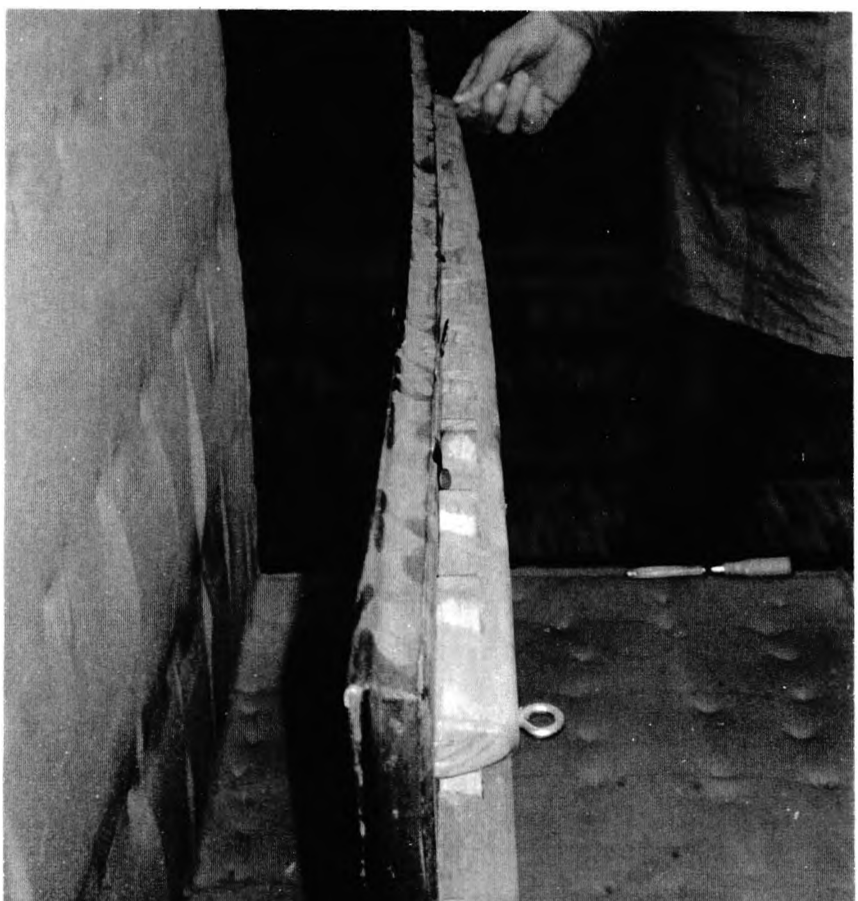


Figure 22. Panel deformation due to a cradle: out-of-plane bend parallel to the panel longitudinal-grain direction, viewed from above a longitudinal-grain edge.

Flattening was usually encouraged by other means than thinning, often by applying moisture to the panel back to swell and flexibilise it further prior to gluing of the cradle. Many cradled panels were undoubtedly then dried under pressure using weight, clamps, or a veneer press. These practices have permanently altered and damaged many panels.

Detrimental effects, familiar to most painting conservators, have been cited in many publications, such as [64, p. 239], and treatment records. These are usually either a local regular pattern of out-of-plane deformations (called "washboarding") and sometimes flaking paint directly related to the lattice structure of the cradle, or splits which are usually associated with seizure of the sliding battens (cradle is said to be "locked" or "jammed"). Seizure can often be traced to one or more causes: excess glue squeezed from beneath the fixed battens during cradle application to fix the sliding battens; warp may have caused sufficent contact and friction between panel and sliding battens to impede panel movement, similar to sliding batten problems cited above; too tight fit of the battens in their channels due to faulty construction. Tolerances of batten channels may also have diminished if the panel was moved to a different RH from where it was assembled. Many cradled panels also show overall concave warps across and/or with the panel grain (Figure 22).

Conversely, some cradled panels have shown little or no visible damage, which is confusing in light of the problems just cited. Some have been applied to panels that would have remained flat and sound without them. Also, there is probably a historical precedent which has fostered ambivalent assessment and added to confusion. That is, cradle damages may have become more apparent as cradled panels were subjected to environments that were different or less stable than when the cradles were applied, such as the extremes which accompanied the onset of central heating [22]. Such confusion, the fact that few easily-applied alternative overall reinforcements were available for drastically thinned panels until development of balsa laminates (below), and fear of creating an even more precarious problem have made many conservators reluctant to interfere with cradled panels. Usually constructed by skilled woodworkers, cradles have also been popular with clients who, from the author's experience, place high value on appearance while having a limited understanding of correct function for preservation.

The cradle's continued acceptance has therefore been for several reasons: many panels did not appear to have suffered damage; cradles certainly flatten and reinforce effectively at first; they give the panel back a pleasing appearance; there were few proposed alternatives. To understand the long-term deterioration of many cradled panels the author tryed to look beyond immediate appearances.

Many panels were cradled routinely and usually thinned in the process during the 19th and 20th century. For example, many of the panels in the Kunsthistoriches, Vienna, were cradled between 1820 and 1835 [4, 62] and many damages have been associated with this "cradling legacy". The author noted several displayed panels with substantial "washboarded" surfaces. In the United States in 1947 Pease [65, p. 120] noted that "it was recently announced that all the panel paintings in a museum collection of national importance had been newly cradled". In England, many cradles applied to panels during the 19th and 20th centuries can still be found with the stamp "Morrill" impressed in the cradle wood, usually on the outer side of the sliding battens. William Morrill and Sons cradled many panels for the National Gallery [66, p. 32].

Cradling is still done, mainly in private studios, partly because dealers like the appearance [31]. At a recent conference in England, this assertion was supported by a treatment which promoted flattening under vacuum pressure restrained by a combined laminate of balsa, a veneer of the same wood as the panel, and a cradle backing, then edge-strips of the same wood in the same grain direction as the panel. Together, these components constitute a rigid laminate [66]. The treatment was directed at flattening while preserving the illusion of a relatively thick (unaltered) original panel. The cradle appeared functionally unnecessary, but its presence symbolised an aesthetic which clients have come to expect and which has promoted the cradle's continued use.

Several museum professionals have expressed doubts about cradle effects. For example, in 1888, William Morrill, a craftsman with considerable experience in treating panels, expressed his reluctance to thin and cradle (parquet) a painting to the Keeper of the National Gallery in London:

"...The panel itself is very much out of shape or uneven on the surface. I mean, to alter which, It would require to be planed down and parquetted but I think we might do without parquetting this time unless you require the surface to be more level than it is at present." [67]

Put in such a way, Morrill's council shows that he was working to satisfy a policy of flattening which depended mainly on thinning and cradling. Then-director of the National Gallery Sir Charles Eastlake also had his reservations:

"Panels on which fine pictures have been executed are often injured by the misapplication of parquetting." [68, p. 415]

In his foreword to Helmut Ruhemann's important book on restoration [69, p. 21], Sir Philip Hendy, then Director of the National Gallery, describes the general state of restoration practice in England 40 years before the book's publication in 1965. He refers to the deleterious effects of treating painting supports, relating the practice of attaching cradles to panels ("...panels submitted to the restraint of wooden 'cradles'...") to subsequent 'blistering' (flaking) of the paint layers. This allusion in a short foreword by an eminent art historian and curator shows awareness of the deleterious effects of cradles at a high administrative level.

However, returning to Eastlake, he also condoned cradles as a "success":

"Another mode which has been adopted with success for picture panels (which are sometimes too thin to admit of sinking grooves in them with safety) is to glue battens...[goes on to describe cradle]" [68, p. 416]

Eastlake made several appropriate remarks on damage prevention however. Referring to potential glue misapplication and construction errors, he noted slightly dryly that sliding members were to be

"...not only not glued, but not even tightly fitted."

Several generations of museum professionals, private restorers, artists and collectors have also condoned cradles. A catalogue excerpt from 19th and early 20th century accounts of Charles Roberson and Co., artists' supplier, reads:

"Pictures carefully lined, cleaned, repaired, and varnished, panels parqueted" [70, p. 67]

In 1931, Papari [71, p. 11], a curator of paintings, noted:

"Lorsque les panneaux sont trop détériorés ou trop courbés, il est indiqué de les consolider au moyen d'un parquetage..." ["When panels are too deteriorated or too warped, it is appropriate to consolidate them by means of a cradle..."]

Also in 1931, a German restorer at the Kunsthalle in Hamburg, Victor Bauer-Bolton, discussed cradle effects at some length. A brief excerpt (from the French translation of the original German text) makes passing reference to possible causes:

"Dans l'ignorance évidente de la matière, on renforce notablement, par le parquetage, la pression latérale si extraordinairement dangereuse, qui s'exerce sur la couche picturale à la suite de rétrécissement du panneau." [In an evident misunderstanding of the material [of the object], one reinforces so strongly by cradling that an extremely dangerous lateral pressure is applied to the paint layers following contraction of the panel.] [72]

He went on to describe how, because of these pressures, cradled panels sooner or later develop blistered areas of paint ("...les fameuses cloques et boursouflures..."). To replace the cradle, he recommended thinning of the original and laminating to plywood, which he felt was a very stable reinforcement.

A manual for the conservation of paintings from 1939 notes:

"Le parquetage est une opération qui a été longtemps considérée comme le seul remède efficace contre les déformations des panneau de bois et même contre des détériorations d'autre nature auxquelles ces tableaux sont exposés." [Cradling is an operation that has been long considered the only effective remedy against panel deformations and even against other deteriorations to which such paintings have been exposed.] [64, p. 241]

Before museum environmental conditions were improved, cradle problems blossomed anew in American collections, where panels were imported from Europe and often placed in drier centrally-heated interiors.

In 1941, David Rosen summarised and evaluated the effects of the procedures available to the "old-time restorer... which tradition and hitherto accepted practice indicated" [73, p. 125]. He explicitly stated as a basic principle of restoration "the *preservation intact* [his italics] of as much of the original work as possible" [73, p. 125], a principle which has since gained greater emphasis. He stated that cradles "...are the cause of such major problems as to render their use highly debatable." [73, p. 126]. He then urged "...that badly warped pictures which are otherwise sound be left as they are...", and later, "...if the paint film is sound, nothing should be attempted" [73, p. 127]. This is apparently one of the earliest published statements of acceptance of warp in panels. He then goes on to suggest several reinforcement techniques for panels which have been weakened by thinning or damaged by cradling, such as wax-resin impregnation with heat and various laminates then being developed in the eastern United States by Murray Pease and others.

In 1948, Pease discussed new laminates further and commented that cradles did not "provide for [the] progressive warping [and] movement due to atmospheric changes" of panels [65, p. 119]. "The cradle design... opposes by fixed rigidity the inherent tendency of the panel to assume what would be a simple, relatively harmless overall warp". He cited Rosen's article, above, and referring to restoration practice, associated cradling with "a business which is but slowly emerging from the cupping and bloodletting stage of its development". Underlying the text is an apparent wish to overcome cradling deficiencies by new methods. New laminating techniques developed at the Fogg Museum at Harvard were then briefly described. Notably, these involved the initial flattening of the panel with moisture.

In reporting the treatment of cradled and damaged panels in 1947, Packard and Kirby [74] echoed Rosen's negative assessment of cradles. Similarly, they attributed damages to "stresses and strains produced by the contraction and expansion of the stationary members" (called fixed members in this thesis), citing the location of damages as evidence.

It is appropriate here to introduce the work of Richard Buck, who contributed much to the understanding of painted panel and reinforcment effects. Kolch [44] described in detail Buck's involvement with the development of laminate techniques at the Fogg Art Museum in America, notably the balsa and wax-resin laminate which became associated with his name and which was developed over several years as an alternative to the cradle. Buck concentrated his efforts on understanding wood and painted panel behaviour in terms of mechanics [19], particularly with respect to viscoelastic properties [75], whose fundamental importance he introduced to conservators.

In 1962, Buck devoted an article to cradles [13], arguing for their replacement with another type of reinforcement. There, he cited Kozlowski's contemporary cradle design modification [76] as a significant advance. Specifically, he approved of Kozlowski's method of overcoming permanent panel warp by building up the panel back with spacers beneath the fixed cradle members, which avoided thinning and flattening during application while maintaining the cradle's flat structure. In Buck's assessment, this was important because by accepting existing warp and not thinning, the panel's "maximum volume-to-surface ratio" is maintained. In other words, he understood the importance of not thinning panels and was beginning to accept permanent warp.

Kozlowski, though obviously condoning cradles, at least those based on his modifications, makes some comments of interest here. "In the case of very lively panels, warp should not be entirely constrained, and the thickness of the cross-members [that is, the sliding members] should be judged accordingly in the light of experience." [76, p. 64] He acknowledges the possibility of thinning battens for greater flexibility to allow the panel to undergo temporary warp. With regard to flattening warped panels with water prior to cradling, he says that "it is sometimes seen to increase warping after drying."

Buck's most detailed theoretical assessment of cradle effects was given at the IIC Rome Conference in 1961 [19]. There he placed all reinforcements into one of three classes, those providing no control (that is, no reinforcement), fixed control (for example, fixed rigid battens or laminates), and free control.

Classing the cradle as a "free control" device, where transverse-grain movement is allowed by the sliding members, Buck describes the neutral axis through a panel section around which compressive and tensile stresses develop from warp restraint. He identifies at least one probable underlying cause of cradle damages: "With the free control device the normal shrinkage [that is, contraction from in-plane movement] is not inhibited; but the increase in warp is restrained and translated into amplified compressive strains on the front sides, amplified tension on the back." This produces "compression at the front ... that causes dangerous shear on the paint layers" and on the back surface, "tension stresses..., causing checks and splits."

Then he summarises the situation,

"But wood is also subject to plastic deformation... Therefore the stresses on the paint of a warped panel controlled by a free or movable mechanical device are equal to the sum of the normal stresses found in relaxed panels, plus the stress from elastic strain, plus the stress from plastic strain. The last two factors vary with the amount of restraining force applied." [19, p. 160]

Buck criticised the ambiguity of treatments in which "first attention [is] given to reduction of warp." Then, reminiscent of Rosen's views, he wrote,

"There is evidence that a wood panel and its associated paint have not consistently been regarded as parts of a single mechanical system in which each component presents problems that must be solved with reference to the other. Finally, we must admit that our knowledge of the mechanical behaviour of painted panels is still elementary."

In Germany, a review of wood and panel behaviour by Rolf Straub [35] appeared shortly after Buck's 1963 publication. Schießl [4] cites it as an important indictment of cradling. It represents the last important published examination of cradle effects. Straub discussed the latest research, including Buck's work. He looked at current reinforcements and also discussed cradles, some of whose effects are illustrated with excellent photographs. A diagram [35, p. 163] shows convex planar deformations of the exposed area between fixed cradle members which are explained by localised swelling at the back.

Thereafter, no further contributions to Buck's advances in understanding panel mechanics appear and comments on cradles become brief and often repetitive.

In 1973, counsel from a prominent American authority on artist's methods and materials strongly condoned cradling:

"When the wood of a panel picture splits, warps, or is in danger of ...disintegration, it is made sound and permanently conserved by cradling..." [77, p. 522]

Though the book has been published in several editions and has justifiably been a reference on artist's techniques and materials, such brief, unsubstantiated declarations are misleading.

Kühn's book on conservation, 1986, says that though "the basic idea behind the constructions used to restrain panels is to avoid restricting [in-plane movement] but to restrict warping, attempts to restrain panel paintings that have a tendency to warp are likely to cause the wood to crack" [63, p. 6]. There is no mention of a reinforcing role. Moistening the back is only temporarily effective until the moisture leaves. He agrees with Kozlowski, saying that moistening is likely to increase warp [63, p. 7]. Sliding battens of any sort will seize with "the slightest sign of warping". He asserts that "thousands of paintings must have been cradled since the 18th century". He also notes that oak panels are more likely to crack from cradle restraint than "the more easily deformed poplar", a rare reference to the role of wood type in panel preservation.

Verougstraete-Marc and Van Schoute [78, p. 26], who have documented the structure of many northern European panels, gave a brief, negative assessment of cradles, attributing damages to rigidity and nothing else,

"Due to its excessive rigidity, this method has caused innumerable amount of damage to old supports."

Stiffness or restraint is probably what is meant by the term rigidity.

In treatment records consulted by the author, most cradled panels had damages which were or could be attributed to cradling. A few examples were: John Crome, *A Windmill Near Norwich (1816)*, TG.NO0926 (splits, one of which included the central fixed cradle member); John Linnell, *Mrs Ann Hawkins*, TG.NO1112 (tented and flaking paint attributed to compression toward the panel middle); Hans Baldung, *A Senator* NG.245 (splits); Bartolomeo Vivarini, *The Virgin and Child With Saints Paul and Jerome*, NG.284 (splits, concave warp, paint flaking); Girolamo da Treviso (the Younger), *Madonna and Child Enthroned*, NG.623 (splits); Giulio Romano *The Infancy of Jupiter*, NG.624 (splits, flaking paint); Florentine School, *Portrait of a Boy*, NG.649 (splits, deformations); Bernardino Lanino, *The Holy Family*, NG.700 (splits, deformations, flaking paint); Hans Eworth, *An English Nobleman*, WC.P535 (deformations, splits); Anthony Van Dyck, *Madonna and Child*, FW.PD48-1976 (concave warp with- grain, splits, washboarding); Teniers, *The Riverside Inn*, WC.196 (split); Gerolamo Bassano, *L'Entrée des Animaux dans l'Arche/The Animals Entering the Arc*, LV.INV428 (splits); Cima da Conegliano *Vierge et l'Enfant/Virgin and Child*, LV.RF2100 (deformations, splits); Sassetta, *La Vierge et l'Enfant Entoures de Six Anges/Virgin and Child Surrounded by Six Angels*, LV.RF1956-11 (splits); Paolo Uccello *Bataille de San Romano/The Battle of San Romano*, LV.MI469 (deformations, splits, flaking paint); Mathis Gerung, *La Destruction de Troie/The Destruction of Troy*, LV.MNR940 (splits); Lucas Cranach the Elder, *Adam and Eve*, CI. Lee Collection No.0125 (splits along edges of fixed members, washboarding).

However, the author encountered a few cradles which were obviously constructed with thin sliding members, apparently to allow for warp. Lébas [79] showed a painting on oak (Figure 23) with a "low" cradle of softwood whose sliding members were thin and flexible relative to the panel's rigidity. The panel had a slight convex warp but no breaks. Another example of a panel with a thin, flexible cradle which seems to have faired well is Rubens' oil sketch of *Abraham et Melchisedeah* (LV.MI963).

A relatively large, thinned softwood panel painting by Le Sueur (*La Naissance de L'Amour/The Birth of Love*, LV.INV8050, 1820X1250X4-5mm thick) had a thin softwood cradle (Figure 24). A photograph shows splits exactly in the areas of greatest tangential character (Figure 24b) aligned with the perpendicular plane of the ray cells where the wood was weakest. The treatment record entry cites the cause as the cradle being too weak, ie. too flexible, and the spaces between members too large:

"Barres collées et traverses coulissantes trop faible et trop espacées. [Fixed battens and sliding cross-members too weak and too widely spaced.] [80]

Other similarly sized Le Sueurs had similar cradles and splits (*L'Amour Reçoit l'Hommage de Diane/Love Receiving the Homage of Diana, d'Apollon et de Mercure/Apollo and Mercury*, LV.INV8053; *Clio, Euterpe, et Thalie/Clio, Euterpê, and Thalia*, LV.INV8057), not surprising due to their high ratio of cross-grain dimension to thickness. This author's assessment, based on the treatment records and not on examination, is that the cradles had too much restraint of both in-plane and warp movement due to the sliding members being too tightly fitted. Still, the apparent flexibility of such a large cradled panel and the associated splits raise questions about handling care and the possibility of too much flexibility.

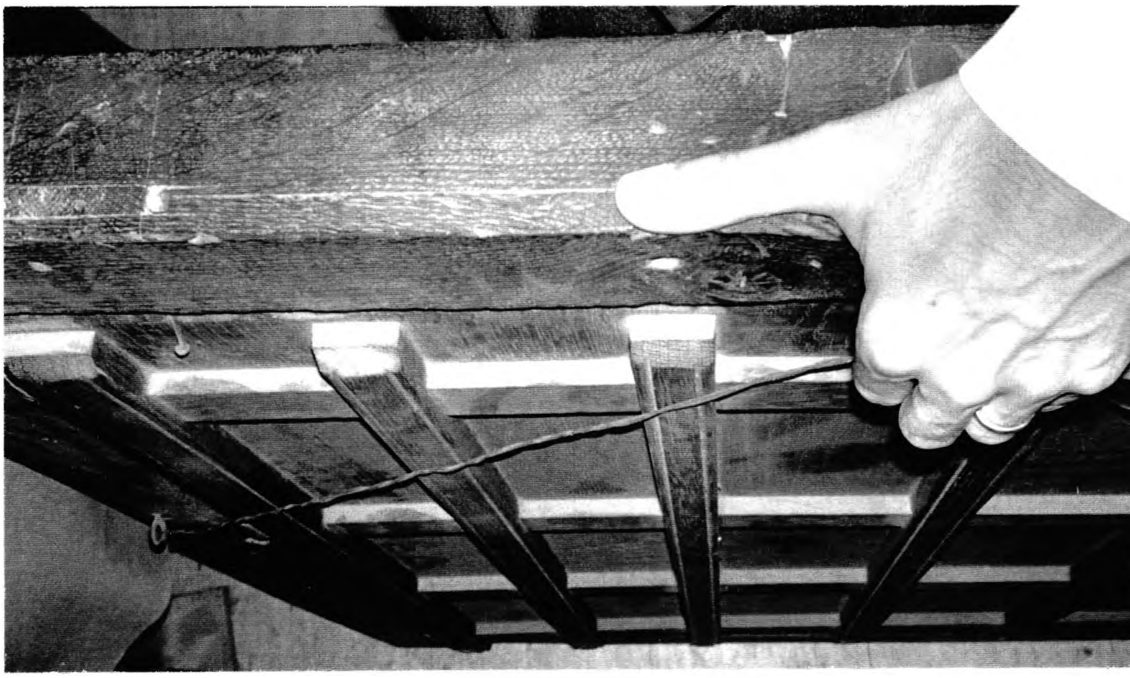


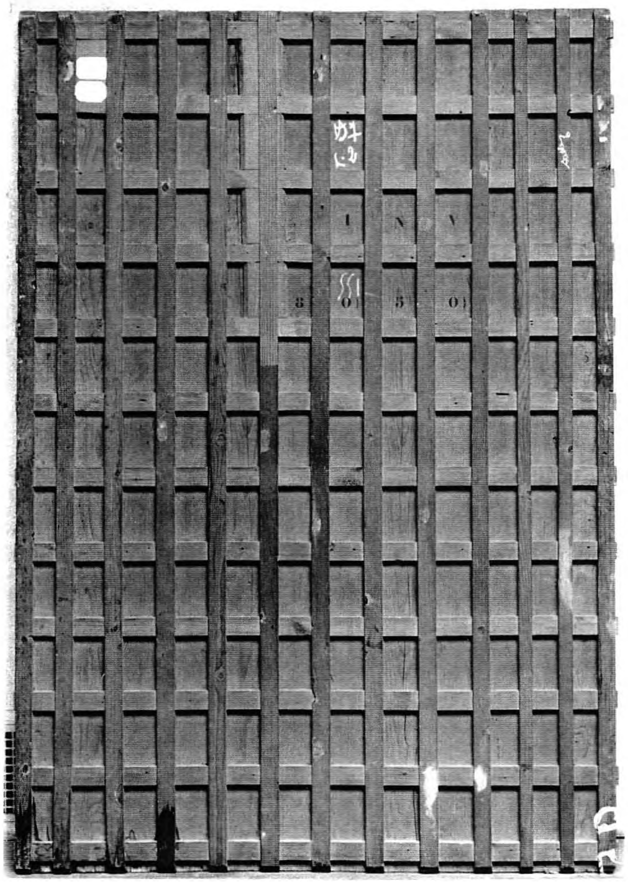
Figure 23. A cradle with flexible sliding members which have partly conformed to the panel's convex warp.

Thinning of sliding members to free panel movement has been common in treatments if the battens can be removed without panel damage. Less common is thinning them to allow for greater warp movement, as Kozlowski [76] suggested. In terms of mechanics, thinning serves the same purpose in both cases. However, the reason for thinning- the intention of the conservator- is different.

(d) Laminates

For the conservation of panels in general, laminates have not enjoyed the popularity of cradles and battening methods. Possibly this has been because of the difficulty of controlling detrimental swelling effects of water-based glues which have been used for lamination. Of 483 panels surveyed, only 20 had been laminated, 6 of which also had either battens or cradles attached to the laminate for good measure. Though this survey did not find many laminates described in treatment records, the author was informed that, at the Hamburg Kunsthalle in the 1930's, many panels were thinned to as little as 1mm and laminated to manufactured boards (plywood, etc.). Like cradling

a)



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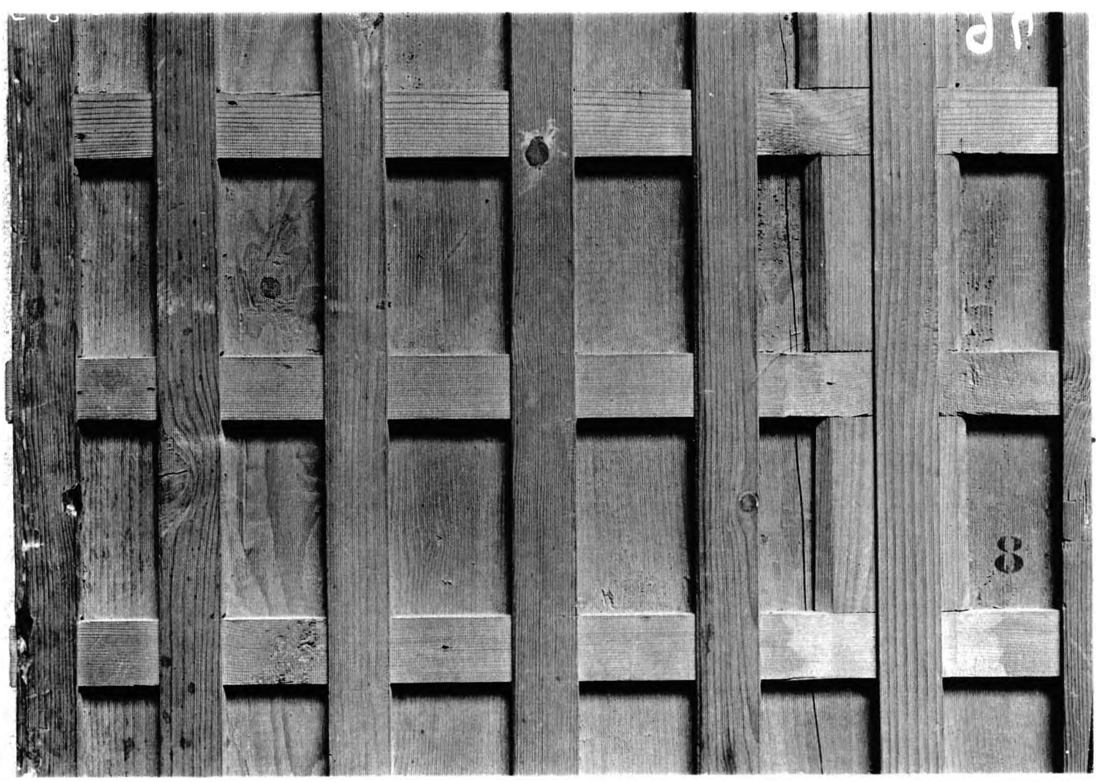


Figure 24. Splits in tangentially cut areas of a softwood panel with a relatively flexible cradle: a) one visible in panel lower half, just right of middle and b) (detail) another at upper left (Eustache Le Sueur, "La Naissance de l'Amour", 1820X1250X4mm, Louvre INV8050.) Photos Laboratoire de Recherche des Musées de France (1957).

treatments, this probably represents only one example of such a collective treatment policy.

Panel paintings have received various types of laminate to flatten and/or reinforce, usually in conjunction with thinning of the original panel (Figure 25). In Paris in 1851, Déon noted that "doublage" [lamination] was done to very thin panels [81, pp. 23, 24], while thicker panels were generally cradled. Schießl [4] noted that thinning and gluing to wood panels was also done in Germany.

At the Detroit Institute of Fine Arts in 1932, William Suhr [82] described a laminate "build-up" consisting of plywood constructed from radially-sawn veneers. Rather than wax-resin, the panel was thinned to the extreme ("until quite limp and smooth") and joined with animal glue to the plywood and a back veneer in a veneer press over 24 hours. He noted that Helmut Ruhemann (later head of conservation at the National Gallery, London) had tested and followed-up the method on other similarly treated panels in Berlin. The nature of Ruhemann's test(s) was not discussed.

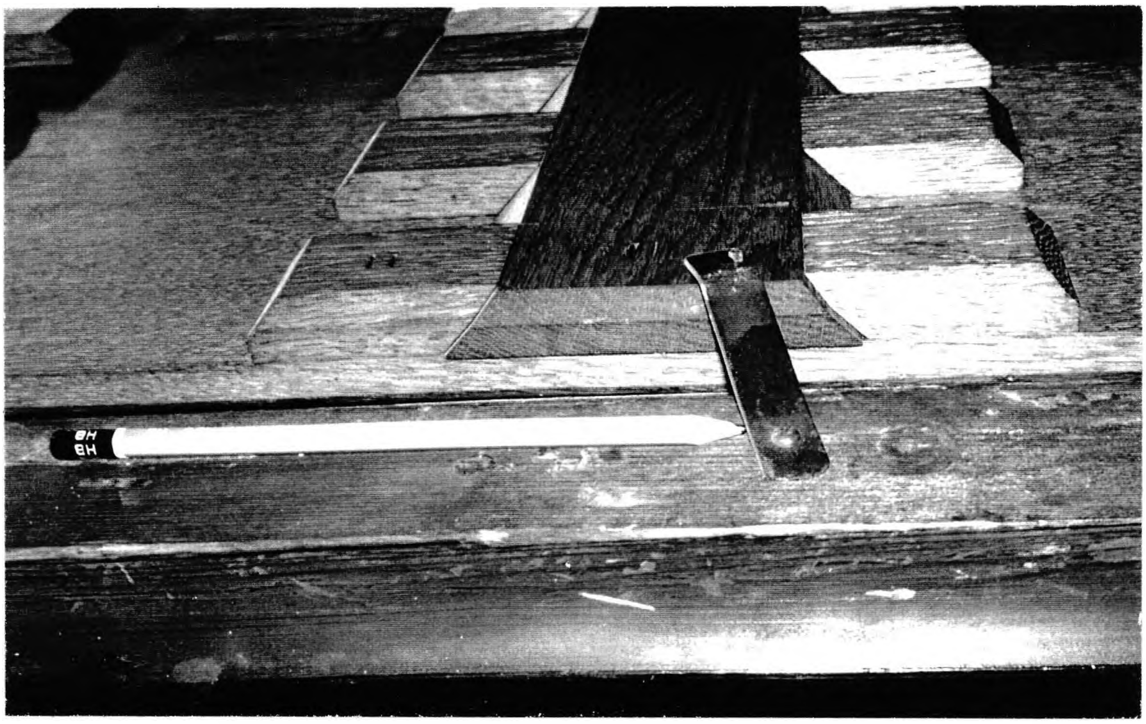


Figure 25. A laminated panel. The panel has been thinned to about 1mm (darker layer above pencil), laminated to thicker oak planks, then reinforced further with relatively rigid sliding oak battens.

About 10 years later, Packard and Kirby [74] condemned thinning and cradling and applied a similar laminate to two pine panels which had been thinned previously to about 1/8 inch (3mm), laminated to pine, and cradled. The paper suggests that differences in movement between the previous pine laminate and panel caused problems which would be overcome by using a more stable plywood laminate. Though not stated explicitly, use of a veneer press suggests an aqueous adhesive was used.

Laurie [83] suggested that to reinforce a weak panel and avoid cradling stresses, "...the best plan would be to cement on to the back a thick second panel of well-seasoned wood, using a flexible cement of beeswax and resin...We thus... avoid setting up stresses in the old panel." He recommended a relatively thick marine-type plywood as a laminate, stable to moisture and high stresses ie. rigid and relatively inert. There are at least four assumptions in this short declaration: 1) that what he prescribes is the "best plan", that 2) beeswax and resin adhesive is suitably flexible to avoid stresses between the panel painting and a "thick second panel of well-seasoned wood", whose 3) rigidity and 4) relative stability would supposedly be a benefit.

Potentially detrimental effects or damage from laminates, developed after and not during application, have not been well-documented in the conservation literature. Some of the 20 laminated panels surveyed which showed damages more or less attributable to a laminate were: Bernardo Luini, *La Vierge et l'Enfant/Virgin and Child*, LV.RF2083 (large losses undoubtedly due to the laminate); C.R. Leslie, *Inn Scene*, TG.N01794 (paint craquelure and delamination of the central area from the laminate); attributed to Van Dyck, *Sketch for a Dying Saint*, RC. Hampton Court, HKI.1204 (tented flaking and paint losses attributed to in-plane compression of the paint layers); Hieronymus Bosch, *La Nef des Fous/The Ship of Fools*, LV.RF2218 (splits and extruded putties in the splits attributed to panel movement probably accentuated by the laminate; the record states that "the cause was not the laminate, but the fact that the panel had not been sufficiently thinned [before lamination]" [84]); Studio of Rubens, *Portrait d'Anne d'Autruche/Portrait of Anne of Austria*, LV.INV 1794 (split due to or aggravated by the laminate; a thick panel with thick laminate, similar to the previous example). Some of these examples showed concave warps or twists. Twists were noted in panels laminated with another of the same wood laid with grains perpendicular (Lucas Cranach the Elder, *Portrait of a Young Lady*, NG.291) and with grains parallel (Dosso Dossi, *Ritter u. Knappe/Knight and A Page* SG.INV137). Cracks of surface veneers, flaking, and overall twists have been noted in some original plywood supports (Jessie Dismorr, *Abstract Composition 1915*, TG.T1084 (twist); Norman Garstin, *Burford*, TG.T03165 (cracks and shrinkage); L.S. Lowry, *Coming Out of School (1927)*, TG.N05912 (saddle-shaped warp, splits)).

By 1948 [44; 65, p. 121], wax-resin reconstructions were becoming accepted in some major American museums. Not by chance, the method was developed there to combat movement/warp effects from broader humidity ranges imposed on imported European panels (see Kolch [44, p. 9], on Edward Waldo Forbes). Kolch reviewed reinforcement development and related attitudes in America through the middle 20th c.. He noted that for the type of panels treated, the "creation of permanent and stable supports" that were reversible was an urgency. The basic principle was to "discourage movement rather than to oppose it. ...The panel is thoroughly barricaded by a thick layer of non-absorbing materials against the chief cause of movement- atmospheric fluctuations." The front was not barricaded likewise.

In many cases described during these early developments, the panel was also rigidly reinforced, suggesting that some opposition to movement was indeed intended. In practice [65, p. 121], thinning and flattening with moisture, the inclusion of Californian redwood (*Sequoia sempirvirens*

(D.Don) Endl.) inserted cross-grain and hardwood with-grain, and wrapping in wax-resin impregnated linen of "high-tensile strength", leaves no doubt that any movement would be opposed. Also, wax-resin impregnation with heat was an important part of many such treatments. Later, this became less common as associated dangers of dessication, the essential irreversibility in more porous or insect-damaged woods, and the fundamental change imposed on the wood became more objectionable.

Kolch [44] attributes Bradley's manual [85] with first mention of the use of "composite panels of balsa...in wax-resin filler and paste". This became the accepted norm to which international recognition was given in the important review of panel methods in 1955 [8, pp. 161, 162) which Stout edited. Balsa and wax-resin laminates have since enjoyed greater popularity, more recently at the Institut Royal du Patrimoine Artistique (IRPA), Brussels [86], and at the Service de Restauration des Musées de France (SRMF) in France [87]. This is probably because there are few accepted recourses to reinforce extremely thin panels, most of which have resulted from previous cradling practices as noted above.

Since 1955, publications describing treatments show that balsa laminates have tended toward three basic structural types: following Buck's refined method [19, p. 162], where he abandoned heat-lamp impregnation and wrestled with accepting warp (Buck emphasised this last point 10 years later [75, p. 1]), end-grain balsa blocks cut square and applied to the panel with sides diagonal to the panel grain in one or more layers, with or without an outer adhered fabric [86]; cross-grain laminated layers of planks, usually including fabric layers [88, 89, 90]; (usually multiple) layers of balsa blocks (Figure 26) applied parallel to the panel grain with no fabric [91, 92, 93].

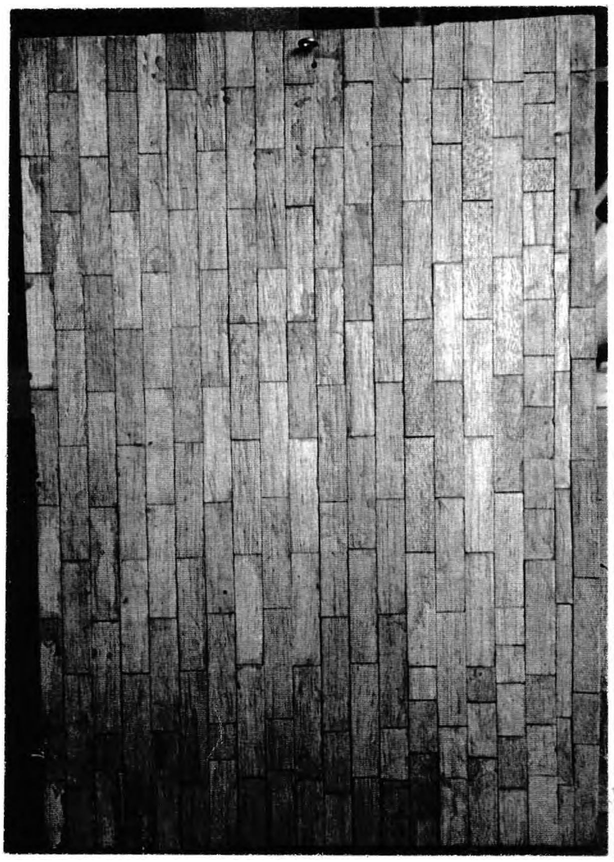
Many modifications of the balsa/wax-resin laminate have appeared, such as angling the balsa block edges to allow for greater warp movement and using carvable epoxy [94] instead of wax-resin adhesive.

Contrary to Kolch's assertion [44, p. 60], application of balsa/wax-resin is a relatively unskilled method ("...messy but not difficult to master...", as Pease wrote [65, p. 124]), compared to competent, traditional hand-crafted work (eg. cradles, or hand-fitting of V-inserts, for example.) As Wehlte remarked in relation to his battening method [33], this is a critical advantage, especially if conservators have limited woodworking skills and must rely on themselves to apply reinforcements. It partly explains the balsa/wax-resin laminate's continued popularity.

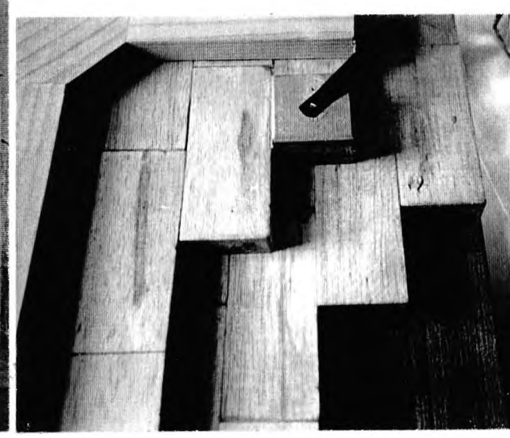
Some such laminates have developed twists and/or concave deformations immediately after being applied [95]. A surveyed example had assumed a concave deformation (N. de Gyslaer, *Interior of a Hall* FW.422, HKI.1434). Flaking paint was attributed to another (Dutch School, *Saint Peter Healing Saint Agatha*, FW.PD102, HKI.407). Some panels assumed a flatter or more convex shape after the laminate was removed [96]. Repeated paint flaking was reported after two cases (Cima da Conegliano, *Saint Lanfranc Enthroned Between Saint John the Baptist and Saint Liberius*, FW.M16, HKI.607; Piero della Francesca, *The Nativity*, NG.908).

The latter case (NG.908) was documented in some detail and deserves more attention here. The panel had suffered extensive insect damage and had been previously thinned and cradled. In 1949, Richard Buck thinned the panel again to 2-3mm thickness, impregnated it with a wax-resin mixture "...heated to c. 150F...", and then laminated it with balsa reinforced further with aluminium T-section and tubular section bars and an outer heavy linen fabric. Damage was noted immediately where paint detached at splits and joints.

"The reason for this behaviour is not clear, but it would appear to have some relation to either the flexing of the structure during the treatment, or to the drying, and



a)



b)

c)

Figure 26. Balsa-block laminates: a) view of the back of a laminated panel, b) a model showing a two-layered structure with loose backing-frame, c) a balsa laminate which has detached from an area of permanent panel warp.

consequent warping, of the wood while it was heated for the wax manipulation." [97]

Extreme thinning of wood and use of heat in treatments was criticised in later examinations of the panel.

Discussion of laminate treatments with conservators elicited various opinions. One conservator was considering a plywood laminate for a very thin panel [59]. Another [49] felt that it was not good if balsa laminates were intentionally made to delaminate under stress. He felt that this held similar dangers to partial delamination of battens glued across the panel grain. In such cases, the panel generally assumes a different curvature in the delaminated area than in the surrounding area. It is thus forced into a greater bend at the border of the delaminated area where there is an inflection. The stresses of delamination are concentrated there, much as at the tip of a developing crack [98].

Interestingly, it has been suggested that the tendency to delaminate is an advantage [99]. This belief has probably been derived from the notion that, if failure is to occur, it is better for it not to occur in the original. The question remains if such delamination does not increase the chance of failure in the panel where the stresses are concentrated, in which case it may be better that the laminate remain adhered overall.

The author examined a balsa laminate similar to the first type described above which had been flattened with moisture beforehand. Delamination showed along the endgrain edge of a more tangentially-cut plank which had assumed a convex warp (Figure 26c).

The author was shown a 20-year old balsa laminate of the third type described above (Figure 26a) [93], which had been applied to an oak panel that had been flattened first with moisture. Delamination was occurring in the area where the panel had had the greatest permanent warp before it was flattened. The conservator said that application of balsa laminates had been stopped because of concern about heat effects.

The author was shown three thinned softwood panels that had been balsa laminated 15 years previously according to the third method above [31]. They had been first flattened and impregnated with an ethylene glycol, alcohol, shellac solution, known as the "Munich method" [4]. Stored under relatively constant RH, one had subsequently partially delaminated, one had warped on one side, and the third had remained relatively flat.

(e) Lattices and Perimeter Frames

A lattice results when a set of parallel members are joined to a set of perpendicular members. Whether and how the members are joined at their junctures would determine some structural characteristics. Lattices fixed to the panel, where the joints are usually half-lapped and may be glued or screwed to each other (Figure 27a), are rarely found because most woodworkers realise they are dangerously restrictive, even more so than battens fixed across the panel grain. This is probably because they impose restraint in all three dimensions. The damages discussed and illustrated in [12, 100], concerning Palmezzano's *Mystic Marriage of St. Catherine* (HKI.1302), and Mytens' *Portrait of Sir Philip Sydney and His Sister the Countess of Pembroke* HKI1277 (Figure 27b), were mainly due to fixed lattice structures.

Figure 28 shows an example which illustrates potential damages and the benefits of removal of such a reinforcement. Photographs before and after treatment of the front in reflected light, carefully adjusted to be nearly the same incident angle, show both the regular pattern of splits which defines the lattice and a dramatic improvement in surface contour. Such an improvement of a larger example following removal of excessively restrictive reinforcement is also illustrated in [12]. The change

a)

b)

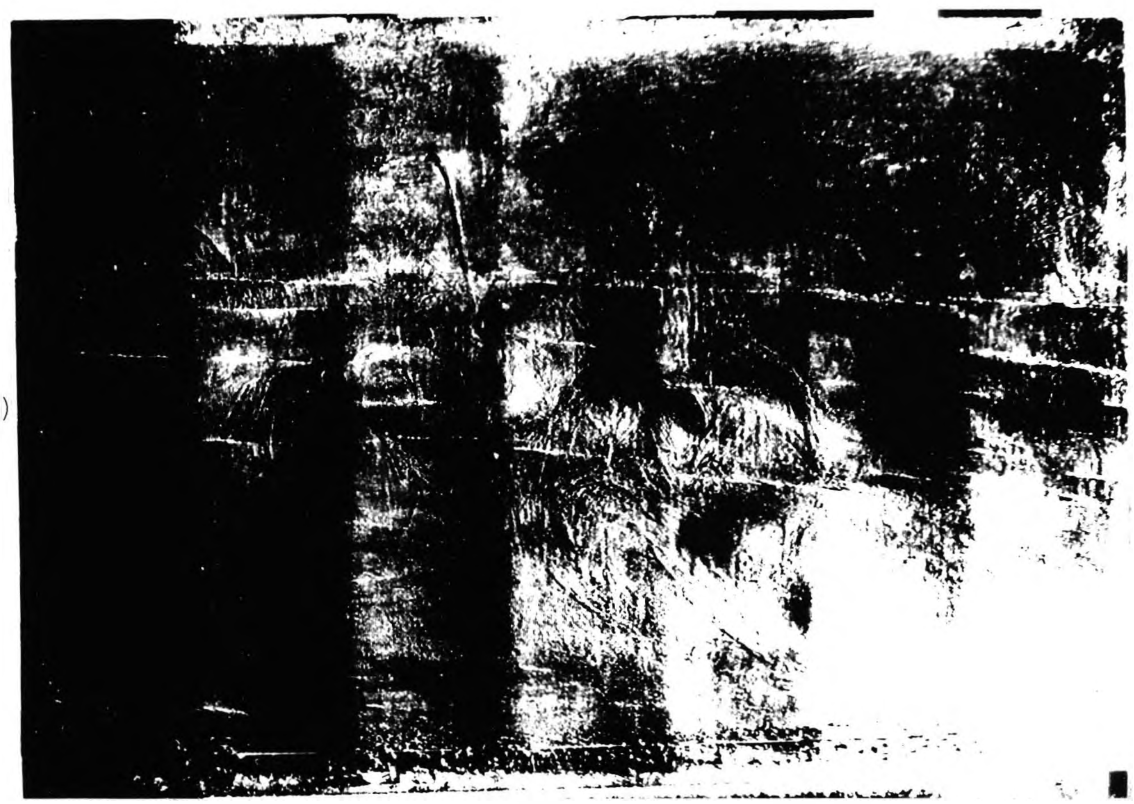


Figure 27. Lattices with fixed joints: a) an example screwed to the panel back, b) "washboard"-like deformations on the front of a panel with a glued lattice, in raking light cast parallel to the (horizontal) grain. (Photos a) Master of Burgo de Osma (Valencia, 15th c.), "St. John the Baptist", 1320X720X20mm, Louvre RF1708. Photo Laboratoire de Recherche des Musées de France (1957), b) Jan Mytens, "Portrait of Sir Philip Sydney and His Sister the Countess of Pembroke", 446X655X3mm, private collection, HKI.1277).

illustrates that the deformations imposed by such overly restrictive reinforcements result from elastic stresses and are partially reversible.

Besides the cradle, which is a lattice-type structure, various other reinforcements have been applied which share structural characteristics with lattices and perimeter frames. A perimeter frame is defined here as a rigid structure of the same shape as the panel, usually rectangular, much like a typical picture frame. Original grooved frames on northern school panels (see 2.3.2(c)) are a type of perimeter frame. However, the perimeter frame may be behind the panel, flush with the edges when viewed from front or back. Or, it may have a perimeter larger than the panel, such as a picture frame, or the panel may lie within the inner edges of the perimeter frame members, suspended by some means.

To take advantage of their individual qualities, lattices and perimeter frames have been combined in some reinforcements. The Istituto Centrale also developed lattice-type structures during the 1950's which heralded a different approach to reinforcement by accommodating warp. One design was originally published by Carità [40]. A rigid tubular steel frame provided an armature across which several parallel and relatively flexible brass rods were tensioned. This self-supporting loom ("telaio") was then attached to the panel back by retainers, regularly spaced along the rods and individually cut to accomodate existing panel deformations. The rods were slid through holes in the retainers, attached to the steel frame's perimeter, and tensioned. The panel was thus partially suspended from the brass rods and able to slide on them.

It must be emphasised that Carità apparently considered the panel wood so insect-damaged and altered by consolidation that it no longer reacted to moisture changes:

"La tavola, pur disinfettata e consolidata con sostanze indurenti, restava pur sempre una "larva" di legname senza resistenza a possibili sollecitazioni." [The panel, having

a)

b)

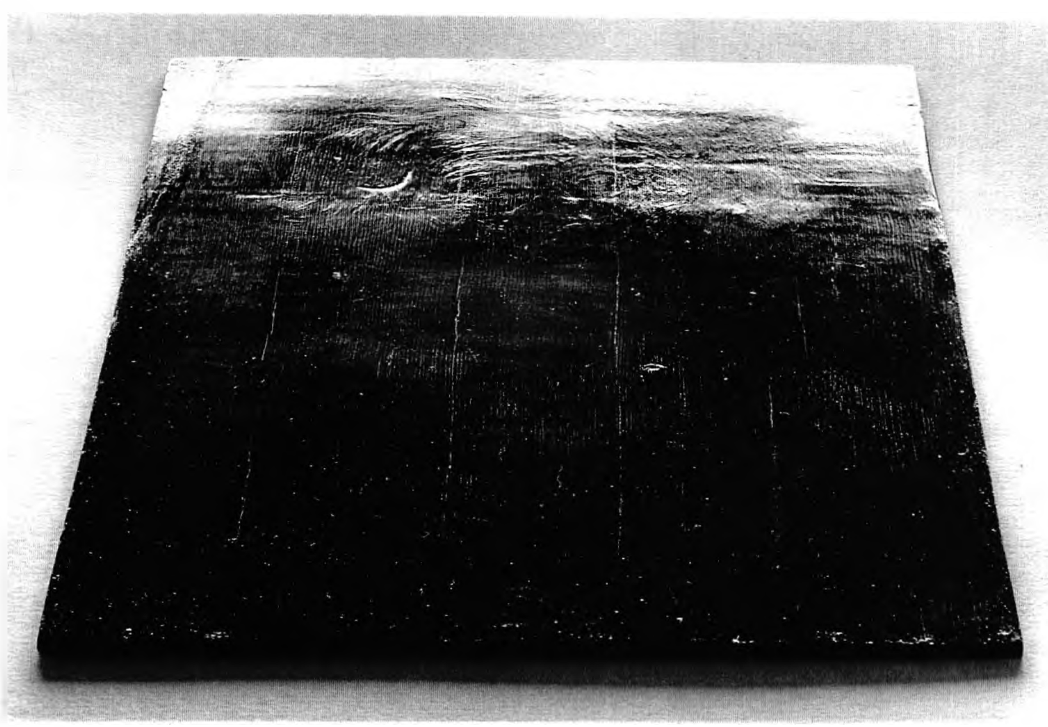


Figure 28. The effects of removal of a fixed lattice: a) splits and "washboard"-like deformations shown in the same aspect and lighting angle before removal and, b) with deformations reduced after removal (Abraham Bloemart, (Flemish 16th c.), "Head of an Old Man", The National Trust, Tatton Park, HKI.1525). Photos Christopher Hurst.

just been disinfected and consolidated with a hard substance, remained only a "shadow" of its woody structure with no reaction.]

Therefore, though conforming to existing planar deformations, it is unlikely that this design was intended to allow for warp movement as well. Still, by partially suspending the panel in such a way and though not stated explicitly with respect to warp movement, the design represented new possibilities for tailoring panel restraint. Carità published other loom designs, some incorporating retainers with spring and roller mechanisms to allow panel movement in all three dimensions.

Von Reventlow [49] showed the author designs developed especially for thin or weakened panels, whose principle has some similarities with Carità's loom. Several tensioned cables are stretched across a perimeter frame of the same shape and size as the panel. The panel lies against the frame, partly suspended from the cables and partly resting on the proper frame rebate. It is attached to the cables with small wood retainers glued to the the back (Von Reventlow called these "low-friction staples"). Each cable is adjustable for tension. This arrangement is meant to allow both lateral and out-of-plane movement, while confining the general plane of the panel to that of the frame upon which the cables are stretched. The design had been used on a Rubens sketch in the Boston Museum of Fine Arts which was relatively thin and of horizontal grain.

Nearly forty years later, conservators in England used the same beam formula for exactly the opposite purpose for which it had been used to design reinforcement for Duccio's *Maestà*, turning the formula on its head to calculate batten sections which would bend and conform to panel warp. Marchant [101], collaborating with Bobak [102], essentially modified the flexible battens embodied in the latter's tray design (see section 2.3.3(f)), joined them into a lattice and attached them to the panel back in a way which allowed for in-plane and warp movement in all directions. The lattice is held against the panel by thin battens sliding through wooden retainers glued to the panel back. The panel and attached lattice are held in the rebate of an auxiliary frame, the depth of which is based on anticipated panel movement and warp. The frame protects the panel from handling and framing stresses and is intended to accompany the panel, framed within the proper frame rebate.

(f) Trays

This section begins with a reinforcement which is not a tray, as described below, but whose structure can be cited as an important forerunner. In 1963, Wolters [53, p. 164] briefly mentioned use of a flexible frame reinforcement to ensure that "the panel has a limited elastic possibility of warping and full freedom to expand", referring to illustrations in the *Museum* summary of 1955 [8, pp. 178, 179] on which he had collaborated. The flexible elements were a thin synthetic panel (4mm "presswood", a type of wood particle-board) with a thin foam rubber sheet between the two panels. The reinforcement was pressured to conform to the panel curvature using one or more rigid battens aligned parallel to the painted panel's grain and clamped to the back of the frame. The panel was of relatively small perimeter and of substantial, possibly original thickness. Therefore, the reinforcement as described would require significant modification to be effective with more flexible, weaker panels having a higher ratio of cross-grain dimension to thickness. However, it is an important change in approach.

In 1978, Stolow and Sack [103] described a tray-like reinforcement constructed to protect an Egyptian Fayum portrait, one of the oldest panel paintings in existence (about 2000 years). Often intentionally created with a marked curvature which has distorted with time and in some cases been flattened by ignorant restoration, many such panels are fragile when handled, etc., though they still exhibit wood movement. The tray, as the design has been called, is basically a frame with the back closed by a supporting panel (called the backing panel here). The panel painting is laid face-up on cushioned support, which is attached to the backing panel interior, and then retained at the perimeter by a rebated frame which is usually screwed to the backing panel. It is intended to "float" within the tray structure, to which it is not otherwise attached.

The National Gallery of London published a similar though more simplified design which used disc-shaped "buttons" of Plastazote (a closed-cell polyethylene foam) glued in a regular pattern to a light, inert backing panel made of aluminium honeycomb-core and fibreglass skins ("sandwich" panel) [104]. In this thesis, this design is called a foam-cushion tray. It has been modified since this research was done [105], holes having been cut in the back of the honeycomb panel to help equalise moisture exchange with the exposed front surface. A number of modifications have been made by conservators in practice, but few are published. Most attention has been devoted to shaping, sizing, or orienting the foam buttons in various ways to tailor cushioning.

A very similar design described by Barrington [106], with some interesting modifications against thievery, is published without specific reference to [104] and should not be taken as a new design, though the National Gallery is cited as advising on use of honeycomb-core panel.

The condition of panels bearing more modern reinforcement designs in museum collections coincides with better environmental control. Thus, damages are less likely to have occurred. This may be the case with many of the foam-cushion trays applied at the National Gallery since 1984, when the tray design was sanctioned by publication, because environmental control has been continually improved in the meantime.

Bobak has refined another tray design over several years which has recently been published [102]. A backing panel of manufactured board rather than honeycomb panel is used and more space for in-plane movement is allowed for fitting the painting. The greatest departure from the foam-cushion tray is in the use of flexible wooden strips which act as leaf springs to cushion the panel, rather than using foam pads. Formerly, strip flexibility was determined empirically, but collaboration with Marchant [101] has pushed the structure toward a firmer basis in beam bending theory.

(g) Attitudes Toward Flattening of Panels

The notion of flattening panels is intimately linked to reinforcement. It is one of the main reasons for many reinforcements and therefore warrants some consideration here. It could be argued that, since panels were originally intended to remain flat, efforts should be made to ensure they remain so. The foregoing shows that many paintings have been damaged or have developed damages, or both, as a result of this rationale. This author is convinced that flattening by thinning and/or with moisture has damaged many panels subsequently reinforced flat.

Publications are partly an expression of the general thinking on how panel paintings should look and be conserved at a particular time in history. In many cases in the past, but not always, these attitudes toward the appearance of paintings determined treatment policy. In some cases it was simply a museum Director or curator's personal conviction of how paintings should look. Normally, though those working directly on panels, usually wood craftsmen, neither determined treatment policy nor did they always agree with it, they were expected to produce a particular result.

Flattening with moisture, either applied directly as water or water vapour by raising surrounding RH prior to restraint with a reinforcement, has been the most popular method and will be discussed briefly here. Schießl [4] reviews the history of flattening methods in the Germanic countries, including use of water and water vapour, noting that most museum-based conservation institutions in western

Germany had rejected flattening with water by 1952, but not with water vapour. A number of articles describing treatments cite use of moisture for flattening [52, 53, 75, 86, 88, 90]. A few others have warned against its use. Kozlowski [76, p. 64], citing 27 years of experience, said,

"If water is used, it is sometimes seen to increase warping after drying."

Some interviewed conservators pointed out the disadvantages of use of moisture. One had treated several panels damaged in the Florence flood of 1966, saying that the flood had shown dramatically that moisture applied directly (panel soaked) tended to increase convex warp [59]. For example, the author was shown an extremely large panel at the Opificio delle Pietre Dure, Florence, which had been damaged severely in the flood and was about to be treated. Each vertical plank had disjoined and assumed a marked convex warp [107].

It is evident that by 1972, Buck [75] had rejected thinning, at least, for the purpose of flattening. He recounted treatments in 1967 of panels which had "warped to a degree that was distracting to the viewer."..."Our predilection was toward partial or complete transfer [that is, thinning or complete removal of the original wood support followed by application of a new rigid laminate]. But after careful deliberation we decided to flatten the panels without thinning them significantly..." which he then justifies with a notable discussion of wood rheology based on such fundamental wood science texts as those of Barkas [108], Stamm [109], and Tiemann [110].

Though tacit approval of flattening with moisture and restraint is shown in publications such as Wolters', Buck's publications on mechanics and rheology lent theoretical weight to the idea. The persistent belief that moisture and restraint can flatten the wood by plastic deformation in the transverse-grain direction has since become an important justification for such panel treatment. Counter to Buck's theoretical conclusions and his hopes concerning plastic behaviour of wood, it has not been shown that the initial elastic stress is relieved by plastic strain, certainly not at the molecular level as he discussed. If it is occurring, it has not been shown that such plastic strain is safe for painting preservation. The author has discussed the unlikely and risky aspects of the use of moisture and restraint [12].

The acceptance of warp in museum circles has changed greatly in this century. In practice, though thinning and flattening was part of earlier treatments, it has been increasingly avoided, signaling a wider agreement in practice with Rosen's earlier, significant plea [73] to accept warp ("...if the paint film is sound, nothing should be attempted."). Rosen's article argues for acceptance of "badly warped pictures" and against support alterations. But at the same time it discusses and illustrates thinning and flattening of a warped panel using moisture and wax impregnation, which by the conservation standards current in some circles would be considered completely unnecessary. The warp before flattening was minor, but the reader is left with the implication that drastic alteration of the support to flatten was justified in this case. Such contradiction in one article is representative of similar contradictions regarding beliefs and practices regarding conservation in general.

There is ample evidence that flattening is still a policy that many conservation studios attempt to satisfy. Two conservators said they had had to treat splits in many panels which had been recently flattened with moisture and pressure and reinforced with cradles, etc. [111, 112]. The National Gallery of London uses raised humidity to temporarily swell panel backs to flatten prior to balsa lamination [105]. IRPA uses similar methods for balsa laminates [45, 86]. Another conservator avoided flattening panels but had resorted to it occasionally in recent years [93]. The author was shown three balsa-laminated panels that had been flattened in a previous treatment using ethylene glycol/alcohol/shellac for swelling and impregnation [31]. One panel had delaminated and was being re-flattened with a similar chemical treatment prior to re-application of balsa. Another conservator, faced with the daunting case of a large, damaged, battened panel, many planks of which had assumed marked convex warps, had experimented extensively by applying controlled RH and slow controlled force to flatten. Shown one flattened test plank, the author was able to point out a number of fine splits toward the plank middle under low magnification which the conservator had not seen.

In Prague, a conservator working for the Czech National Gallery collection was attempting to remove a faulty reinforcement of battens glued across the panel grain. Like many in a similar situation, the conservator was evidently anxious about removing the battens because he realised that the panel might assume a marked convex warp. He noted that various techniques were still used to flatten panels, such as making saw-cuts in the panel back, parallel to the panel grain, into which V-shaped section wooden inserts were forced and glued. Thus, flattening was evidently the policy, though the conservator was well aware of the dangers, citing each technique and its disadvantages.

Others have avoided flattening, tending to build the reinforcement to accommodate local and overall permanent deformations of plane, rather than forcing the panel to do the reverse. A treatment record of a poplar panel by Giovanni Buonconsiglio (*Saint John the Baptist*, NG.3076) reflects a progressive change in attitude toward flattening. Noting cracks from a batten glued across the back,

"Evidently the panel was attempting to move into its permanent convex warp, but was being prevented ...by the battens on the back." The batten was removed and the panel warped considerably. It was decided to constrain the picture in the frame with shaped slips and balsa-wood bars at the back. The report continues, "The difference between the present and previous constraints is that previously it was constrained flat, whereas after...treatment it was constrained in its equilibrium position." [113]

Use of balsa-wood bars implies an allowance for warp movement. Indeed, a subsequent entry reported the panel "badly warped". Why "badly"?

Accepting permanent warp, some conservators interviewed were building up or bridging irregular panel surfaces with wooden blocks or inserts to provide more continuous contact beneath battens [114]. In some cases, original batten channels were treated thus to accommodate new battens [115]. Instead of removing original wood and flattening the panel for a balsa laminate, one conservator shaped each block of the first balsa layer to fit the panel surface before building the laminate [79].

Behind the policy of flattening is an aesthetic perception of how panel paintings should look. There are very few important published theoretical discussions which relate aesthetics and treatment policy. A major example in Europe was given by Brandi [116]. It pertains directly to flattening and it has undoubtedly guided the practice of panel reinforcement in some quarters. Such publications can be used as a written reference for treatment decisions.

Founder of the Istituto Centrale in Rome, Cesare Brandi made a huge contribution to the development of conservation. In one of his most important publications, he expressed in several principles the relationship of preservation of the image with that of the object as a whole, its material aspects, including the support. One principle states:

"Il secondo principio è relativo alla materia di cui risulta l'immagine, la quale è insostituibile solo ove collabori direttamente alla figuratività dell'immagine in quanto cioè è aspetto e non per tutto quanto è struttura.

Da ciò deriva, ma sempre in armonia con l'istanza storica, la piú grande libertà di azione relativamente ai supporti, alle strutture portanti e via dicendo." [116, p. 17] [The second principle concerns the material from which the work of art is made. It is irreplaceable only where it directly contributes to the visual appearance of the work of art, in which case it is a visual aspect and not a structural aspect. From there it can be concluded, provided the historic meaning remains intact, that freedom of action concerning supports and structural carriers is allowed.]

It would be relatively simple for a conservator to make a liberal interpretation of this principle and then, motivated by a belief that panel paintings should be flat, justify such treatments as transfer, thinning, and other permanent alterations of the support, such as consolidant impregnation. The respect accorded Brandi's treatise after its first publication in 1963, reinforced by the desperate need for coherent treatment policy surrounding the flood of Florence shortly afterward, in 1966, may have inadvertently sanctioned such treatments and subsequent deteriorations of the image.

By contrast, modern practice should make a more conservative interpretation of the same principle, considering the litany of damages and re-restorations resulting from thinning and flattening by cradle restraint, a few examples of which are listed above. It is not the principle so much as the interpretation, based on an individual's subjective belief of how the painting should look, which has determined whether or not and to what degree and by what means panels have been flattened.

2.3.4 Review Summary

This review supports observations from the preliminary search (section 1.2). In general, faulty restraint of moisture-related panel movement by reinforcement structures causes structural problems such as unusual distortions, splits, and flaking paint. It is evident that more structural damage is associated with reinforced than with unreinforced panels. In general, detrimental effects increase with the degree of restraint. For example, fixed battens or lattices (sections 2.3.2(a), 2.3.3(a), 2.3.3(e)) cause more problems than do sliding battens (sections 2.3.2(b), 2.3.3(b)).

To summarise more specify, original reinforcements evolved from fixed rigid batten and/or frame structures to sliding structures which allow for in-plane movement. Movement out-of-plane (warp) was discouraged by relatively rigid fixed batten/frame-like structures (section 2.3.2(a)) due to their large cross-sections and/or to their being a stiffer wood type relative to the panel. Twists, joint disturbances, and splits were often evident. A departure from methods generally found, some Spanish panels were assembled from unseasoned planks that were allowed to shrink and distort and then were planed flat and restrained by wedges against further warp.

Non-original reinforcements showed a mechanical evolution from rigid sliding structures to sprung or flexible structures which allow for out-of-plane panel deformations. Nonetheless, most reinforcements, whether original or not, have been rigid relative to the panel.

Changes toward flexible structures reflect a greater understanding of panel warp resulting from inherent movement and a greater acceptance of a warped condition. The same beam formula as was used in the 1950's [38] to design for rigidity to maintain flatness has been used recently [11, 101] to design for flexibility to allow for some warp. Diametrically opposed, these differing purposes exemplify the change toward accepting warp and allowing for greater panel movement.

Some changes in non-original reinforcements have been developed independently by individuals or institutions, usually working from an empirical basis. Significantly, this work has converged toward the same principle of greater reinforcement flexibility. Interestingly, where cradles were the norm for nearly two centuries, these changes have only begun to appear in the middle of the 20th century, probably coinciding with development of conservation as a profession. However, many current reinforcements applied to panels remain rigid structures, allowing only for in-plane movement. The author examined a large number of damaged panels still constrained by overly rigid reinforcement. The acceptance and application of these changes within the restoration world has been limited to the few individuals and institutions which have concerned themselves with such developments.

On the whole, the development of panel reinforcements was and still is by trial and error, despite advances in the understanding of fundamental aspects by a few individuals. After general acceptance and a period of use or abuse of a new design, the general realisation of its suitability has taken a relatively long period of time during which controversy and uncertainty has reigned. The cradle, for example, is still around after nearly 250 years. A more widespread acceptance of some of its obvious shortcomings (section 2.3.3(c)) and a concerted search for alternatives did not really occur until the middle of this century with the balsa laminate (section 2.3.3(d)). Today, the balsa laminate is undergoing the "test of time". A degree of trial and error must be accepted in the best of designs. However, it could be greatly reduced for the sake of panel painting preservation if the interaction of panels with reinforcement restraint was better defined through research.

It can be seen that certain individuals, such as Carità and Buck, have made important contributions to the development and/or understanding of panel reinforcement. Many ideas for sliding and sprung designs appear to have derived from Carità's ideas, while balsa laminates are among Buck's contributions. Without intending to nationalise comparisons, Italian workers must be given credit for many advances in design. Also, accounts such as by Bünsche [52] and of Duccio's *Maestà* [38] are very useful for improving designs because they explain both principle and method in sufficient detail to allow for some reasoned assessment of performance and potential effects. Reviews of past treatments, such as by Kolch [44] and Samet [99], are also useful. Despite these developments, many lessons have been ignored in practice.

Some conservators have rejected non-original designs after having treated associated damages, including fixed battens and fixed lattices. A few cases of damage from more modern designs, developed since 1930, have been recorded in treatment records. For example, some sliding batten designs have been rejected, probably due to a tendency to seize. Naturally, conservators may be more prepared to condemn older designs, such as cradles, or those which they themselves do not apply, so reliable information on modern design performance must be weighed carefully. Also, conservators seem reluctant to criticise current designs, possibly to avoid conflict, understandable in such a small profession. However, if the vicissitudes of trial and error are not to be repeated *ad infinitum*, it is essential that conservators examine their methods continually and critically. Again, some form of objective testing could be applied to reinforcements.

The most important missing element in most publications on new or modified reinforcements, and in many treatment records, is this: how has the painting reacted since it was treated, that is, since the reinforcement was applied? Only by knowing this over a sufficiently long period can a design assessment be truly complete. This is because, at least in conservation, a method's proof is in its long-term performance with real paintings. Treatment records provide a possible means, but if they are incomplete or too general, then little can be learned.

Turning specifically to battens, there are several "schools of thought" on appropriate sliding designs which, interestingly, have a definite geographic pedigree. Though these designs differ in some fundamental restraint aspects, such as degree of rigidity and sliding friction, there is some convergence toward allowing greater freedom of both in-plane and warp movement. Still, even one trained engineer dismissed effects of warp movement, maintaining that rigid sliding structures are appropriate reinforcements. A greater understanding of panel wood movement and restraint could clarify the various positions.

To summarise cradle reinforcements (section 2.3.3(c)), there has been some research on history, modifications, and methods, but little on their mechanical interaction with panel wood movement and subsequent deformation. Cradles have caused deformations, such as "washboarding" and concave warp both with and across the grain, splits and disjoins, especially along or near edges of fixed members, and tented and flaking paint. Aside from rare and contradictory remarks about the strength (more correctly called stiffness or rigidity in mechanical terms) of sliding members, no apparent causal relationship with the type of wood- of either panel or cradle- or the cradle design, whether the high or low type, could be derived from the records. A few cradles have been built with relatively flexible sliding members. If too tight, many sliding members have been thinned to free in-plane panel movement, and in a few cases, when judged too rigid, they have been thinned to allow greater warp movement.

Continued acceptance of cradles seems to have been for several reasons: many panels did not appear to have suffered damage; cradles certainly flatten and reinforce effectively at first; they give the panel back a pleasing appearance; there is a lack of proven alternatives. Certainly the weight of evidence from publications and panel records is against application of cradles in their classic form. They have design and application problems that in too many cases compromise long-term preservation of the artwork. However, they are still being applied by some workers and existing cradles continue to cause damage. Confusion persists over the exact nature of their mechanical effects on panels. Therefore, many conservators have adopted an ambiguous stance, both critical and accepting.

Cradles are still applied and many older ones remain on panels. Conservators need more information to make critical treatment decisions about their detrimental effects and reinforcement role. Straub's summary and observations of cradle behaviour can be verified and extended to basic causes by focussing research on mechanics.

Alternatives have been proposed. Buck was instrumental in evolving balsa laminates based on his research into wood science and mechanics. However, he did not critically test the effects of balsa laminates on panels. The idea of plastic deformation of the panel is an important justification of Buck's approach, though the existence and the nature of such deformations in balsa-reinforced panels have not be verified.

Rigid laminates must restrict panel movement at least as much as fixed battens or lattices. Mechanically, are balsa laminates any better and if so, how? Do they conform any better to panel movement than a relatively rigid laminate? Many assumptions have been made or implied regarding the effectiveness of materials, such as Laurie's assertions [60], discussed above (section 1.3.3(d)). Also, deformations of plane which ensue in balsa/wax-resin laminates shortly after their application have not been explained definitively. Thus, the effects of laminates are not well understood and there are still many unanswered questions concerning the effects of more accepted laminates such as balsa/wax-resin.

There is a rich range of ideas for flexible designs, from various battens and lattices to cable suspension. Individual efforts should continue. This is important because only one "agreed" design could lead to a dogmatic, uncritical approach where potentially detrimental features are conserved and improvement is impeded, as in excessively bureaucratic societies.

The belief that flattening is necessary seems to stem from an aesthetic tradition and a perception based partly on the initial flatness of the original image. Often against their better judgement, panel workers have imposed the will of clients or collection administrators to meet this "flattening imperative". Flattening has often been done in ignorance of the changes in the panel over time and the damaging and irreversible effects of attempting to forestall such changes. Questions about flattening with moisture and restraint have not been seriously examined though the practice continues. Some treatments appear to use a mixture of materials and techniques from different reinforcement designs in an apparent attempt to combine accepted practice with client demands.

There has been some confusion between reinforcement *per se* and reinforcement for flattening. It is possible to reinforce while maintaining set warp, that is, without flattening, and without totally inhibiting movement. More flexible designs can be fitted to panel curvature, such as by shaping balsa laminates or by cutting or steam-bending more flexible battens.

CHAPTER 3 CONTROLLED-ENVIRONMENT STUDY

With the intention of addressing some of the questions posed above, a range of reinforcement designs were examined under controlled conditions in the form of a pilot study from which more detailed analyses could be pursued.

From the foregoing survey, reinforcement types could be broadly classified and a representative range chosen for the CE study. The study was done in two parts carried out cooperatively between the HKI and City University and the National Physical Laboratory. Digital photogrammetry [14, 15] and moiré fringe analysis ([16]) were used to record changes in panel shape and dimensions quantitatively. The latter method focussed on cradled panel behaviour. The former study, described here, included all reinforcement types examined. In it, raking-light photographs were also made before and after RH-cycling and during a high-RH period. Observations on the condition of all panels were made and noted at regular occasions during the study.

3.1 Classification of Reinforcements

To simplify this research, it is useful to classify reinforcements in greater detail than did Buck [19]. It can be seen that coverage varies from local, such as one or more battens, to overall, such as laminates. Taken as a whole, however, and from the review above, most reinforcements can be classified according to their 1) structure and 2) mode of restraint. Structure, which varies in complexity and detail, can usually be described as batten(s), lattice, perimeter frame, or laminate, or sometimes a combination. Depending partly on the elasticity of the reinforcement structure, modes of restraint may act in all spatial directions. For classification, these may be reduced to three principal directions or axes with respect to the panel plane and the panel's grain direction.

Conceptually, the mode of restraint encompasses the 1) degree of restraint and 2), the method of attachment, as follows:

1) The degree of restraint describes the relative elasticity of the structure, as imposed stiffness (parallel to the panel plane) or rigidity/flexibility (perpendicular to the panel plane). It varies considerably for all reinforcements and with environmental conditions. In a simple classification, degree of restraint can only be used as a relative term to distinguish classes, for example, as rigid or flexible.

2) The method of attachment describes whether the reinforcement is attached intermittently or overall and whether the attachment mechanism is fixed or sliding. Modes of restraint may act in all directions. Thus a rigid laminate with fixed overall attachment would, for practical purposes, completely restrain movement in all three dimensions. A rigid sliding batten would restrain movement in two dimensions, in-plane and parallel to the batten axis (ie. across the panel grain), and out-of-plane. A softly cushioned tray would allow movement in all three dimensions. In reality, terms such as "rigid", "flexible", and "fixed" are all relative because restraint is never absolute.

3.2 Controlled-environment Room Description

A CE room was constructed (Appendix 3 and Figure 29) in which to house and measure the panel models during the study. It was insulated and equipped to maintain desired levels of temperature (T) and RH. Sufficient space was provided to store the panels vertically on their end-grain edges, to help minimise stress and allow free air-circulation around each panel and easy manipulation during their assembly and measurement.

Two dual RH/T sensors and a data-logger continuously recorded environmental conditions during the study.

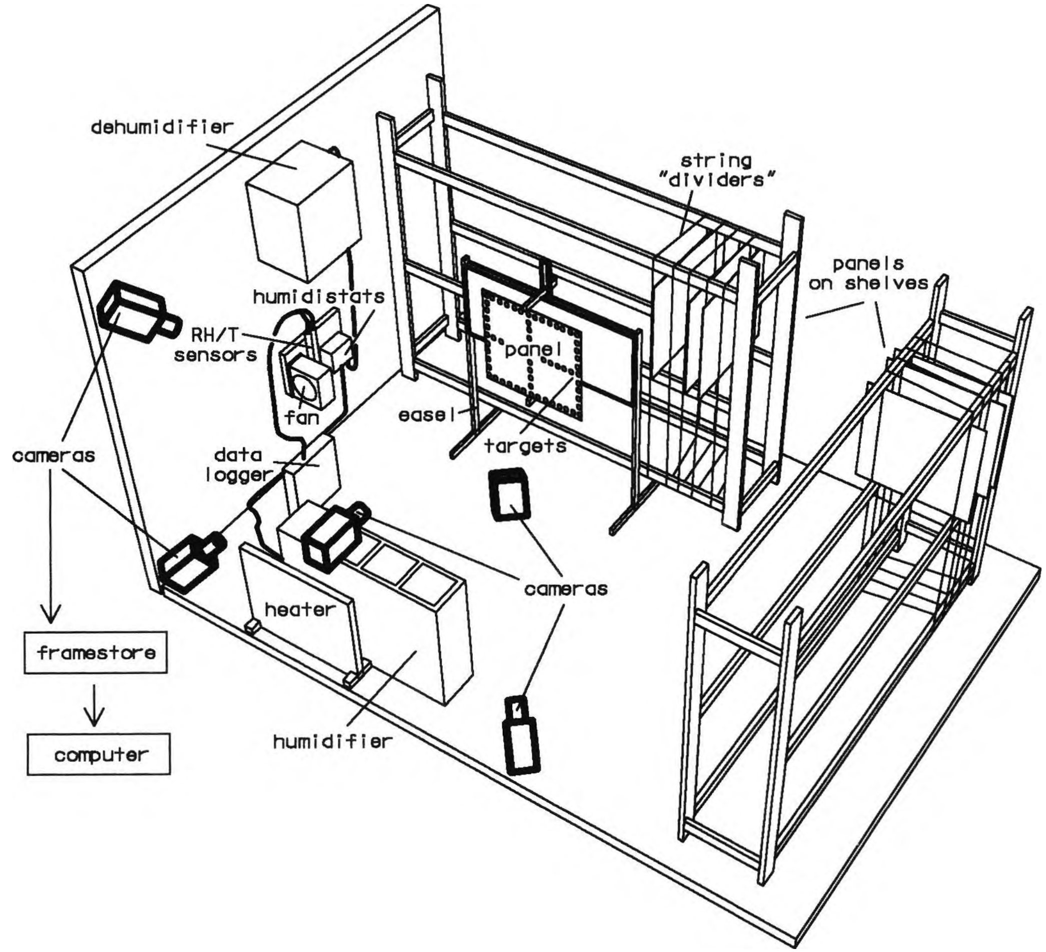


Figure 29. Elevated perspective view of the controlled environment room. A panel is on the easel to be recorded by the five wall-mounted digital cameras.

Temperature sensors had been calibrated by the manufacturer within the past year so this was not repeated. Humidity sensors were calibrated beforehand to within +/-1% RH of low- and high-RH calibration salts. Each sensor was dedicated to recording either low or high RH to reduce possible errors associated with exposure to broad RH extremes [117]. Sensors were alternately exposed during each cycle and protected during alternate periods by capping with the calibration vials, which also provided a calibration check.

3.3 Humidity Schedule

Applied RH-levels were based partly on extremes prevailing in relatively uncontrolled interiors [13, p. 71; 72; 118, p. 81; 119, p. 18]. Relative humidity in an English country house, for example, can range annually from 40% to 95% if unheated, and from 20 to 70% if it is adequately heated "for comfort" [120].

RH cycling (Figure 30 and Table 2) was done in late autumn, when it was possible to maintain moderately stable, cool temperatures outside the CE room to allow better environmental control within. For two weeks before and one month after assembly, test panels were subjected to a conditioning period at moderate RH (60%), followed by three repeated cycles of constant RH extremes, alternating between low (40%) and high (80%) levels, and finally returned to the initial moderate level, all at constant temperature. Thus, the short-term pattern of panel response could be compared between cycles, trends identified, and more long-term effects detected by comparing response before and after cycling.

Humidification and dehumidification rates differed due to differences in machine efficiency. An abberation in constant high RH occurred early in the third cycle due to humidifier malfunction.

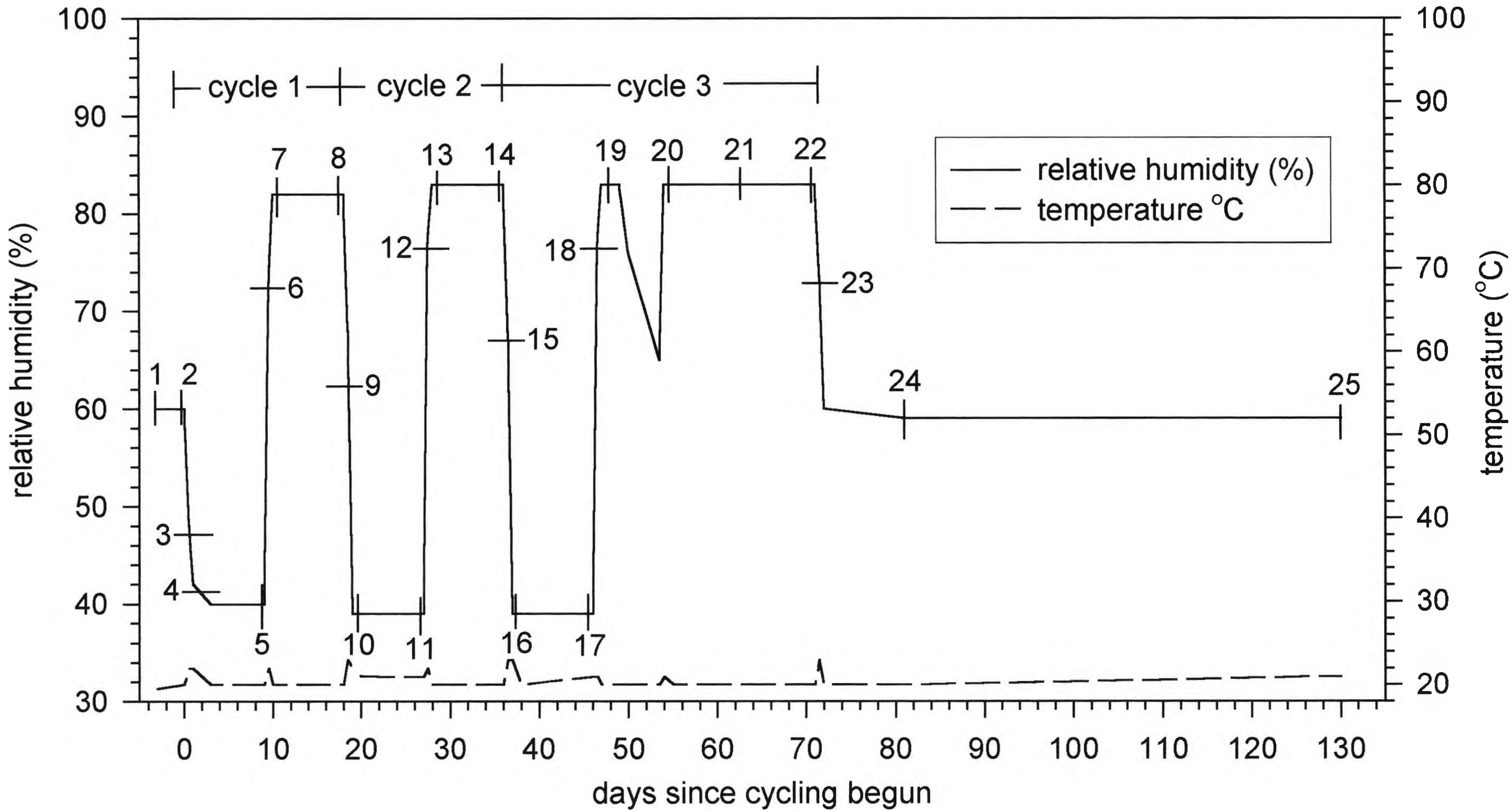


Figure 30. Relative humidity (RH) and temperature changes during the study: cycles numbered at the top, measurement epochs numbered along the humidity trace. RH fell temporarily in cycle 3 due to humidifier malfunction.

Previous studies ([121, 122, 123]) and this author's observations on panel behaviour were used to establish minimum low- and high-RH equilibration periods at about 10 days for a grounded unreinforced oak test panel. Mock-up equilibrations would vary greatly but it was hoped that their general response would be adequately demonstrated within 10 days. A longer period of high RH was imposed during the last cycle to investigate more long-term effects under moist conditions, when creep would be more likely [18, pp. 100-102; 124, pp. 561-569].

PERIOD	**RELATIVE HUMIDITY (%)**		**TEMPERATURE (°C)**		**NUMBER OF READINGS**
	Mean	Standard Deviation	Mean	Standard Deviation	(RH/T) per (Days)
before and after cycling(a)	59.3	1.0	19.5	0.6	6720/6720 per 70
low RH periods(b)	39.3	1.1	20.6	1.0	840/1680 per 17.5
high RH periods(b)	82.8	1.5	19.8	0.6	1608/3216 per 33.5
		Mean	20.0	0.7	9168/11616 per 121
(a)RH and T= mean of 2 sensors					
(b)RH= mean of 1 sensor; T= mean of 2 sensors					

Table 2. Statistics for recorded relative humidity (RH) and temperature during periods of relatively constant RH extremes.

3.4 Panel Mock-ups

Panel mock-ups were made from four wood types commonly found in panel paintings [3]. All were 600.0mm square. Most were 3.30mm thick. One set of all four wood types was left uncoated, another was sized, and the remaining sets, called *coated panels*, received both size and ground/paint layers.

Using the classification above, a range of reinforcements from each class and some experimental types were chosen (Table 3) and applied to the coated panels.

Here, unreinforced and reinforced panels of all types are referred to collectively as *test panels*. All the test panels were given a coded label (Appendix 4) consisting of a number for each reinforcement type (1 to 23), a letter for the wood type (L= linden, O= oak, P= poplar, S= Scots pine), and a number for each panel of a given wood type (1, 2, 3, etc.). Thus "9O12" is oak panel #12 reinforced with sliding rigid battens (reinforcement #9). There were 73 test panels, including unreinforced, and 23 different reinforcement types. Though effects of panel thickness were not of primary interest, two thicker unreinforced and coated poplar panels were also constructed.

Knotless planks from three naturally-grown tree species were selected for quality and uniformity of cut: oak (*Quercus robur* L. or *Quercus petraea* (Mattuschka) Liebl.), Scots pine (*Pinus sylvestris* L.), and poplar. Several attempts to acquire suitable white poplar (*Populus alba* L.), as typically found in Italian panels, were unsuccessful. Instead, a lower-density English-grown natural hybrid of black poplar (*Populus nigra* L., probably *Populus X euramericana* (Dode) Guiner) was used [30, 126].

Timber for a fourth wood type, European linden or lime (*Tilia* sp.), had very irregular grain not typical of most linden found in panel paintings. Results in general were very dependent on grain effects. Most linden results were consequently adversely affected and therefore discarded.

Panels of each wood type were constructed in the same manner (Appendix 5). Planks of pine and oak with uniform grain characteristics were chosen to reduce variation in moisture response between planks. Scots pine planks were of very similar tangential cuts and ring density, straight-grained, with the pith located perpendicular to the center of each plank. Oak planks were all very nearly radial cuts

Unreinforced

-uncoated wood (4), sized (4), sized and grounded (4)
-sized and grounded, 10mm thick (1 poplar)
-sized and grounded, 20mm thick (1 poplar)

Reinforced

Batten structures:
-fixed and rigid (4)
-sliding and rigid (*traverses*) (4) [43, p. 24, Ill. 5]
-sliding and flexible (4) [58]

Lattice structures:
-fixed and rigid (4)
-sliding and rigid (cradle) (4)
-sliding and flexible (4) (attached lattice) [101]

Tray structures:
-sliding and flexible (1 oak) (unattached lattice) [102]
-foam-cushion (4) [104]

Perimeter frame structures:
-rebated frame, brass retainers (4)
-"chassis cadre" (4) [43, p. 24, Ill. 6]
-cable suspension (4) [49]

Laminate structures:
-fixed/rigid overall-
    -medium density fibreboard (MDF) panel (4)
    -planks, same wood (1 oak)
-fixed/flexible overall-
    -balsa planks (4) [88, 90, 125]
    -balsa blocks (4) [91, 92]
-fixed/flexible intermittently-
    -parquets, same wood (1 oak) [49]

experimental laminates:
    -tissue strips (1 oak)
    -rectangular-cell (OX) honeycomb core/PVA (1 poplar)
    -rectangular-cell (OX) honeycomb core/epoxy (1 linden)
    -hexagonal-cell (HEX) honeycomb core/epoxy (1 pine)

Table 3. Test panel descriptions with the number of constructed examples of each type in parentheses. A '4' means one of each wood type (oak, poplar, pine, linden) was constructed. Otherwise, a single wood type is indicated.

with slightly irregular grain. As with pine, ring density was approximately uniform for all planks. Grain characteristics between poplar planks was less uniform. Poplar grain varied between radial and tangential cuts, was moderately irregular, and ring widths varied by several centimeters. Though typical of many Italian poplar panels [127], these characteristics decreased uniformity of the poplar test panels.

During resawing, some planks- especially oak- developed concave cupping on the sawn face from latent drying stresses. Cupping in such planks could not be entirely attributed to RH-cycling during the study (see section 3.7.1).

Square format was chosen to simplify construction, measurement, and handling. Panel perimeter was made large enough so that panel movement and restraint reactions would be within the sensitivity of techniques used to record deformations. Thickness was chosen to represent panel paintings of similar size that have been thinned, flattened and reinforced [128]. Very thin panels are the most difficult to reinforce safely and would be more likely to demonstrate restraint effects as measurable deformations. Grounded unreinforced poplar panels of two greater thicknesses were prepared to examine effects of thickness on movement and warp.

After trials, two thin spray-coats of low-concentration animal glue size (3.5g/100ml distilled water) were applied for uniformity and to minimise swelling distortions associated with brush application. With the blower at 1/3 full position and the 1.0mm-diameter spray nozzle set to a vertical elliptical pattern, the spray was applied using a horizontal motion.

A uniformly distributed, relatively dark and matte surface was necessary to minimise differences in moisture permeability and to provide suitable surfaces to measure deformation. Aqueous grounds were rejected due to swelling effects. Black and white oil paints with no solvent were mixed 3:2 by weight with a spatula and applied to each panel with a scraper-blade. This effectively combined ground and paint in one relatively quick-drying layer.

Scraper application left the tops of the wood ridges created by sanding nearly bare to generally mimic coating permeability due to craquelure on real panel paintings.

3.5 Reinforcement Methods

Reinforcement types are numbered and their construction described in Appendix 6. Important references, mostly illustrated, are noted in Table 3. Choices were based partly on popular usage, such as balsa laminates. Some types represented a relative range of movement allowed in-plane and out-of-plane. This is shown by the batten series from rigid and fixed (restrains both types of movement), to rigid and sliding (intended to restrain mainly out-of-plane movement), to flexible and sliding (intended to allow greater movement of both types), and similarly for choosing lattice types.

Laminates restrain both types of movement and because they are fixed overall, are potentially the most restraining reinforcement type. Again, to explore a range of restraint, chosen laminates ranged from relatively rigid 12mm-thick medium density fibreboard (MDF) panel to nonwet-strength tissue. Two laminates of oak were applied to oak panels to see how laminates of the same wood type and grain strcture would perform, one continuous and the other consisting of independent parquets.

Some designs were developed to allow flexibility, such as by Von Reventlow [49] in America or by the HKI in England [11, 101, 102], or for other purposes. Some purely experimental designs were included, such as honeycomb-core applied with flexible adhesives.

The author was assisted in construction of the following designs: rigid sliding battens (*traverses coulissantes*) and *châssis cadres* were copied and applied at the HKI by the author after examples of each built to specification by Claude Huot, Paris, who was instrumental in their development [129]; the author was supervised and aided by

Tony Reeve and colleagues at the National Gallery, London, in constructing foam-cushion trays [104] and balsa laminates [125]; Ray Marchant and Simon Bobak built attached [101] and unattached [102] flexible lattices.

Aside from the foregoing exceptions, reinforcements were constructed at the HKI by the author in RH of 55+/-4%. For most reinforcements, identical examples were applied to each wood type. A few were applied to only one wood type to avoid redundant comparisons. Attempts were made to unify structures within each reinforcement type to facilitate comparisons. For example, batten longitudinal centrelines were positioned identically for all three types. Parts of the reinforcements exposed to the recording cameras were finished with matte black paint or self-adhesive felt tape to reduce light reflection and prevent interference with retro-reflective dot reflectivity.

Following are some comments on specific reinforcements used.

3.5.1 Honeycomb-core Laminates

Construction is described in Appendix 6, Reinforcements #4, 5, and 6.

These were experimental reinforcements considered mainly for panel paintings which have been thinned to the extreme of 1 to 3mm, where a laminate would seem the only recourse. If not restrained in-plane to some degree, a condition lacking in a tray-like reinforcement for example, such thin panels can bend and buckle under their own weight when stood vertically. It was anticipated that typical rigid laminates would not conform well to panel wood movement. A flexible honeycomb structure might conform well to transverse-grain panel movement, provided that the corresponding active deformation in the honeycomb did not cause too much passive deformation parallel to the panel grain. The latter would tend to influence panel deformation in both directions. In other words, a Poisson ratio (passive over active strain, strain being negative) greater than -1 was considered to be desirable. These were measured for the two cell types, the HEX type being near -1.0 and the OX type somewhat greater (estimated at -0.6). At the same time, it was thought that though honeycomb-core is quite flimsy (ie. has low stiffness) in itself, attachment to the panel back with a suitably flexible adhesive would create a more rigid structure than the panel alone.

Adhesives were another consideration. It was thought important that the adhesive not form a stiff and/or rigid layer nor should it inhibit moisture exchange too much. A non-aqueous flexible epoxy/microballoon mortar [130] and an aqueous dispersion of PVA, a typical wood glue, were chosen. Epoxy has low moisture permeability. This was overcome by applying the adhesive to the honeycomb in such a way that the cell openings created holes in the adhesive layer, the adhesive forming a meniscus between the cell wall and the panel surface just beneath to ensure a good bond. The viscosity and adhesive characteristics of wet epoxy makes it highly suitable for forming a meniscus with the phenolic-resin coated honeycomb. The PVA dispersion had to be diluted with water to achieve a suitable viscosity and similar effect.

Both adhesives were prevented from direct contact with the panel back by an isolation/release layer.

Though rigid honeycomb-core panels have been used, for example, in marouflage-type reinforcement of paintings on fabric, this is the first time that honeycomb-core has been applied directly to the wood surface for the specific purpose of conforming to panel wood movement.

3.5.2 Foam-cushion Tray

Construction is described in Appendix 6, Reinforcement #15.

Any sufficiently rigid panel would be adequate for the tray base. Aluminium honeycomb-core panel with epoxy-impregnated fiberglass skins is preferred for being light in weight and physically and chemically inert.

Though only 1/2 inch (12.5mm) was allowed for panel deflection, it was expected that the test panels would deflect as much as 12 times this measure over a 40% humidity range. However, the National Gallery conservators and the author agreed that the test panels should be built to show the effect of underestimating the deflection and to allow comparison of the reaction of the different panel woods to the same limiting conditions. Normally, one would allow for a deflection within the region of the maximum expected under the average environmental conditions *in situ*, but not so much that the panel will be too loose. Also, the rebate foam-padding is normally cut to the curved profile of the panel edges since most panel paintings have some permanent deformation. For the flat test panels, padding was cut straight without profiling.

3.5.3 Cable Suspension

Construction is described in Appendix 6, Reinforcement #17.

The method was modified from Victor Von Reventlow's design after discussions at his studio in Brooklyn, New York, January, 1992. It differed in many respects, especially with regard to the tensioning mechanism. The author could not acquire the same materials to build the mechanism, so improvisation was necessary. This accounted for the greater complexity in comparison with Von Reventlow's more elegant original.

The principle of the design was preserved, however. Some care was taken to allow the wires to be tensioned equally with fine control. The test reinforcement was thus a working model rather than a finished piece. Von Reventlow had developed the idea of cable suspension beyond this basic approach though no other mock-ups were included in this study.

3.5.4 Balsa Plank Laminate

Construction is described in Appendix 6, Reinforcement #18.

The adhesive-impregnated fabric was intended to act as a barrier layer to prevent the wax-resin from penetrating the panel support.

The balsa thickness was chosen according to the amount of rigidity desired in the final structure. The intention is to produce approximately the same counter-tensions in the structure as the painting support would have experienced in its original thickness. Thus an oak panel would have a different thickness of balsa applied than would a poplar panel. To limit variables here, the same thickness was applied to all four mock-up wood-types.

The balsa planks should have been cut with an excess length of at least 50mm at each end. This is important, because 1) the planks are more easily pressed into place to force out the excess mortar, 2) the chance of the planks being set with one end inside the painting's edge is reduced, and 3) it is much easier to trim the planks to the panel edge with a saw if the structure is balsa without mortar since saw-teeth plug easily with mortar.

3.5.5 Balsa Block Laminate

Lebas [92] used Lascaux 445 wax-resin rather than the mixture used here.

3.6 Measurement and Interpretation

Three methods of recording deformations were used. Digital photogrammetry was used for the CE study described in the body of this thesis. Moiré fringe analysis of cradled panels is described in Appendix 7. Raking-light photography, used as a qualitative complement to the other two methods, is described and presented in Appendix 8.

Ideally, a means of instantaneously recording "snap-shots" of overall panel shape in three dimensions was desired which could later be analysed in detail. These would be multiple records of a 600mm square area of sufficient resolution to detect expected deformations. Poplar, the lowest density and therefore least moisture-responsive panel wood used, shows radial movement of about 1.2% from 90% to 60%RH at 25°C [131, p. 170], or about 7mm over 600mm. To detect expected deformations within this range, methods should resolve accurately to at least 0.1mm which requires a minimum resolution of 0.05mm.

In a plank, in-plane wood movement in the transverse-grain direction is commonly calculated based on changes in the plank's width, that is, changes in dimension in the plane of the plank's largest face. Reported values are from small wood samples which limits any error from warp changes during measurement [18]. In larger samples, such as a panel, warp can cause variations in curvature. Thus, if movement is to be measured directly, then warp must be considered. During an RH change, in panels which remain relatively flat, such as those with radially-sawn planks, movement could be closely approximated using a simple straight-line measure from edge to edge.

However, most panels undergo warp changes with MC for the reasons discussed in section 2.1, especially thinner panels. Warp may vary in degree and in location across a panel, depending on grain orientation. Reinforcement restraint may also influence warp locally. In these cases, a straight-line measure would give an under-estimate of movement. For example, if panel expansion was accompanied by increasing warp, a straight-line measure would indicate less movement than was actually occurring. If warp were great enough, it could even suggest a reduction in dimension, that is, a contraction. If warp were simply a regular curve, a simple correction factor could be applied to straight-line measures. But warp may produce complex profiles which vary with MC, complicating any corrections.

The most obvious solution is to measure movement directly at the panel surface. Several authorities were consulted to help choose suitable methods. Ranging in sophistication, the methods considered could be characterised, more or less, as either manual (eg. hand scale) or automated to some degree (eg. infra-red tape-measure), contact (eg. resistance strain gauges, dial gauges, photo-elastic and brittle coatings [132]) or non-contact (eg. raking light [133], moiré methods [134], speckle pattern interferometry [135]), and partial or full-field (eg. strain gauges versus analogue photogrammetry, respectively).

Methods were rejected for reasons such as: unacceptable loss of information; too time-consuming, technically demanding, or expensive to develop and/or apply; no suitable means of handling large quantities of forthcoming data; excessive interference with moisture permeability (eg. coatings) and/or mechanical properties (eg. strain gauges impose mechanical resistance); no simple means of correction for out-of-plane deformations if wood movement is to be measured adequately over any distance across the panel surface (eg. resistance strain gauges would have to be applied in line at close intervals across the entire panel, necessitating use of a large number and applied by an experienced hand- one faulty gauge would seriously compromise the entire exercise); inappropriate sensitivity (eg. holographic interferometry [136]).

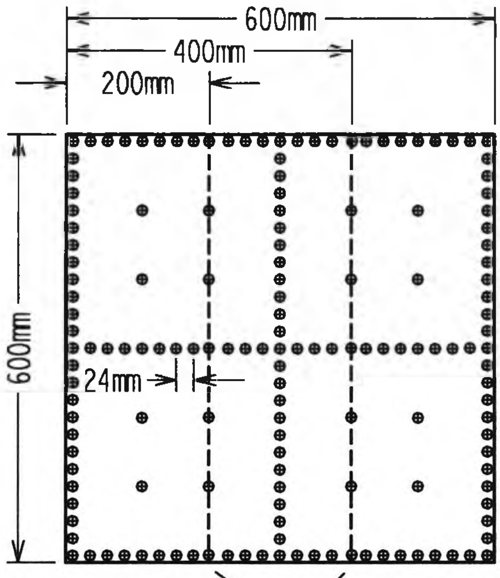
Though analogue photogrammetry was rejected as too time-consuming and difficult to interpret, digital methods were sufficiently developed and expertise was available for their application. Moiré fringe analysis, reported elsewhere, was used in this research to focus on cradled panel behaviour ([16] and Appendix 7).

Multi-image digital photogrammetry [14, 15] provided a suitable quantitative means of recording and comparing panel deformations in the main CE study described here. Change in panel dimensions at the surface was closely approximated by applying circular retro-reflective targets in straight lines across the surface from edge to edge. The closer the targets, the better the approximation. Target patterns were applied by hand to the panel fronts using stencils cut from transparent plastic sheets for positioning. For a control of the measurement system, a glass sheet was prepared with paint and with targets applied in the basic pattern described below (Figure 31a). The control was recorded at each epoch. Images showed no changes in target position.

Using 5 charge-coupled device (CCD) cameras linked to an electronic framestore and an IBM-compatible desk-top computer, sets of convergent images were captured of all 73 panels and the control at 25 measurement epochs during RH cycling (Figure 30). In addition, a grounded oak panel with sliding flexible battens, and three grounded poplar panels were measured during changes of RH at shorter intervals, each minute over 30 minutes, to investigate short-term response rates. Imaged targets were then located and identified in the object space at a resolution of about 0.01mm. Target XYZ co-ordinates with scaled-up vectors of movement between epochs were calculated and transferred to a computer-aided design (CAD) system [137] for visualisation and further analysis.

Minimum target spacing (about 15mm) was close enough to justify using computer-generated Bézier (b-spline) curves to approximate panel curvature between points. Target patterns were conceived based on a thorough consideration of real panel painting deformations, either observed or noted in treatment records. Deformations under high and low RH were visualised and sketched for each reinforcement type and the target patterns planned accordingly to minimise target numbers. Target patterns were either basic (Figure 31a) or more complex (Figure 31b), depending on whether relatively uniform (eg. unreinforced panels) or complex deformations (eg. battened panels) were expected. Assuming double symmetry, one quadrant of the more complex patterns was targetted in detail to minimize target numbers.

a)



b)

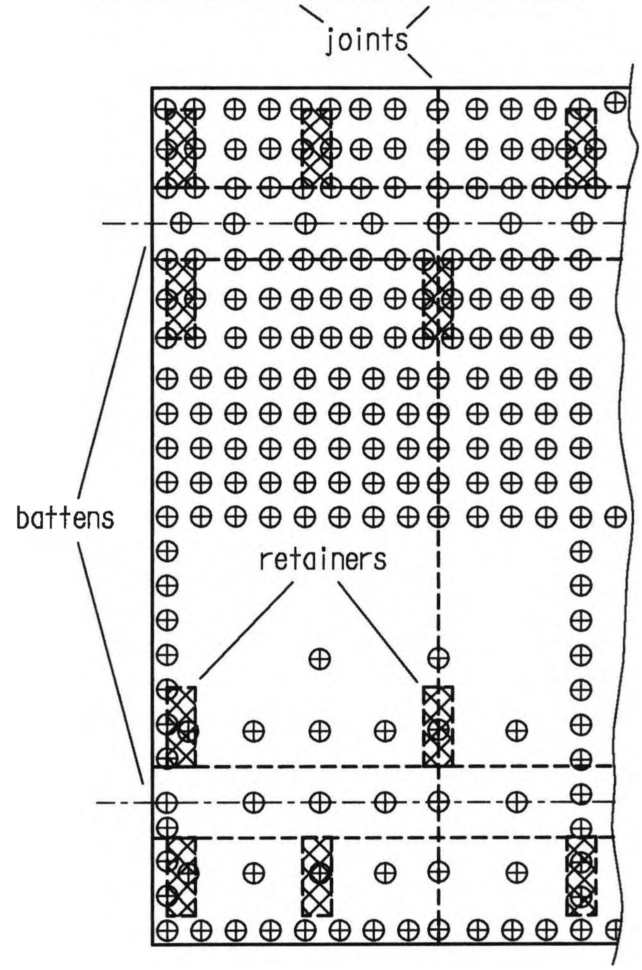


Figure 31. Panel front showing target patterns: a) assuming relatively uniform movement overall, and b) left half and upper quadrant, assuming local deformations near battens (centrelined) and their retainers (crosshatched).

To approximate diminishing response of panels [121] to changes in MC, most equilibration periods (ie. periods when constant RH was applied) contained at least three measurement epochs taken at 1 h, 1 day, and 9 days after each RH change. A longer period of high RH during the last cycle contained two additional epochs. To capture each image, each panel was removed from the shelf and placed upright with grain vertical in an easel designed to fix only the central 20mm of the top and bottom edges (Figure 29). This set-up reduced distortions from pressure and gravity.

The CAD program allowed b-spline curves to be fitted to the surfaces and measured for length, to compare wood movement, and for deflection, to compare warp changes. In an XYZ-coordinate space (Figure 32), the horizontal panel surface may be thought of as lying approximately in the XY-plane, with longitudinal and transverse-grain directions lying parallel to the Y-axis and X-axis, respectively.

Deformations were shown in two main ways for this thesis. Overall surface shape was generally represented by drawing B-spline curves through points along edges, centrelines, and battens. These have been illustrated as isometric views of multiple panel surfaces, each surface representing a measurement epoch, stacked for comparison. For measurement of wood deformations, panel sections or profiles were produced by joining points with 2D b-spline curves lying in planes perpendicular to the panel plane.

Such profiles correspond well to perception of panel shape, which is judged partly in relation to curvature of the edges. However, they could not be drawn, measured, and compared quantitatively simply by joining targets together, though a reasonable approximation of panel curvature could be had this way. Any target misalignment would give an over-estimate of the length of profile being measured. The targets were applied by hand so misalignment, along centrelines for example, was unavoidable. To overcome this,

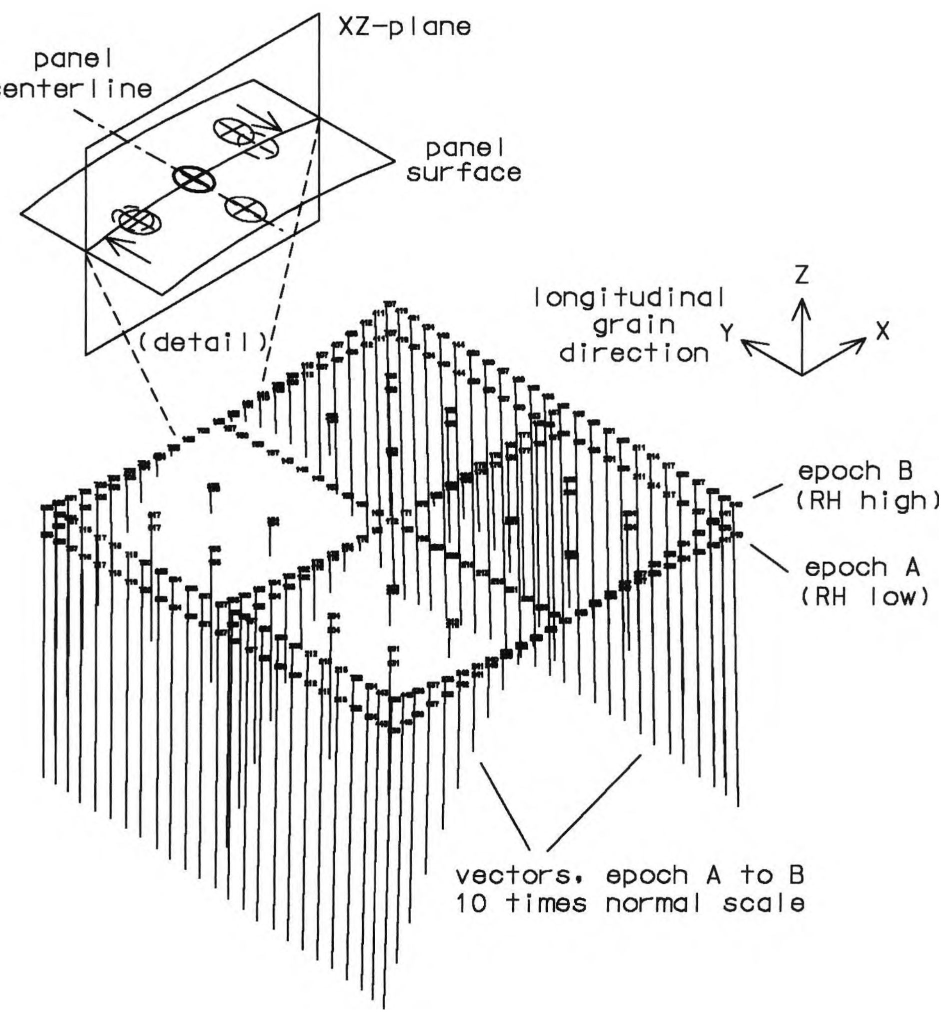


Figure 32. Panel front, isometric view from above showing shape (normal scale) and 10X vectors of 3-dimensional movement between two measurement epochs. Schematic detail shows irregularly-placed targets (circles) graphically constrained (dashed circles) to the vertical XZ-plane.

b-splines were constrained to plane sections passing through the panel center-lines (Figure 32, detail). For transverse-section profiles, for example, b-splines lay on XZ-planes positioned along the longitudinal panel center-line (= Y-axis). This effectively aligned the targets in the Y-direction, providing a better measure of transverse dimensions at the panel surface. These values were used to represent transverse and out-of-plane dimensions. Using these dimensions, proportional dimensional changes could also be calculated and plotted as line-graphs.

3.7 Results and Discussion

Some panels need reinforcement, not for flattening, which is an aesthetic decision (see sections 2.3.3 (g) and 2.3.4), but simply to maintain the panel structurally. It is apparent that detrimental effects increase with panel restraint (section 2.3.4) so that if possible, restraint should be minimised. The author's observations on reinforcement effects and experience in altering or removing previous reinforcements suggests that if possible, panels should not be restrained at all. Comparison of panel deformation with and without reinforcement is one way of trying to understand reinforcement effects. Results for each reinforcement type will be discussed based on such a comparison and in light of the review of real panel painting behaviour.

Results of the CE study characterise changes in shape measured at the front surface due to RH changes. It is essential to consider panel deformations and their causes as three-dimensional spatial phenomena which are time-dependent. In general, deformations of paintings arise from mechanical interactions, whether on relatively thin paper, thicker canvas, or panels. Deformations in reinforced panels may be due to both internal (eg. warp) or external (eg. bending) types of stress whose causes can be difficult to separate.

No test panels broke during the study, mainly because supports were thin, with practically no defects, and relatively "young", as were the coatings in comparison to aged gesso grounds and paint. These characteristics "saved" the reinforced test panels. By comparison, most panel paintings are structurally "old", with greater weakness due to accumulated fractures (often invisible), cyclic stress effects [124, p. 199-208], and perhaps loss of extractives. However, the same degree of localised bending observed in some reinforced test panels would likely have caused splits and/or flaking paint in panel paintings of the same thickness.

These considerations emphasize that CE results must not be applied rigorously to treatment of real paintings, but should be interpreted in light of particular circumstances based on the panel's condition and likely environment of RH, temperature, and mechanical stresses from handling, framing, display, storage, etc.. For example, panel thickness and adhesive and coating characteristics are important factors affecting moisture response and mechanical properties in relation to restraint. Mechanical resistance of coatings to wood movement and bending could not be considered in detail in this research, though they could be studied further using the captured data.

Despite these cautions, test panels showed marked and consistent behaviour explainable by panel and reinforcement characteristics.

In section 3.7.1, sized panel results are included with those for uncoated panels since no conclusive difference in movement could be identified. It should be noted that the sprayed size layers were much thinner than in real paintings, which would have been applied by brush. Thus, brushed size layers could be expected to influence panel behaviour to a greater degree.

The behaviour of most test panels will first be summarised from observations, beginning with the appearance of panels before RH-cycling. Photogrammetric results will follow each summary of observations and will be mainly discussed in relation to isometric renderings of the panel shapes and how they change with RH. This was adequate for comparing shape changes qualitatively for this thesis. Photogrammetric analysis of some panels has not been completed, so in those cases, results from observations and raking-light photography will be discussed.

3.7.1 Unreinforced Panels

Unreinforced panels showed warps before cycling which generally varied between individual planks. Cupping was greater in oak planks, while pine and poplar planks were relatively flat. Greater cupping in oak may be partly attributed to strain from residual drying stresses (see section 2.1) released by resawing into thinner planks, a common reaction in resawn oak. Such behaviour is related to a given wood type's tendency to develop and retain drying stresses, and is usually greater in higher density woods. Drying stresses in poplar are generally lower than in oak so resawing affected them less. Thus, poplar planks were initially flatter than oak.

Secondly, residual drying stresses are likely to influence warp in freshly-sawn planks after changes in ambient RH and T. Despite attempts to minimize these changes, some wood movement was inevitable in the interval between conversion to final dimensions and the beginning of cycling. These warps were evident to varying degrees in all panels.

By magnifying out-of-plane deformations graphically (Figure 33a), it is evident that oak panels in particular gained a further permanent cupped warp during the first period of raised RH. This is also probably due to release of drying stresses. All oak panels may have undergone some deformation from this cause. By comparing transverse dimension when equilibrated to the same RH before and after cycling (Table 4), most panels showed a slight decrease. A decrease would be expected in all cases, greater in coated panels due to compression set induced by the coating on one side. It is interesting to note that uncoated oak actually increased in dimension. This may be evidence of release of drying stresses. Release of drying stresses may also have altered dimensions of the other woods, again due to changes in ambient RH and T, which would be even more likely from the extremes applied during the study. However, because these dimensional changes may be too small to be statistically significant, they must be regarded with skepticism. Confirmation would require more samples.

panel description		transverse dimension at centreline (mm)		change (mm/%)
		before cycling	after cycling	
uncoated	pine	580.06	579.10	-0.96/-0.17
	oak	580.14	580.20	+0.06/+0.01
	poplar	579.38	579.17	-0.21/-0.04
grounded	pine	579.97	579.40	-0.57/-0.10
	oak	580.28	579.65	-0.63/-0.11
	poplar	580.35	579.98	-0.37/-0.06

Table 4. Changes in transverse dimensions of test panels during cycling. Positive change indicates panel expansion.

(a) Coated Panels

For these panels, a consistent pattern of overall warp ensued with changes in RH. Photogrammetric results emphasise the effect of coating one side of a panel on wood movement and warp. The rate and degree of these "temporary" warp changes are of particular interest here because of potential interactions with reinforcement restraint.

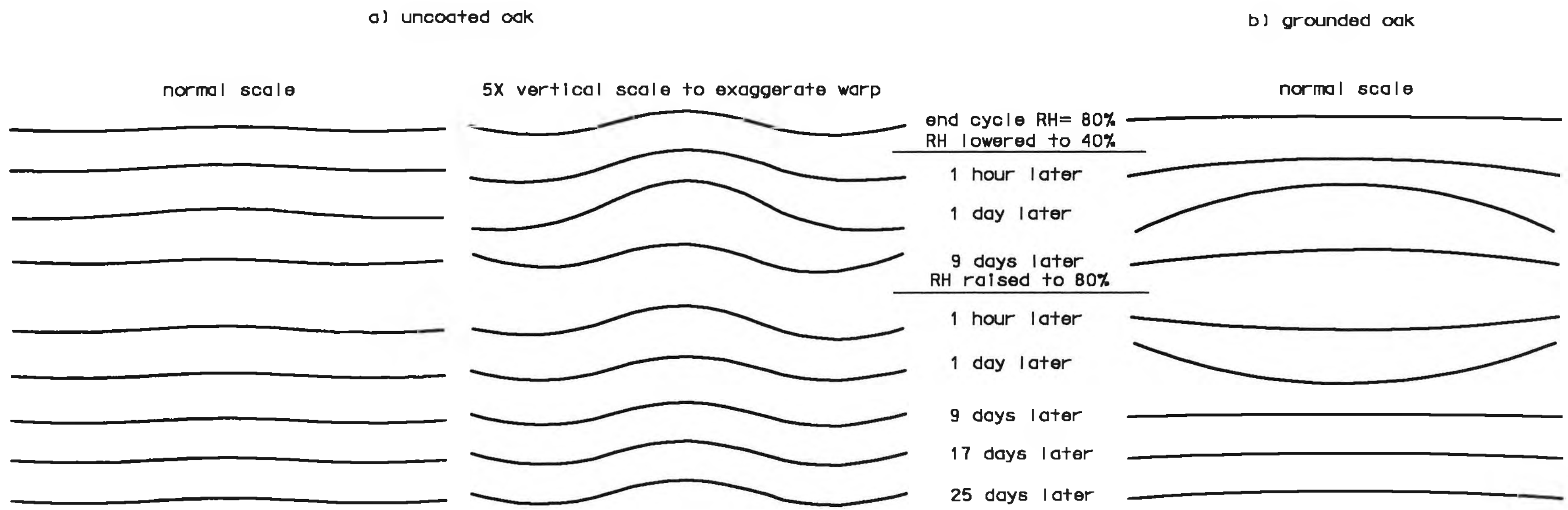


Figure 33. Transverse centreline profiles showing changes during a dry and then a moist period: a) oak, uncoated, b) oak, coated. The upper side is the coated side.

In Figure 34, transverse movement at the panel centreline relative to day 0 is compared for uncoated and coated oak and pine. For these and all unreinforced panels, equilibrium occurred within about 9 days at 80% RH, after which there was little change. This is confirmed by the extended final high-RH period, where the smooth progression was briefly interrupted by humidifier malfunction between the first and ninth day. This temporarily disturbed moisture gradients in all panels. Though no extended low-RH period was applied, equilibration time for contraction would be similar [121].

Transverse movement declined logarithmically during each RH period. During high-RH periods, both pine panels showed greater transverse movement than either oak panel. Oak, whose proportional movement is greater than Scots pine in both radial and tangential grain directions (1.5% and 2.5% versus 1.0% and 2.2%, respectively, from 90% to 60%RH [18, p. 48], moved less because oak planks were radial cuts while those of pine were more tangential. A coating on one side slowed transverse movement of all wood types, as shown here for oak and pine.

The influence of a coating can be appreciated further by considering warp changes, for example, for uncoated and coated oak panels during a high-RH period (Figure 33). Warp is represented by transverse-grain profiles taken across the panel centreline. The uncoated panel appears to remain relatively flat (Figure 33a), while the coated panel showed relatively large overall changes dominated by the coating presence on one side (Figure 33b). Warp occurred regardless of the planks being radially sawn. Under rising RH, warp response of oak was almost instantaneous (Figure 35).

Asymmetrical moisture gradients between the coated front and more exposed back delayed movement toward the coated side [8, p. 148; 19, p. 158]. Viewed from the front, the delay caused all the coated panels to warp overall toward either convexity under falling RH or concavity under rising

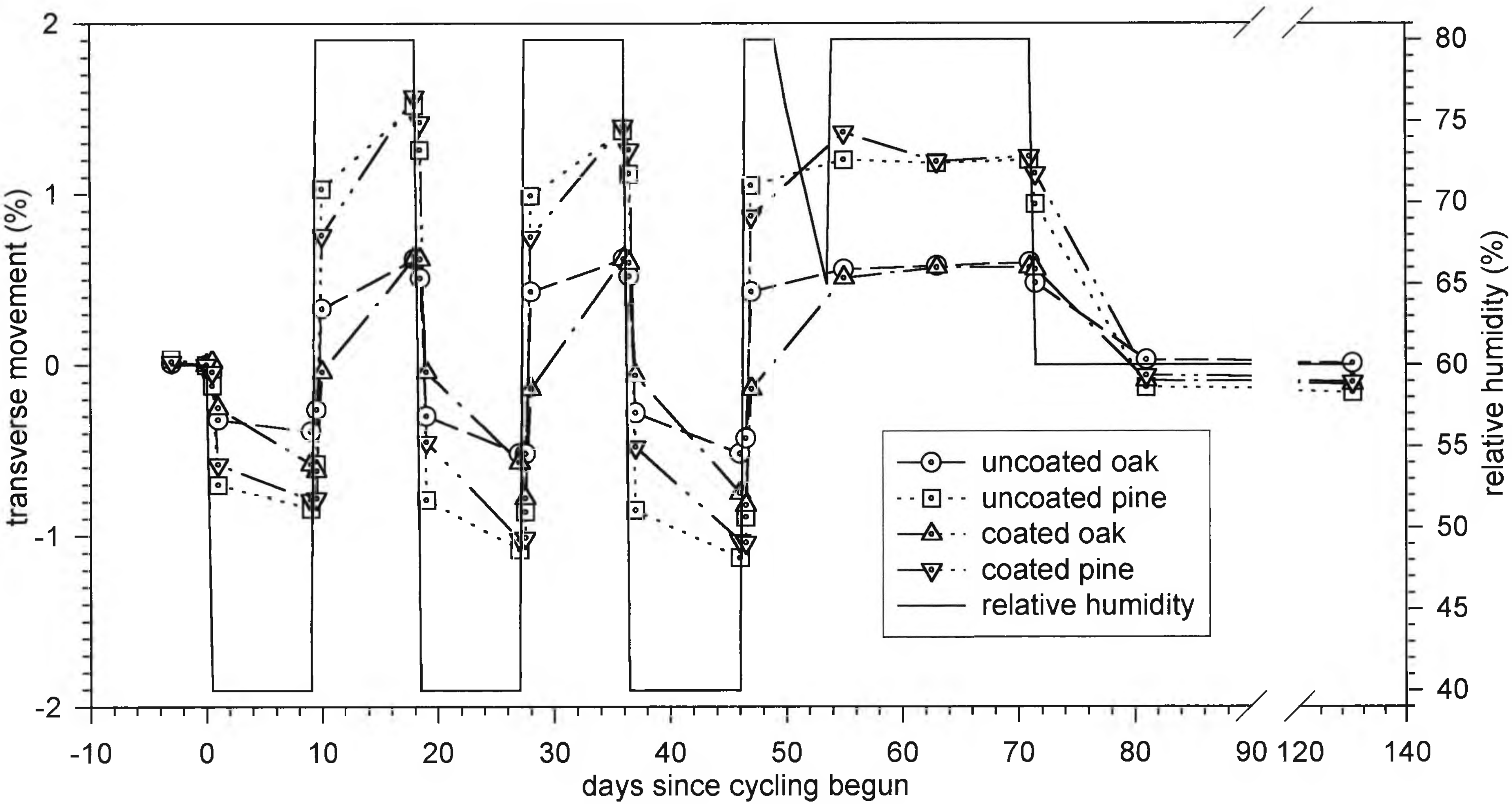


Figure 34. Transverse movement at panel centreline for uncoated and coated oak and pine over the entire study period.

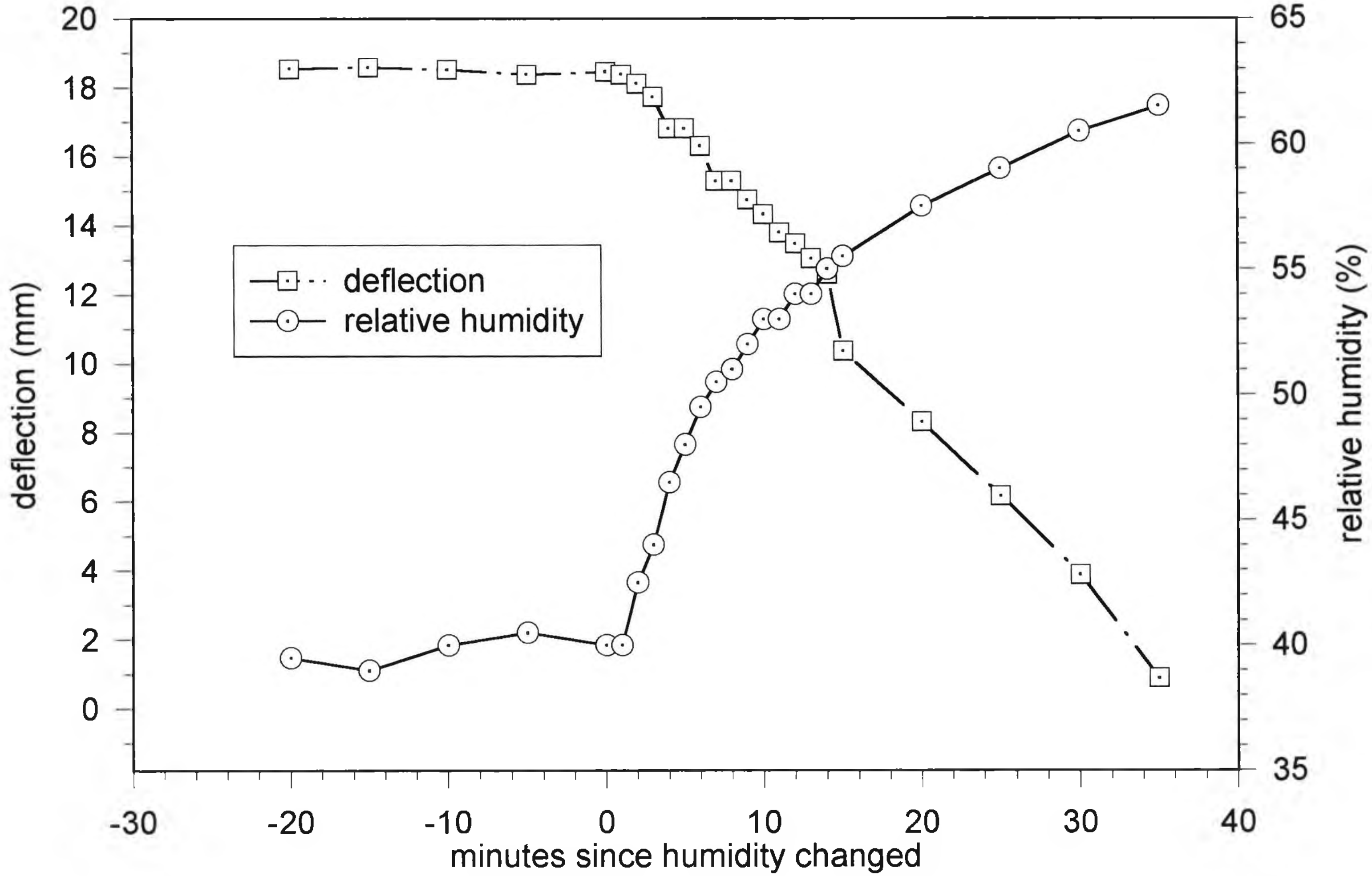


Figure 35. Warp response of coated oak during a change toward higher relative humidity.

RH. By the 9th day, however, warp had reversed direction and approached an equilibrium curvature. The greatest change for this oak panel is shown at about one day after an RH change, though it is unlikely to represent the maximum change before warp reversal. Equilibrium with an increase in RH is shown by little further change in warp after the 9th day of the extended period of high RH.

A similar sequence of temporary warp changes was shown in all three thicknesses of grounded poplar. There, transverse warp during cycling decreased in amplitude and rate with increasing thickness, with maximum amplitudes of 58mm, 33mm, and 19mm, respectively, measured at the panel center. Figure 36 shows changes during equilibration to high RH for the medium-thickness (10.0mm) poplar panel. In the detail, warp has been exaggerated by ten times to illustrate the pattern of warp reversal, numbered 1-3.

The detail shows that Buck's "awkward flapping motion" [19, p. 158] is more than just a simple transverse-grain deflection. The panel also underwent a pattern of warp longitudinally, similar to that across the grain, though somewhat less pronounced. Warp reversal occurred in both cases. Longitudinal movement was expected, but its marked influence on panel warp is of considerable interest here. Though not shown, longitudinal-grain movement followed a similar logarithmic progression to that of transverse movement. Similarly, longitudinal warp coincided with- and was proportional to- longitudinal-grain movement, which was delayed toward the coated side.

At any time during equilibration, the interaction of warp in two directions could produce a panel shape that is not simply cylindrical, with axis parallel to the longitudinal grain. Cylinders distorted into elongated spherical or saddle-like shapes could result, depending on the relative degree of warp in the each direction at any time. Both shapes were also recorded in an oak test panel using moiré fringe analysis ([16] and Appendix 7). Such changes in shape and dimensions could be expected to interact with

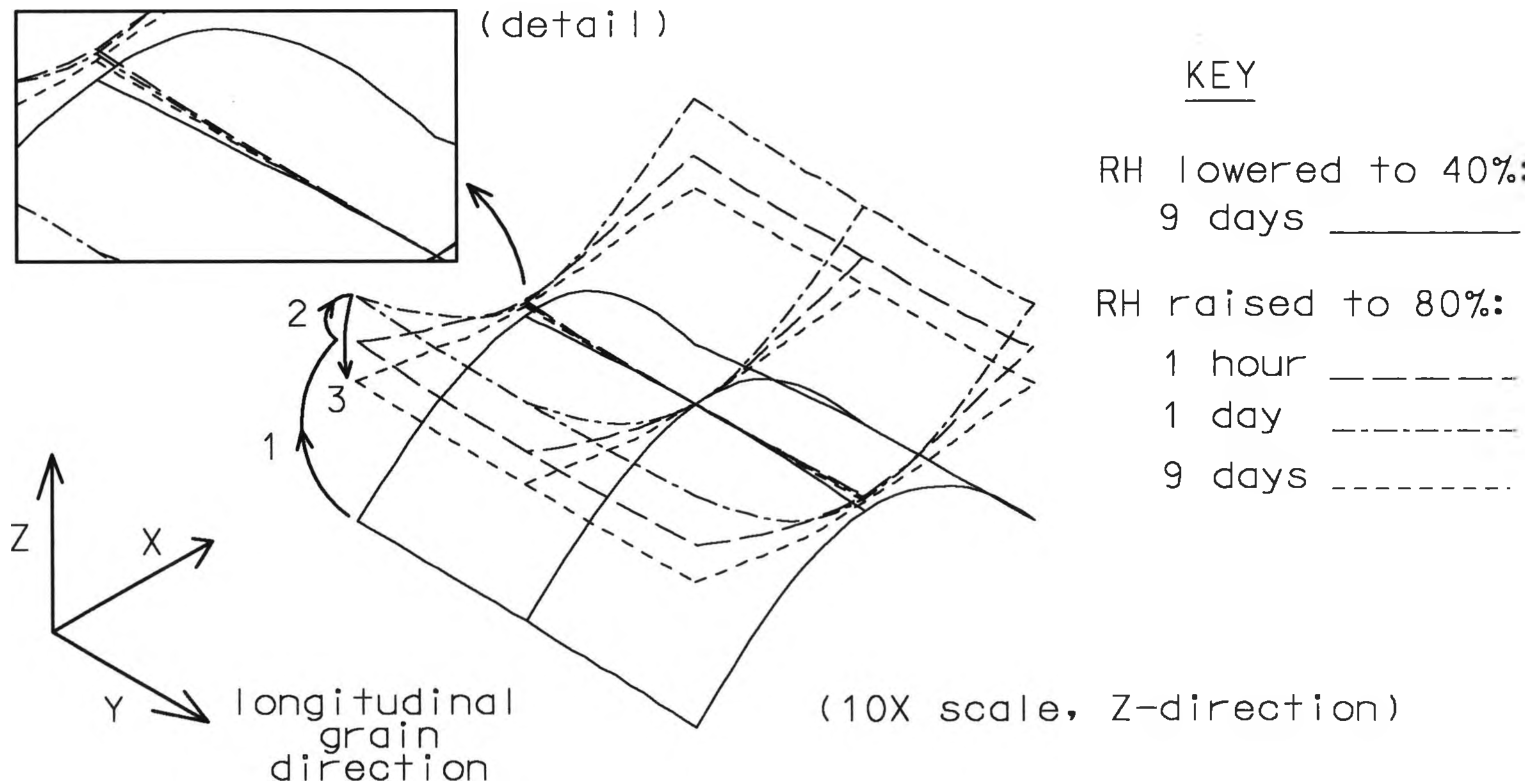


Figure 36. Sequence of warp movement in a coated poplar panel 10mm thick during a rise in relative humidity: isometric view of the front from above with warp (scale in Z direction) exaggerated ten times and changes ordered 1-3. Detail shows warp in the longitudinal grain-direction.

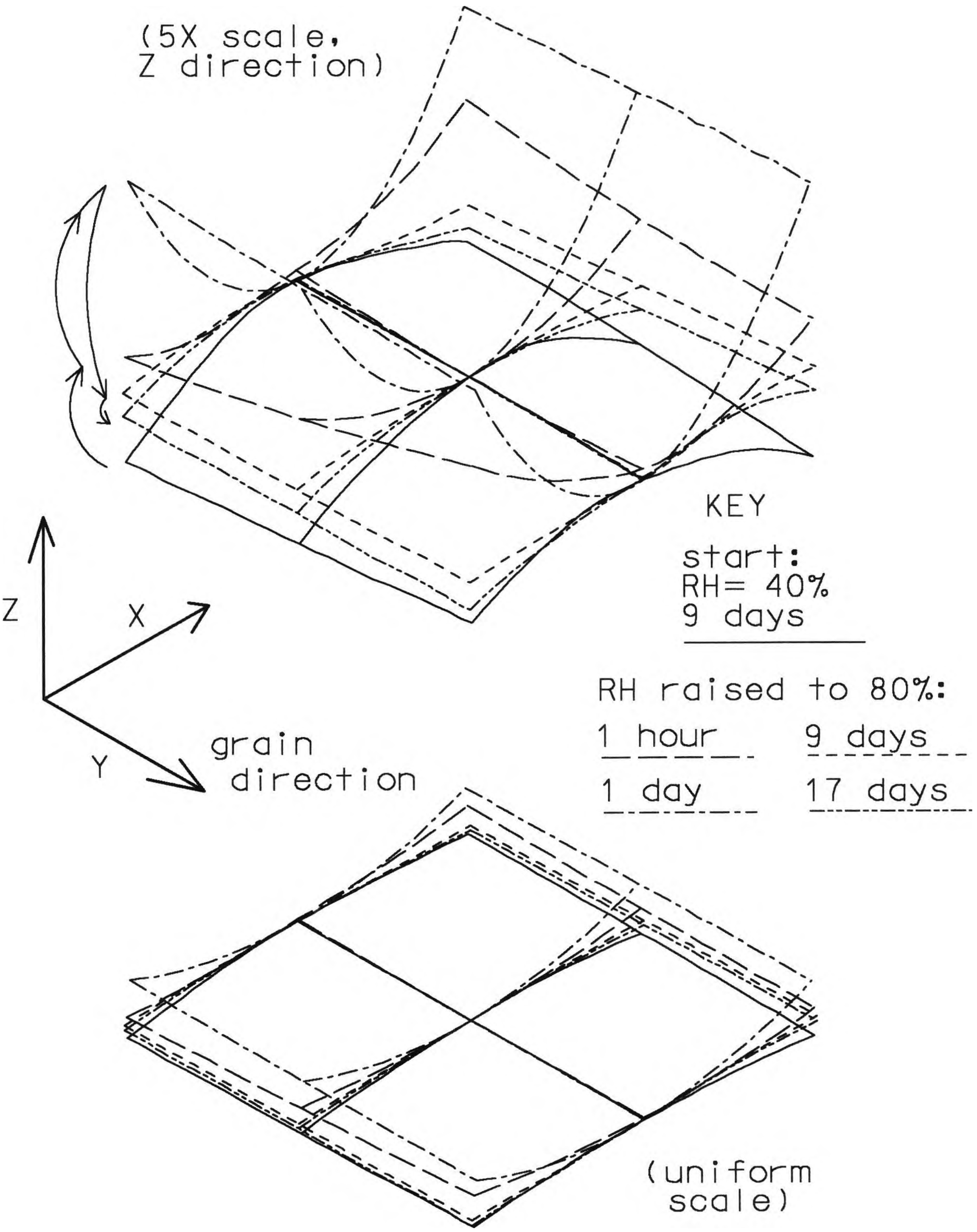


Figure 37. Coated oak, 3.30mm-thick, showing warp changes over the extended high-RH period.

reinforcement restraint in all three spatial dimensions, not just across the grain.

The 3.30mm-thick oak panel (Figure 37) showed a similar warp sequence and amplitude to poplar of the same thickness, though there were undoubtedly wood type differences not yet analysed. Also, a sequence of twist occurred which was not so evident in the thicker poplar panel, probably because of the different thickness. The observed twist may be primarily related to grain variation, more rapid and greater movement and warp having occurred toward one transverse-grain end of the panel than the other. Confirmation must await further analysis of transverse-grain movement. Longitudinal-grain deformations probably interact to modify twist more or less.

3.7.2 Reinforced panels

For reinforced panels, deviations from the pattern of temporary movement shown by coated unreinforced panels are of particular interest, as well as local deformations, whether they occurred before, during, or after RH cycling. Warp movement had been analysed to some degree for some reinforcements at the time of writing this thesis. In-plane movement remains to be explored in detail. Nonetheless, out-of-plane deformations gave a reasonable indication of certain aspects of in-plane behaviour.

In-plane and warp movement of reinforced panels depended on restraint of panel movement by the particular reinforcement. To allow movement and warp more like an unreinforced panel, elasticity of the reinforcement section would have to be less than the panel and the bending characteristics would have to be similar in all directions. The layer distribution in the reinforcement section, including adhesives, each component's elasticity, shape and dimensions would determine its elasticity and bending characteristics. Interaction of reinforcement restraint and panel movement must also be considered in relation to Poisson effects, which influence deformations perpendicular to active strains. Bodig and Jayne [124, pp. 359-385] discuss similar structures theoretically as *layered composite systems,* where bending is analysed using transformed cross sections. The subject is too complex to consider in detail here. Such an analysis is probably most easily appreciated with respect to laminates.

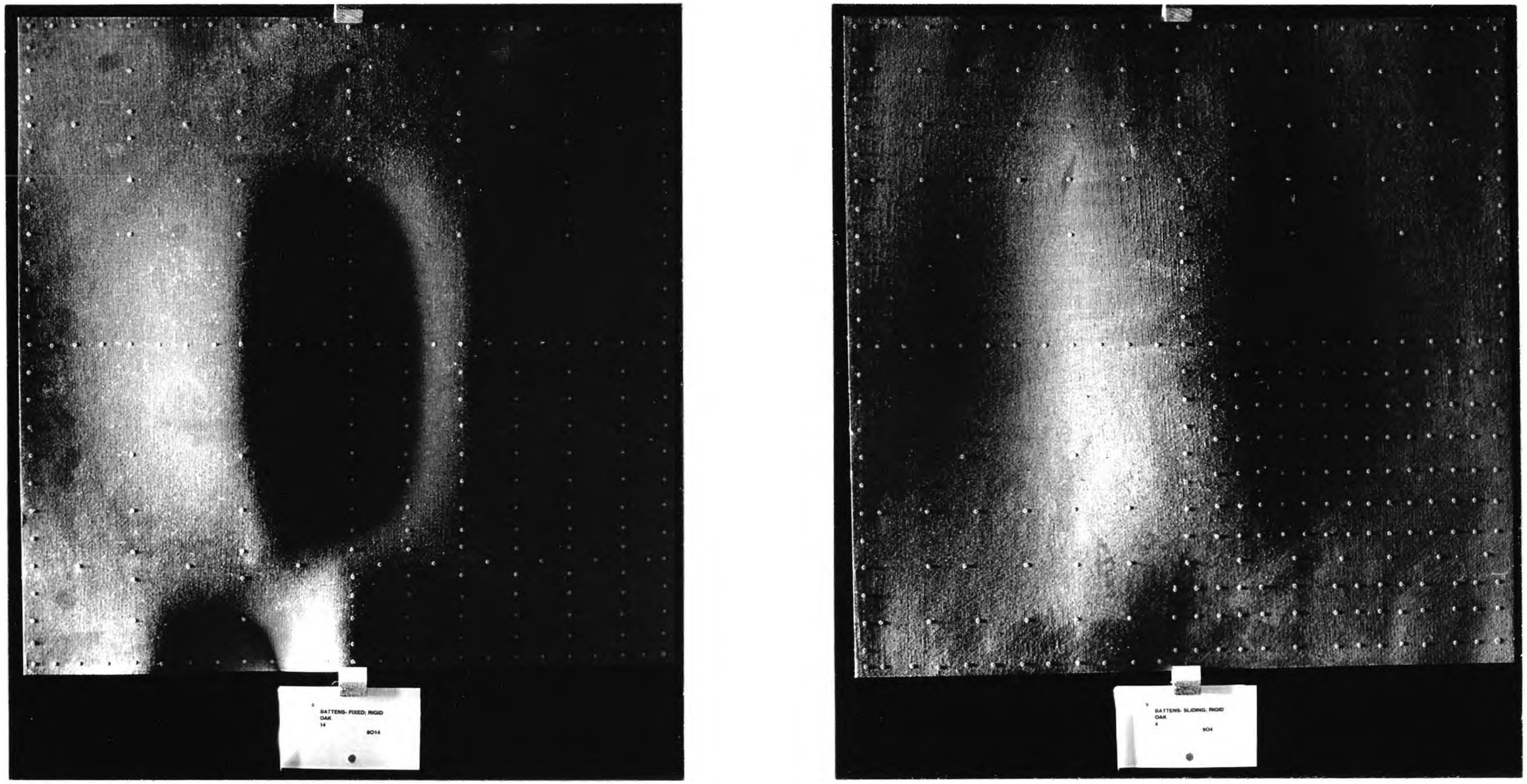
Panel/reinforcement interaction also depends on inherent movement of the reinforcement with RH or T changes, especially where it is fixed to the panel, as with fixed battens and laminates. No temperature effects were expected in the study since T was kept constant. Influence of movement of reinforcements due to RH is noted where the effect seems evident. In general, however, reinforcements were considered to have behaved as environmentally-stable structures.

In the following, Reinforcement numbers from Appendix 6 are quothed after first reference to the corresponding type.

(a) Battens

The three types, fixed rigid battens, sliding rigid battens, and sliding flexible battens (Reinforcements #8, #9, #10), will be compared and contrasted as a group.

During RH cycling, these reinforcements showed that distortions, mainly undulations and twist, increased as freedom of movement in-plane and out-of-plane was restrained. For all three batten types, restraint diminished further away from the battens so that deformations were more evident at the end-grain edges and over the exposed middle zone (Figure 38). Expansion in these less restrained regions was affected by restraint so that any initial warp was exaggerated by a buckling reaction which increased until an equilibrium dimension was reached. Twist tended to accompany the buckling. In addition, though the pattern of warp in the longitudinal-grain direction remained similar to unreinforced oak, the amplitude was greater for all three batten types. This may



a) b)

Figure 38. Deformations in battened panels shown in raking light from the left: a) fixed battens, b) sliding rigid battens, with local deformation around the retainers visible across the bottom and top. Longitudinal-grain direction is vertical.

have been related to greater restraint of warp by the battens in the transverse-grain direction.

For panels with fixed battens (Reinforcement #8), deformations directly over the battens were examined (Figures 39 and 40). When in-plane panel movement in the transverse-grain direction was restrained in shear on one side by the relatively stable battens, the panels deformed out-of-plane. The curvature of this bending reaction was always opposite to the direction in which the panel would warp were it unrestrained. Under drying conditions, an unrestrained panel (section 3.7.1(a)) initially warped convex while a panel with fixed battens bent concave, and *vice versa* under moistening conditions. However, while warp of the unrestrained panel reversed direction as the moisture gradient levelled, bending over the fixed battens increased toward a limit at EMC and persisted until RH was reversed. The force required to bend the battens must have been sufficient to cause considerable compression and tension stresses in the adjacent panel wood. Fixed battens caused the most twist of the three batten types.

Like warp during panel wood movement, twist is a way for panels to deform out-of-plane to reduce in-plane stresses. Twist in battened panels appears to be greatest under drying conditions, or more correctly, when panel contraction is restrained. Twist noted in panel paintings with original fixed battens (section 2.3.2(a)) may also be attributed to restraint of contraction, though in such cases contraction could also be due to accumulated compression set (sections 2.1 and 2.3.1) as well as to wood movement.

Panels with sliding rigid battens (Figures 38b and 41; Appendix 6, Reinforcement #9) showed less pronounced distortions than did panels with fixed battens. Under raised RH, raking-light photographs showed that the free areas between the battens showed exaggerated warp similar to a buckling reaction and some twist did develop. In addition, varying degrees of out-of-plane deformations were

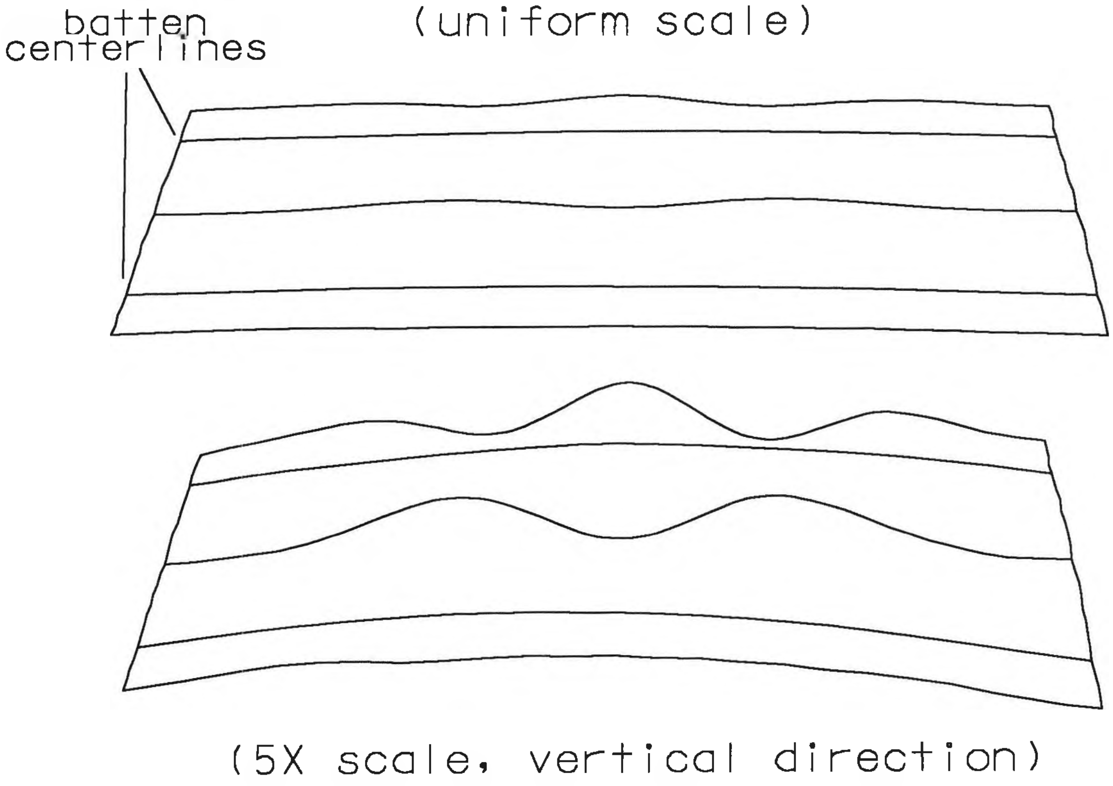


Figure 39. Deformations under raised humidity in an oak panel with fixed rigid battens. The panel is viewed from above the coated side and from one transverse-grain edge to emphasize how the free areas buckle while the fixed areas over the battens bend convexly.

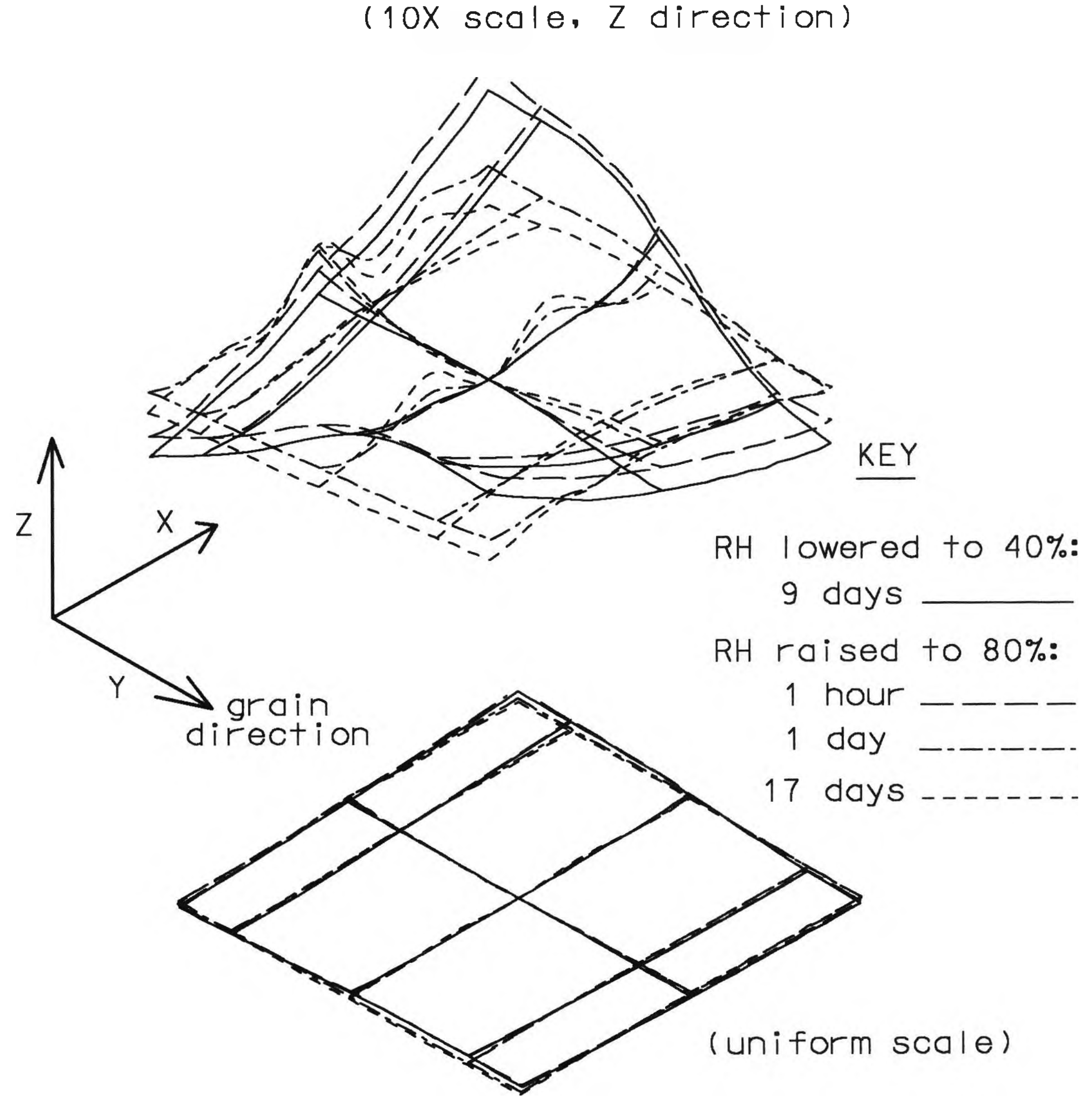


Figure 40. Isometric view from the top of an oak panel with fixed rigid battens showing changes in shape from dry to moist conditions. Note the twist, most evident in dry conditions.

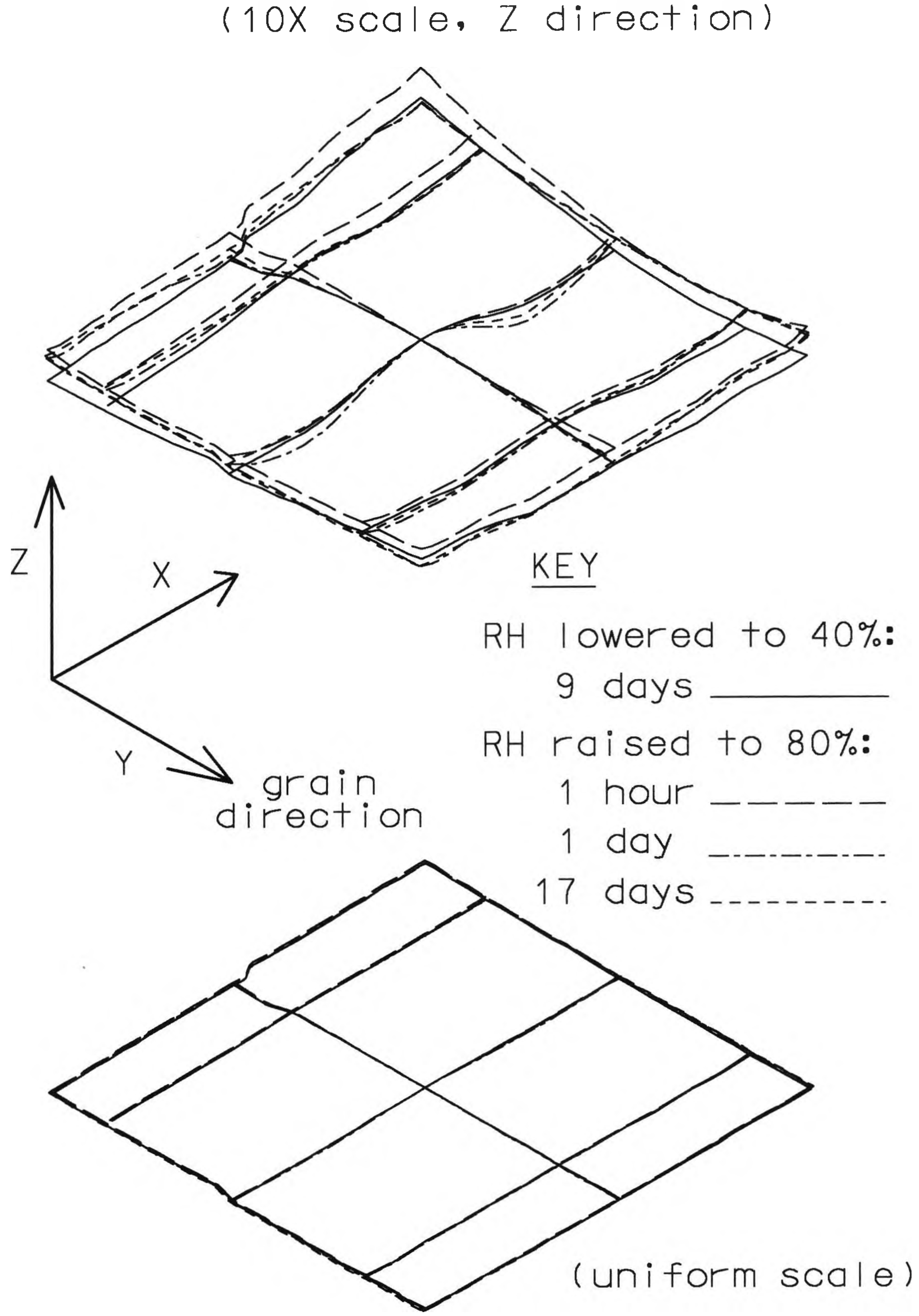


Figure 41. Isometric view from the top of an oak panel with sliding rigid battens showing changes in shape from dry to moist conditions. Note exaggerated warp in the free area between the battens.

visible in the areas beside the battens and between the retainers (Figure 38b) due to restraint of warp (ie. bending). The roller-bearing mechanisms did not seize, partly because the panels tended to bend under warp stresses. In thicker panels, greater pressures from warp restraint could develop so that seizure or breaks in the wood would be more likely. In thicker panels, this danger is offset somewhat by slower response and less amplitude of temporary warp.

During panel warping movement, the rigid sliding battens contacted the panel back, causing friction. This did not cause seizure since again, the panels simply bent, though it could do so with thicker panels.

By contrast, of the three battened panel types, those with sliding flexible battens (Reinforcement #10) allowed transverse movement and warp more like unreinforced panels (Figure 42). For most of each cycle, panels were not obviously restrained in shear so that changes in warp direction with RH followed a pattern more like unrestrained panels, even over the battens. In contrast to panels bearing the other batten types, buckling was not evident in the free area between the battens.

In panels with sliding battens of both the rigid and flexible type, transverse-grain swelling of the wooden battens caused them to contact the retainers to either side, impeding movement of the panels as they equilibrated toward the end of the high-rH periods. This in-plane restraint was similar to that of the fixed rigid battens though it did not occur along the entire batten length. Twist and localised buckling resulted. This fault could be overcome easily for the roller-bearing retainers of the rigid sliding battens by spacing them further away from the batten edges.

Such seizure was surprising for the flexible battens which were relatively narrow, made from wood classed as having small movement [138] and wax-polished with paraffin to

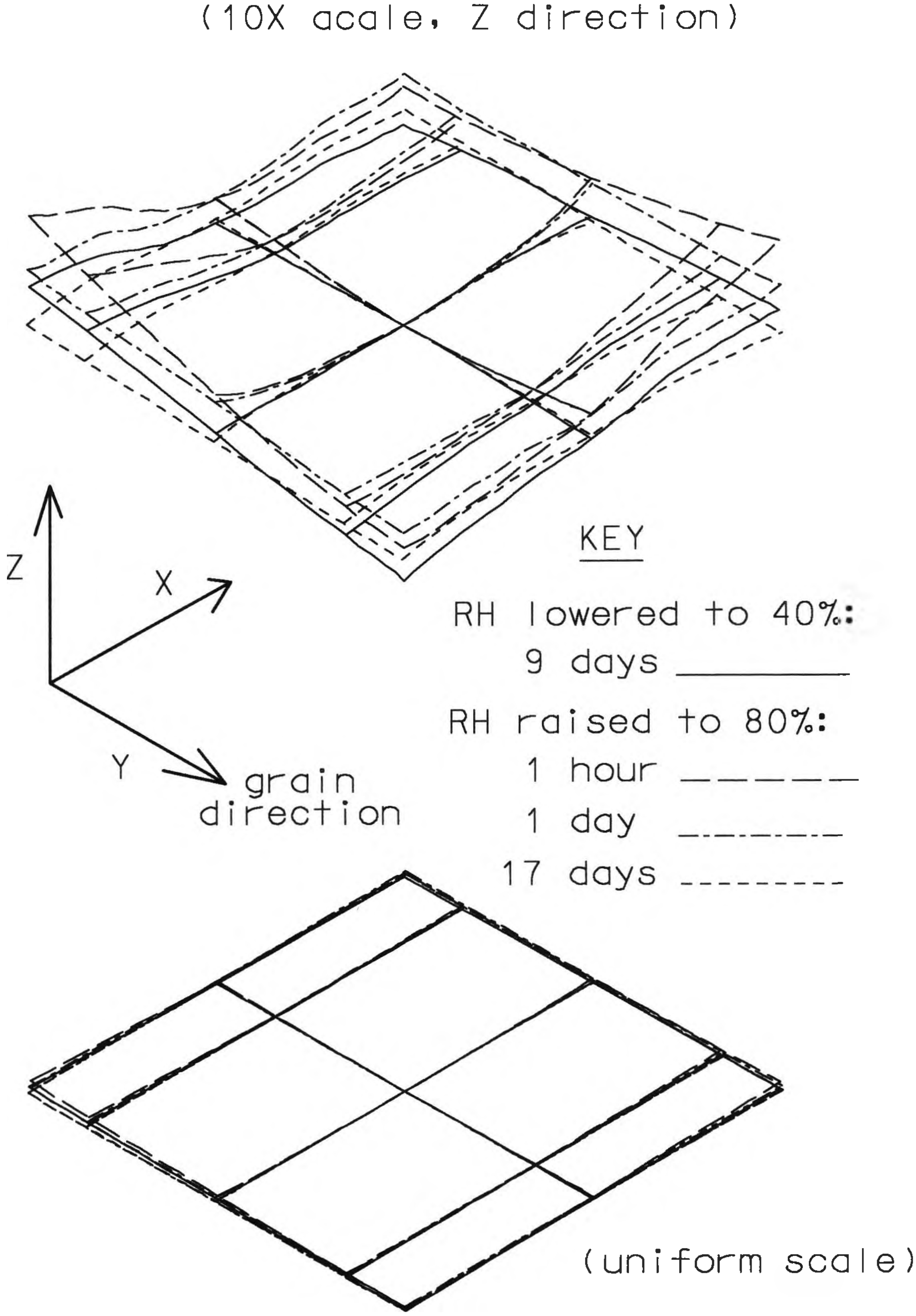


Figure 42. Isometric view from the top of an oak panel with sliding flexible battens showing changes in shape from dry to moist conditions. Note similar pattern over and between battens.

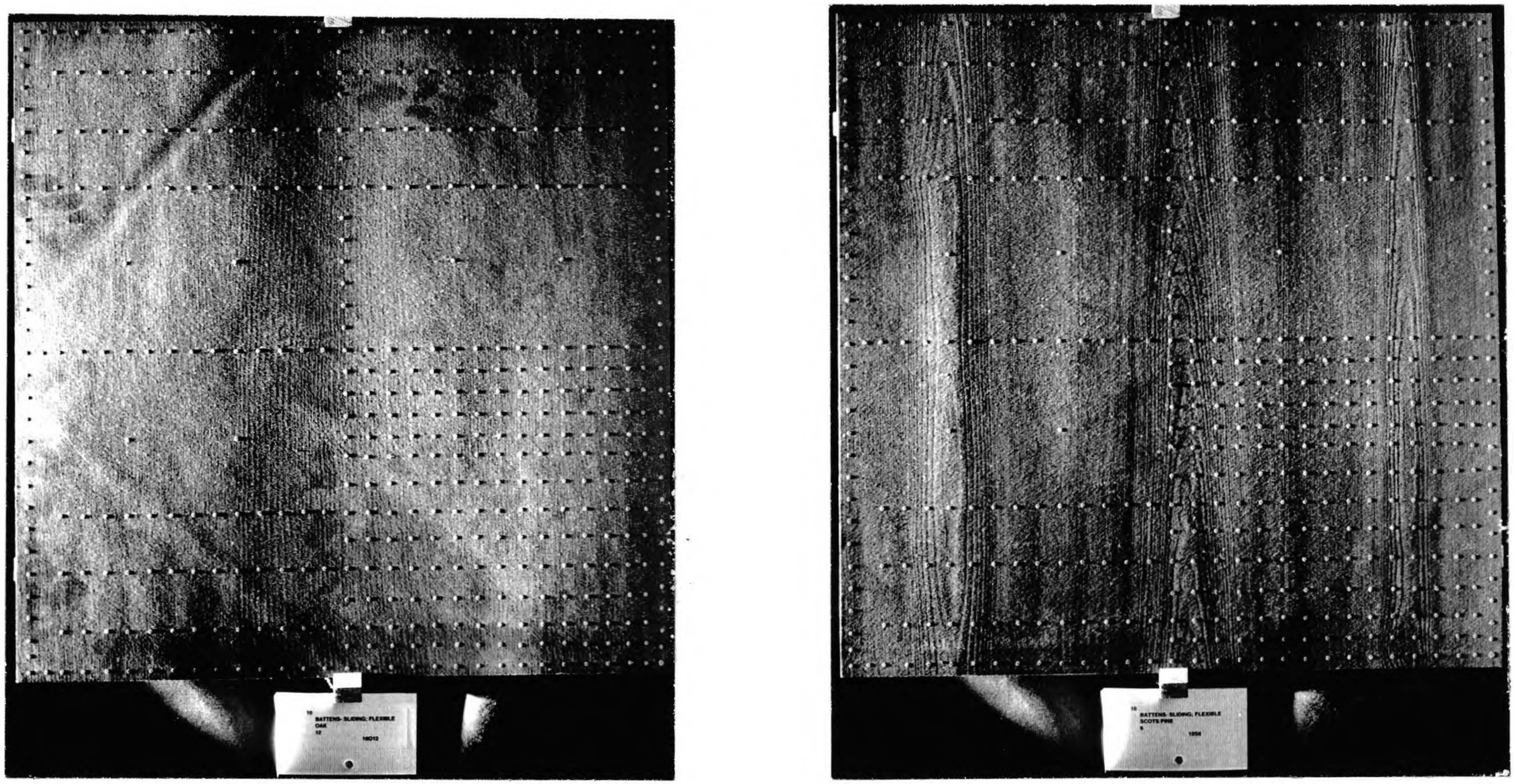
reduce friction and swelling rate. An audible creak was emitted as their transverse-grain expansion was impeded. Similar examples of this type on panel paintings examined by the author had tolerances at least as tight as the test panels. This fault might also be corrected by allowing greater spacing between batten and retainers.

Both rigid and sliding flexible battens caused local distortions to develop around the retainers as RH-cycling progressed. Viewed in raking light (Figure 43a and b), these were most visible at the end of the study. A uniform localised distortion appeared in the panel wood around each retainer of the sliding flexible battens. These distortions may have developed partly from differences in panel wood movement between and over the glued areas of the retainers.

In summary, two different types of overall deformation were detectable in battened panels: in the most restrained areas over the battens and in the areas of diminishing restraint between. These two areas were more apparent as restraint was increased, when twist and especially buckling became more evident in the more free central area. Less restraint both in- and out-of-plane allowed movement more like unrestrained panels. Retainer and batten materials and structure caused seizure under the RH extremes applied in this study. Local deformations near the battens were caused by attachment of retainers before RH cycling and wood movement during RH cycling.

(b) Lattices

Before cycling RH, the fixed and rigid lattices (Reinforcement #11) and the cradle type of lattice (Reinforcement #12) both showed distortions around the glued areas of the fixed members (Figure 44). Animal glue, used in both cases, is very strong and contracts considerably as it dries. This may have contributed to the distortions. Interestingly, retainers used for the sliding battens (section 3.7.2(a)) were glued with PVA dispersion, which is more flexible and weaker than animal glue. They



a) b)

Figure 43. Distortions around retainers developed during the study shown in raking light from the left: a) oak panel and b) pine panel with sliding flexible battens. The diagonal undulations in a) are an artifact of machine sanding during panel preparation.

did not show distortions in raking light before RH-cycling, though distortions did develop later.

Some conservators use epoxy adhesive for attaching retainers, etc., partly because it is non-aqueous and therefore less likely to swell the panel wood locally. Epoxy is a doubtful choice, however, because even in a mortar it will impregnate the panel wood permanently.

A similarly decreasing degree of restraint effects was evident in lattices as in battens, going from fixed and rigid, to sliding and rigid (cradle), to sliding and

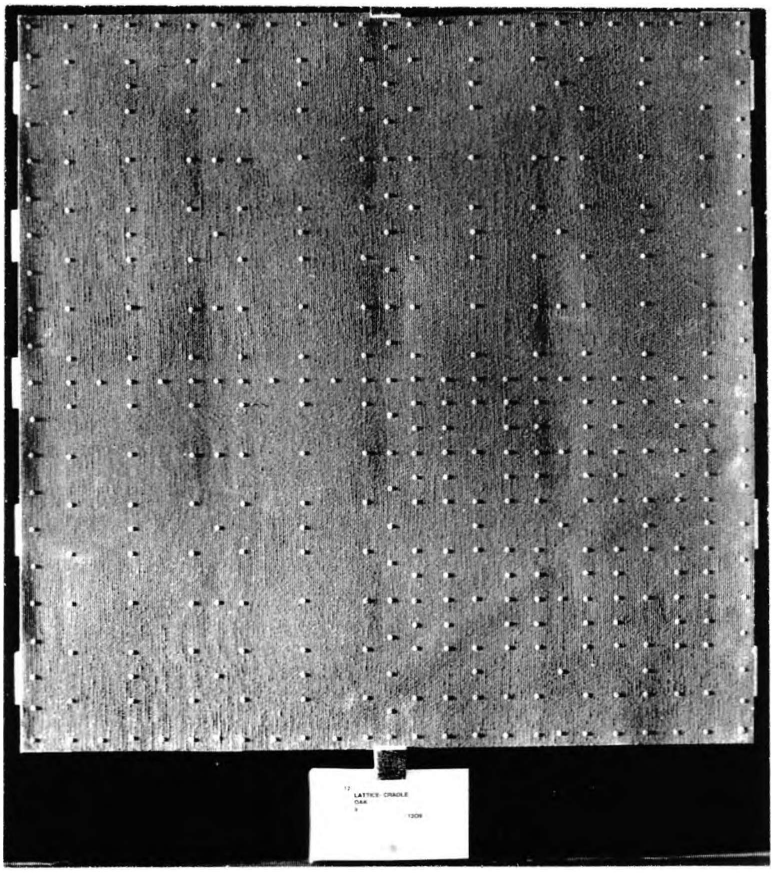


Figure 44. A cradled oak panel in raking light showing distortions around glued areas of fixed members immediately after cradle application.

flexible types. The fixed lattice provided a relatively uniform shear restraint of in-plane movement overall, similar to a laminate (section 3.7.2(d)). Out-of-plane deformation was opposite to the warp of an unrestrained panel and it was relatively uniform. This may be compared to the fixed battens, where restraint of in-plane movement was non-uniform and was accompanied by twists.

For fixed lattices and cradles, out-of-plane deformation occurred parallel to the panel grain as well, suggesting that restraint in shear of panel movement parallel to the grain (section 3.7.1(a)) could also be causing distortions. Similar to transverse-grain effects of fixed battens (section 3.7.2(a)), deformation was an overall bend in opposition to the direction the panel would warp were it unrestrained.

Such longitudinal-grain deformation was of particular interest because it has been observed in cradled panel paintings (Figure 22). This could be due to a difference in MC between the panel and fixed members when the cradle was applied. If, for example, the panel were moistened for flattening and then cradled, then it would contract afterward, putting shear stress on the fixed members so that a concave warp would occur in the longitudinal-grain direction. Another cause may be that the fixed members lying parallel to the panel grain, because they are usually thicker and of a different wood type, would equilibrate to RH changes more slowly and to a different degree than the panel wood, especially where it is exposed to either side.

Moiré fringe analysis was useful in analysing cradle effects in greater detail. During a rise in RH, in-plane compressive strains were detected in the glued areas over the fixed cradle members ([16] and Appendix 7, Figure 16). It seems likely that similar compressive strains could occur when such thin panels are restrained flat locally, whether by fixed lattice members or even glued retainers.

With the help of moiré-generated strain maps, the development of "washboarding" was explained theoretically in greater detail than previously. Possible causes of damages such as splits and flaking paint were identified at a local level and related to restraint of both in-plane and warp movement. At the panel surface, in-plane movement in the transverse-grain direction appears to be increased by restraining warp in a flat plane. This was suggested theoretically by Buck [19, p. 160] when he described cradle-like restraint under drying conditions,

"With the free control device [such as a cradle or rigid sliding battens] the normal shrinkage [in the transverse-grain direction] is not inhibited; but the increase in warp is restrained and translated into amplified compressive strains on the front sides, amplified tension on the back."

Increased compressive strains could contribute to overall compression set in the panel wood. As evidence of this, a reduction in transverse-grain dimensions was visible in cradled panels by the end of RH cycling. The sliding battens projected slightly more beyond the panel edges after cycling than when the cradles were applied, also noted by the author in several cradled panel paintings.

Panels with sliding flexible lattices (Reinforcement #13) warped similarly to unrestrained panels, though warp was partially restrained. This behaviour was similar to the sliding flexible battens. Unlike them, however, little or no twist was observed and areas of greater and lesser restraint of warp were not detectable by visual inspection. This type of lattice restrained in-plane and warp movement much less than the other lattice types, both perpendicular and parallel to the panel grain. While moving the panels on and off the shelves during measurements, the perimeter frames allowed safer handling as intended, even though the test panels were not physically as weak as most panel paintings of similar dimensions. Given plenty of room for in-plane expansion and warp, however, panels tended to slide sideways when handled, away from their previous position. This would be a disadvantage where the visible area of the painting must remain stationary within the sight-size of the frame proper. The fault could be corrected by some type of stop to maintain the initial position rather than packing the panel edges in the perimeter frame, which could inhibit panel expansion.

Despite the relatively narrow retaining strips, their expansion during rising RH caused them to contact some of the retainers. Again, this indicates how easily wood movement is underestimated with respect to panel reinforcements. Though not directly interfering with panel movement, as the sliding flexible battens did under raised RH (section 3.7.2(a)), the expanding strip could apply sufficient torque to the panel via the retainers to cause damage. Greater spacing between the strip and the retainers would avoid this problem.

(c) Trays

The sliding flexible tray (Reinforcement #14) was applied only to one panel of oak because of study constraints and because the principle and structure of the supporting lattice is very similar to the sliding flexible lattice (Reinforcement #13). Of all the reinforcements, it appeared to affect panel movement least. The panel was fitted quite loosely against the perimeter frame rebate and the backing panel was also not sealed tightly. Ambient humidity could diffuse to the enclosed space behind. Thus, though enclosed against rapid RH changes, moisture exchange was not mainly limited to the front surface, as in the more tightly sealed foam-cushion tray (below). However, during handling, as for the attached flexible lattice, loose fitting against the perimeter-frame rebate caused the panel to slide sideways from its initial central position. Otherwise, like the sliding flexible lattice, handling seemed to be safe.

Though not strictly a lattice structure, the foam-cushion (NG) tray (Reinforcement #15) combined a lattice-like support with a perimeter frame. Panel edges were fixed in-plane and RH changes were restricted mainly to the exposed front due to the sealed back and close fitting of foam strips at the rebate edges. This probably partly accounted for development of centralised convex bulges under high RH

(Appendix 8, Photo No.136). Also, rigidity of the structure, including the foam cushions, restricted warp so that bulges were probably encouraged during expansion under rising RH.

The relatively tight fit within the foam-cushion tray also hindered transverse movement, contributing to distortions. More responsive pine and oak panels, especially, did not have sufficient width to expand fully in the rebate. It was necessary to remove the panels briefly from the trays to plane them to fit with more space, which would not be appropriate with panel paintings. These events could have been partially prevented by allowing greater space at the longitudinal edges for expansion and by reducing foam rigidity throughout, especially at the back near the longitudinal edges.

(d) Laminates

Like battens and lattices, the laminate materials used in this study may also be arranged in approximate order of decreasing rigidity, ignoring the respective adhesives, as follows: MDF, oak planks, oak parquets, balsa plank laminate, balsa blocks, honeycomb-core, and paper strips (Reinforcements #20, 22, 23, 18, 19, 4-6, 7, respectively).

For a given laminate/panel combination, deformation from shear restraint was dependent on the elastic properties of the laminate with and across the panel grain. Poisson effects within the laminate probably also influenced deformations of the structure as a whole.

As noted above for fixed-batten reinforcements, in-plane shear stresses from transverse panel movement tended to cause out-of-plane deformations. These distortions were resisted to a degree which appeared to vary directly with the rigidity of the panel/reinforcement structure. Thus, more flexible laminates allowed greater and more irregular distortions from shear stresses than did more rigid laminates. Paper strips (Reinforcement #7) and the various honeycomb-core laminates (Reinforcement #4, #5, #6) all caused large out-of-plane deformations that differed greatly from warp of unreinforced panels.

Effects of adhesives were also more evident with these more flexible laminates. During laminate application, the over-extended honeycomb-core laminate warped quickly as moisture from the drying core adhesive (PVA dispersion) entered the panel back, despite being adhered over a tissue/BEVA layer. Such warps could be easily "locked in" if the adhesive solidified before the panel could return to its initial shape. During RH cycling, the epoxy/microballoon adhesive used to adhere the other two honeycomb-core types added considerable stiffness to the final laminates despite its inherent flexibility. It probably also provided too great a moisture barrier.

Further comments on these flexible laminates must await further analysis of the photogrammetric images. From the general deformations observed, further analysis is of academic interest only and of limited value for this thesis.

(i) MDF

It is best to now consider the most rigid laminate, prior to discussing the balsa laminates most associated with panel painting reinforcement. The panels with MDF laminate (Reinforcement #20) were relatively flat before RH cycling and very rigid in terms of handling. During cycling, however, they showed out-of-plane deformations which were approximately opposite in shape to those of the unreinforced panels, indicating considerable restraint effects. Being rigid, restraint in shear was overall, from edge to edge, so that panel expansion or contraction across the grain was prevented across the entire width. This must create considerable shear stress.

Under raised RH, expansion of the panel on one side of the MDF laminate eventually caused a convex deformation across the grain, where wood movement is greater, and a concave deformation parallel to the grain, producing a saddle shape (Figures 45 and 46). The transition from dry conditions, where a less pronounced saddle shape of opposite curvature occurred, to moist conditions, saw each panel go through an intriguing range of contortions. These were remarkably symmetrical in that little twist occurred. The symmetry may be due to the isotropic elastic properties of MDF, which has a relatively amorphous structure. Incredibly, transverse movement of even the relatively elastic poplar panel applied sufficient in-plane shear stress to bend the MDF, though to a lesser degree than did the oak panel. Out-of-plane deformation from shear stress generally increased with wood density as a result of greater movement and elastic modulus.

Bending a relatively stiff panel like MDF of any appreciable thickness produces a saddle shape due to Poisson effects. Greater movement across the panel grain would cause bending to be greater in that direction, less in the longitudinal grain direction. This gives the saddle shape a consistent orientation so that, under dry conditions for example, the panel is convex across the grain and concave parallel to the grain.

After cycling, the MDF panel laminated to oak showed a saddle that was convex in the direction perpendicular to the panel grain. The panels were delaminated at both longitudinal-grain edges. The poplar/MDF laminate showed a similar but much less pronounced saddle, with no delamination. This shows evidence of stresses which varied with panel stiffness and suggests that the wood panels and/or MDF panels may have undergone some plastic deformation during cycling. Considering the obvious bending stresses undergone by the MDF panel in relation to oak, this does not seem surprising.

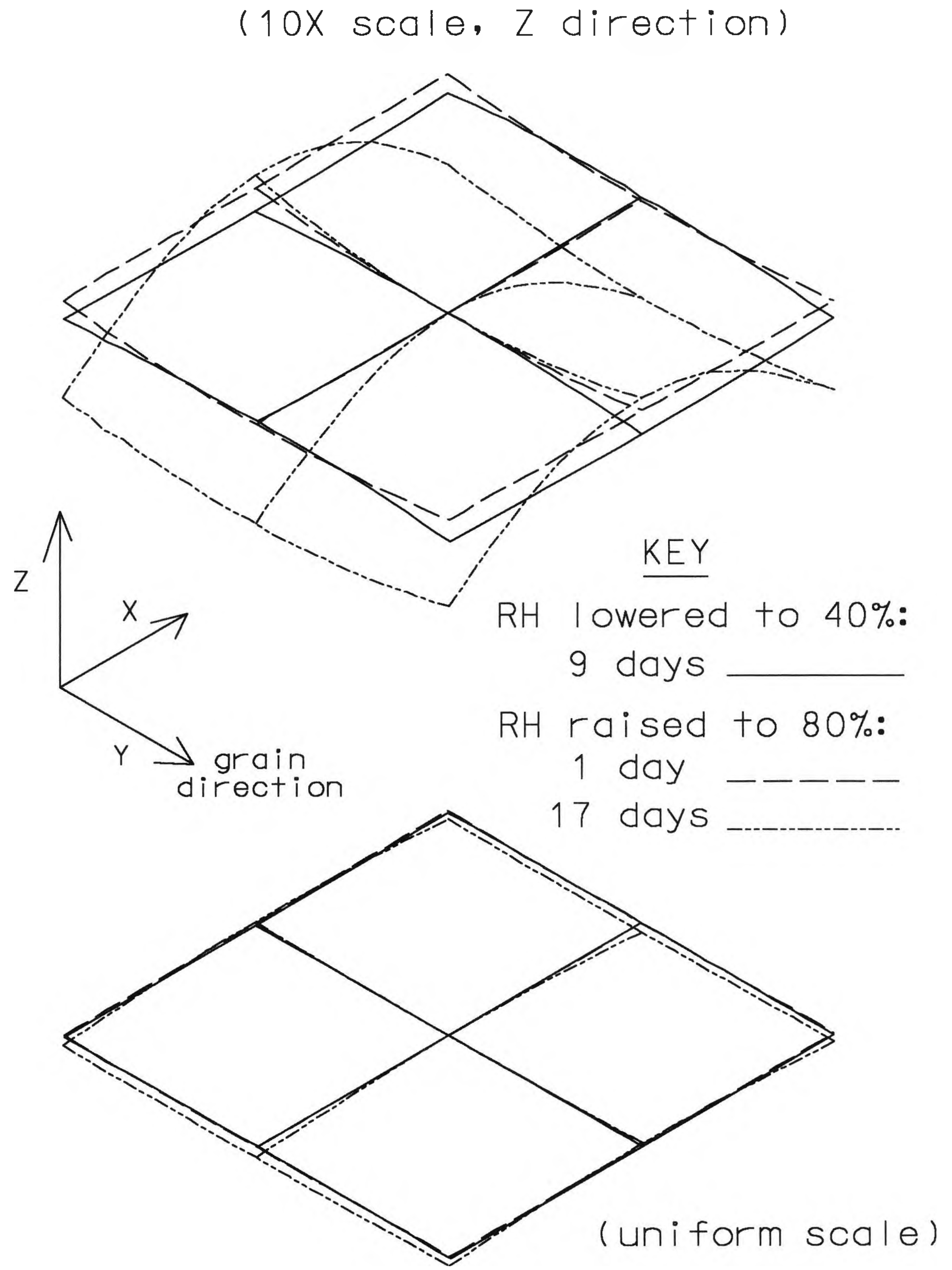


Figure 45. Changes in shape of an oak panel laminated with medium density fibreboard (MDF) in going from dry to moist conditions.

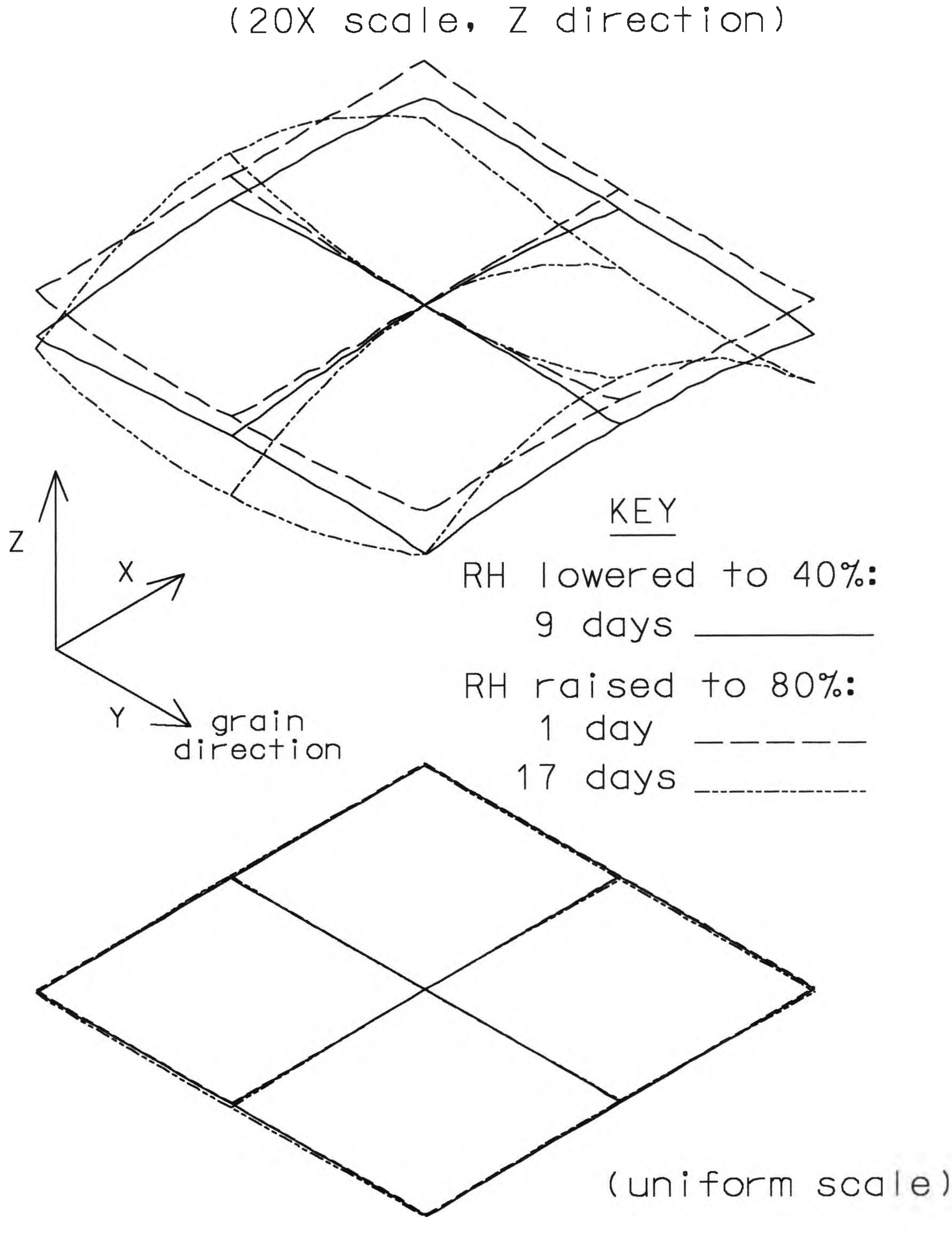


Figure 46. Changes in shape of a poplar panel laminated with medium density fibreboard (MDF) in going from dry to moist conditions.

(ii) Balsa Laminates

Before RH-cycling, close attention was given to possible deformations resulting from the two methods of balsa application. Heat was required in various stages, more for the plank (Reinforcement #18) than for the block type (Reinforcement #19).

In the balsa plank laminate, some oak planks were observed to rapidly assume slightly greater cupped warp during the application process. This occurred when the adhesive-impregnated fabric isolation layer was applied to the panel with a tacking-iron. The heat of the tacking-iron may have caused the panel to conform to latent drying stresses in the planks (see section 2.1, above). A high temperature setting (+120C) was necessary to transfer heat to the panel surface and to overcome rapid heat dissipation in the wood. Similar deformation was not observed in the other wood types but it is possible that they reacted similarly.

Such a cause of deformation is especially of interest for thinned panel paintings. Heat application could cause rapid reactions due to both latent drying stresses in the planks and elastic stresses incurred since the panel was constructed. Rapid strain would threaten paint/ground-layer stability.

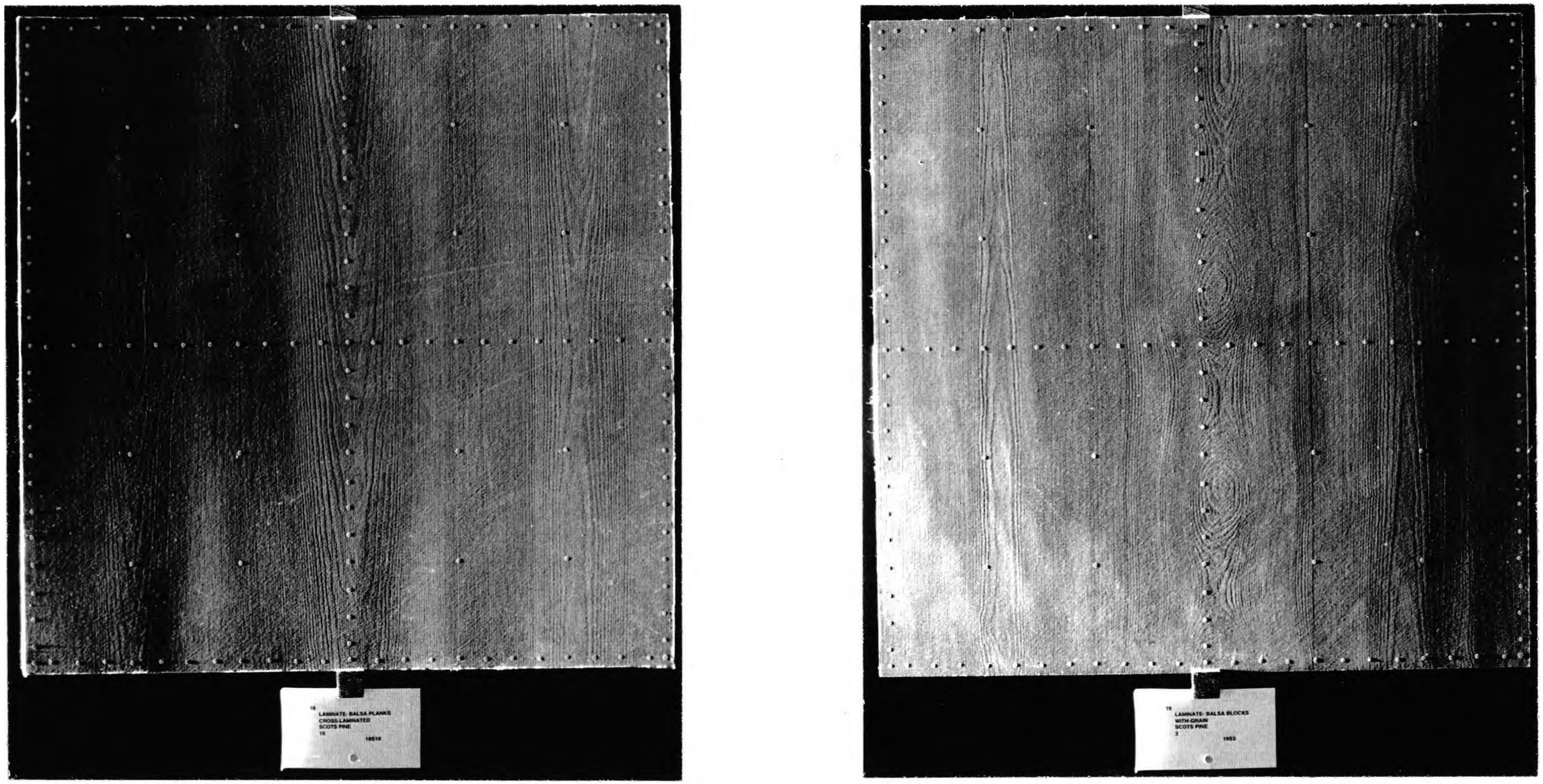
Heating the balsa planks on one side prior to their application caused them to contract across the grain and warp toward the heated side. The balsa may regain lost moisture for some time after the reinforcement is in place, causing expansion across its grain and a shear stress at the panel back. This could be one cause of such panels undergoing concave deformations. This process could extend over a considerably long time, depending on the visco-elastic properties of the laminate structure of panel, balsa, mortar, and fabric layer.

Though not documented in the literature, some paintings laminated with balsa and wax-resin adhesive have been observed to develop twists and/or concave distortion soon after lamination [95]. Before cycling RH, this was observed to varying degrees in all panels which received cross-laminated balsa planks (Figure 47a), while those reinforced with balsa blocks tended to assume a slightly convex warp (Figure 47b).

Several explanations have been suggested for such distortions. Observations on wax-resin behaviour during application of the balsa block laminate revealed another explanation which the author feels is quite plausible.

Wax contracts substantially in volume as it goes from liquid to solid phase. This is visible, for example, as an indented surface when molten candle wax contracts around a wick as it cools. The wax-resin mixture was observed to contract considerably as it cooled in containers used during this study. In the plank laminate, the wax-resin layers were quite thick and sandwiched between balsa layers so they solidified as a unit. It took several hours, perhaps fifteen or more, for the balsa plank laminate to solidify and cool to room temperature. Though some plastic flow of adhesive occurred during contraction, sufficient cohesion would develop to apply contractile stress to the laminate and panel back before contraction ceased, especially in thicker wax-resin layers. Wax-resin contraction during application of such laminates was observed independently by Glatigny [86], who modified technique to compensate for possible detrimental effects.

If stresses develop as such, the type of distortion- whether concave or convex- would depend partly on relative stiffness of the panel and reinforcement layer(s) as they restrained contraction of the wax-resin in shear. The position of the wax-resin layer relative to the other layers in the section is also a factor. Also, thicker layers contracting as a unit would apply greater stress



a) b)

Figure 47. Distortions in panels immediately after lamination with balsa and wax-resin, shown in raking light from the left: a) pine panel with balsa plank laminate before RH cycling showing concave warp, b) pine panel with balsa block laminate before RH cycling showing convex warp.

across a panel than would thinner layers applied and cooled in smaller discrete areas. The former was characteristic of the balsa plank laminate, while balsa blocks were applied as in the latter case.

Extensive analysis is beyond the scope of this thesis, but in general, stiffer reinforcement at the panel back would tend to hinder contraction there, bending the entire structure forward toward concavity. A less stiff reinforcement would allow more contraction toward the back, with less tendency to concave bending. Here, the balsa plank type was a considerably stiffer reinforcement than the balsa block type. Cooling and contraction occurred overall and as a unit in the balsa plank type, with both plank layers already in place. Deformation probably developed at the same time.

Conversely, a consistent convex deformation occurred with the block type that may also be attributed to contractile stresses from the wax-resin. The blocks and adhesive are placed consecutively so they cool relatively quickly and in discrete areas. The reinforcment is less stiff and the blocks can conform more independently to local adhesive contraction. Contractile shear stress is therefore shifted toward the back of the layer structure and away from the stiffer panel side, toward convex deformation.

These contractile effects would probably be less evident in more rigid panels of greater thickness or denser wood type. Distortions such as twist would be less likely than in more flexible panels. Smaller panels would also be less affected because shear stress across the grain would decrease in proportion to total movement.

Warp in panels already laminated with balsa planks has been reduced by heating the panels under a vacuum envelope until the adhesive plasticizes sufficiently to allow movement between layers [139]. It is worth noting that such behaviour of wax-resin could cause contractile stresses during the cooling of wax-lined paintings on fabric.

Differences in stiffness of the laminates was also evident in deformations during cycling (Figure 48 and 49). Comparing oak panels, both types of laminate showed out-of-plane deformations similar to those associated with in-plane shear restraint, bending opposite to warping observed in unreinforced panels (section 3.7.1(a)). Furthermore, the plank laminate behaved more like MDF, showing saddle-like changes similar to a stiffer laminate (Figure 48). The block laminate deformed almost exclusively across the panel grain direction (Figure 49). This suggests that the balsa blocks were less stiff, conforming better to bending stresses. Nonetheless, both types of laminate appear to have applied considerable shear restraint to the panels.

The balsa block laminate was simpler to apply than the balsa plank type. Much less adhesive was used. Thus, the total weight and the moisture barrier effect were less. When the preparation time for materials is considered, the time for application was probably about the same.

For the block laminate, it is easier to tool the back surface of either balsa layer, either to create a flat substrate for the next layer or to produce a satisfactory appearance for the back surface. This is because there is virtually no wax-resin present at the surface. Any adhesive on the surface will immediately clog most bladed tools. This limits tooling options if adhesive is present in excess, as in the balsa plank laminate.

(iii) Oak Laminates

At 4.0mm, the two oak laminates were slightly thicker than the oak panels to which they were applied. The plank laminate (Reinforcement #22) was therefore more rigid than the panel, but rather than being static or having a much different transvere-grain movement than the panel, both it and the parquet laminate (Reinforcement #23) would tend to respond to changes in MC to a similar degree. Unlike the parquet laminate, the plank laminate bore a tissue layer

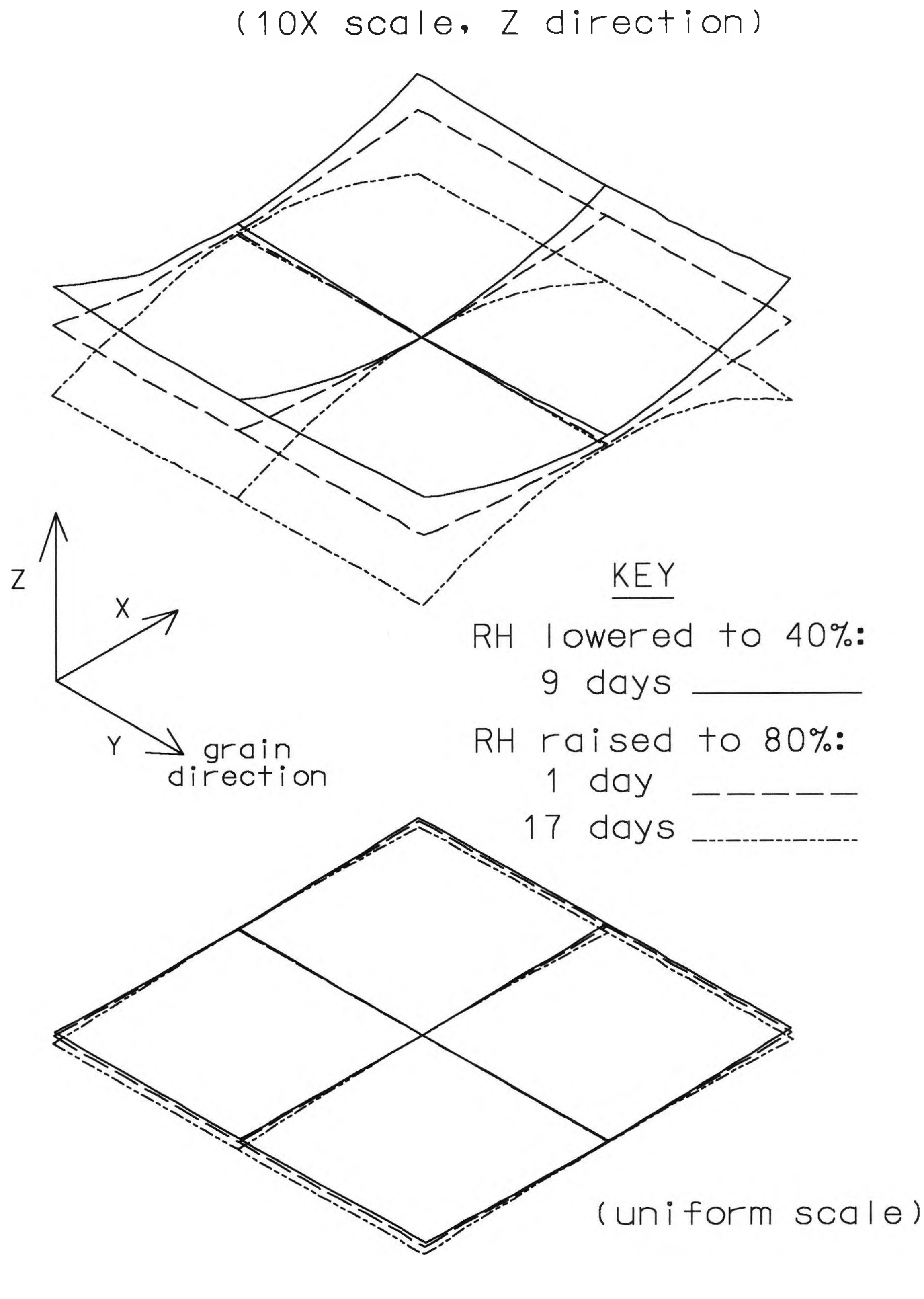


Figure 48. Changes in shape for an oak panel laminated with balsa planks and wax-resin in going from dry to moist conditions.

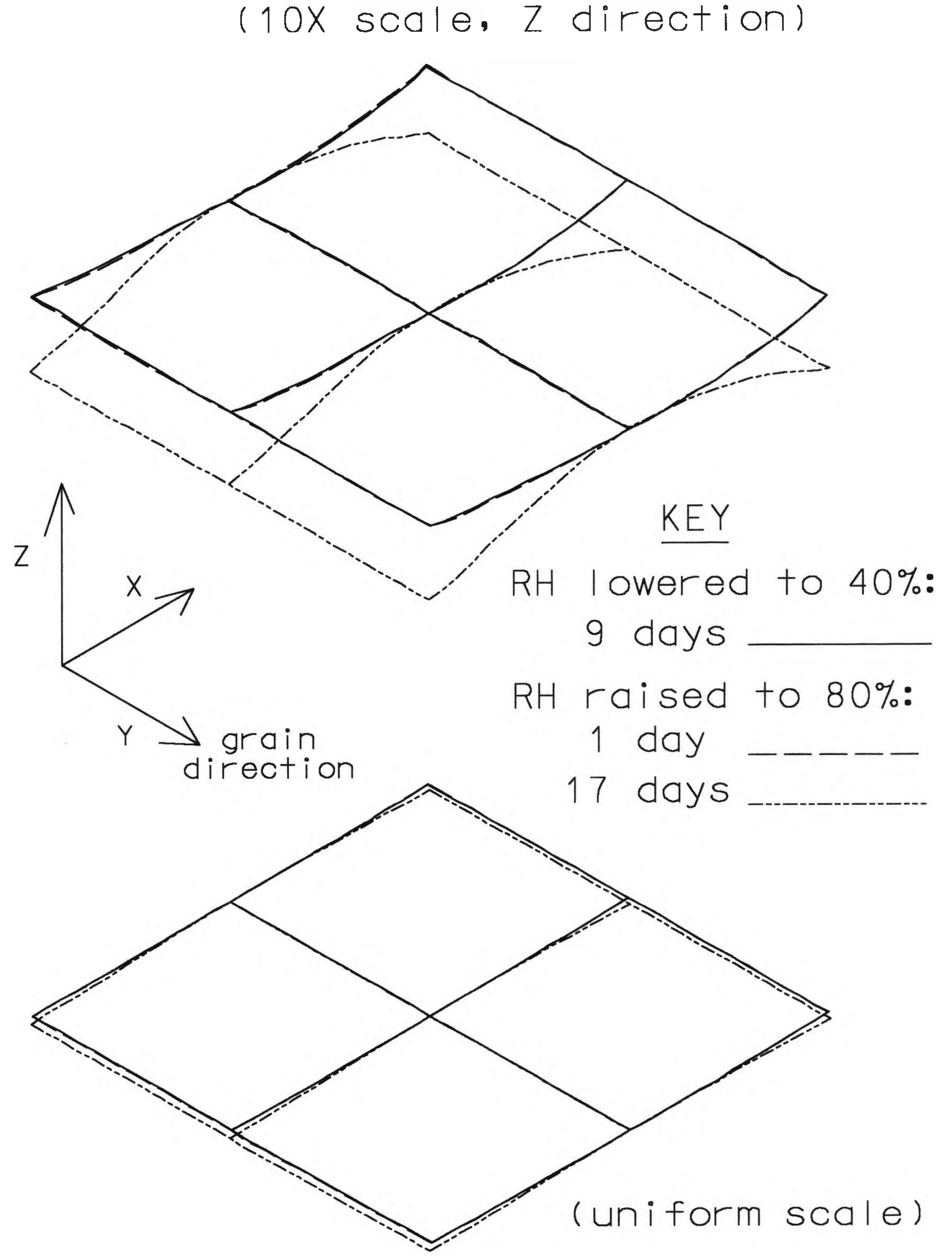


Figure 49. Changes in shape for an oak panel laminated with balsa blocks and wax-resin in going from dry to moist conditions.

between the wood layers. It seems unlikely that the tissue would have changed the relative stiffness of these laminates very much.

Figures 50 and 51 show their warping over time, both very similar to that of coated unreinforced oak (Figure 37), even in the longitudinal-grain direction. The amplitudes are about half that of coated oak, in keeping with the greater thickness of the laminated panels. It is tempting to conclude that the oak-laminated panels were moving similarly to oak panels of the same total thickness. However, the plank type delaminated in the BEVA/tissue layer, extending from both longitudinal-grain edges to about 100mm into the panel middle, indicating differential movement and shear stresses. The parquets did not delaminate though it is still likely that shear stresses occurred because of in-plane restraint, mainly from the epoxy adhesive. Because of their greater thickness, it may be that the back laminates also dominated warp movement, again due to their slightly greater thickness. More may be learned after analysis of transverse-grain movement.

(e) Perimeter Frames

Three reinforcement types were classed as perimeter frames, though other types also employed them as part of their structure, such as the trays and sliding flexible lattice. The main reason for classifying the three types as such was because the frame is an integral and/or primary part of the structure.

The rebated frame with brass retainers (Reinforcement #16) showed how excessive restraint of panel warp by retainers can cause softer panel woods to catch, impeding transverse movement as well, especially under humid conditions when woods are softer. Blocked between a retainer and the frame rebate during subsequent expansion, the pine and poplar panels both tended to buckle. In all panels, restraint of warp by the retainers caused local deformations from bending. Though any panel can be too rigidly restrained by

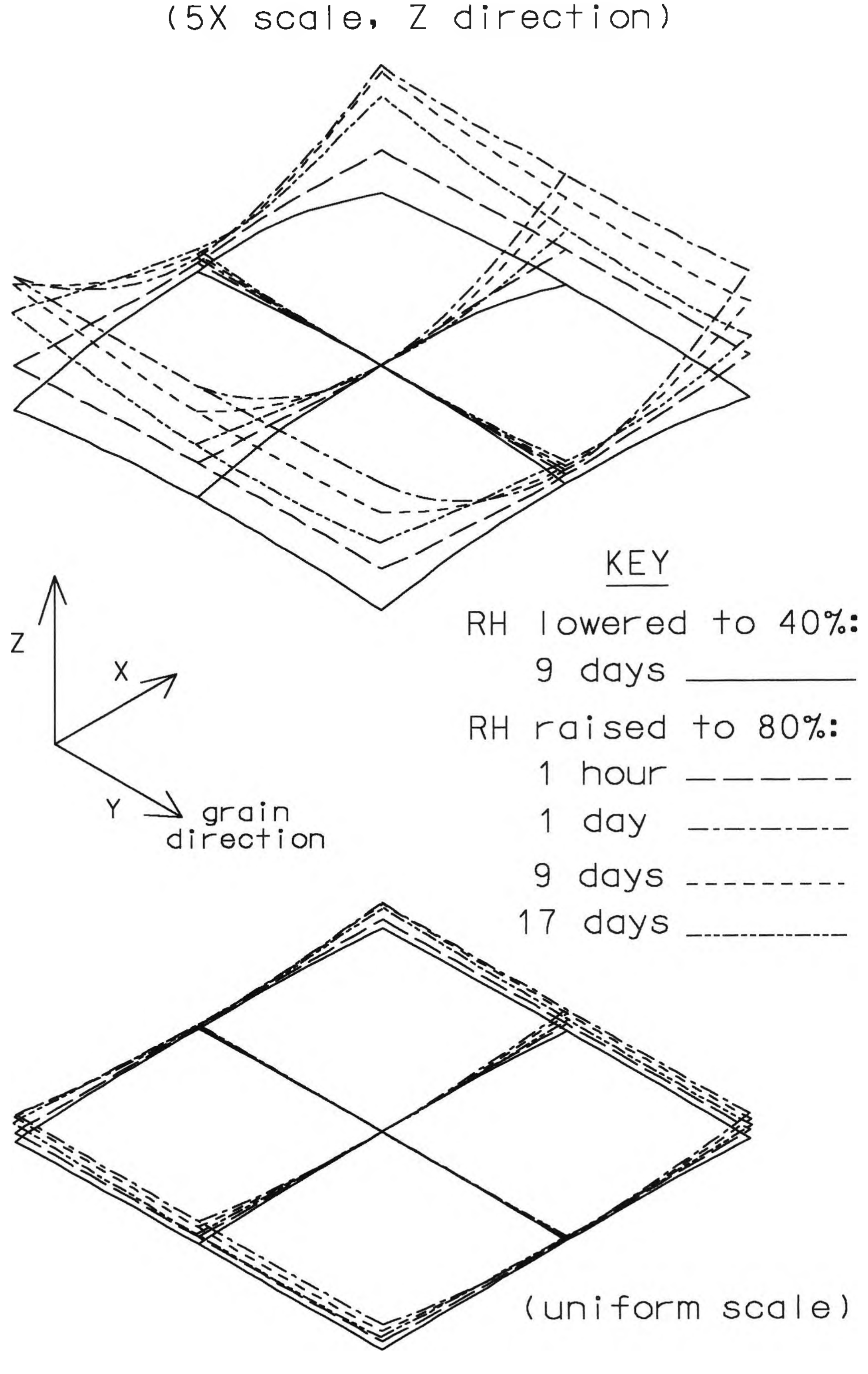


Figure 50. Changes in shape for an oak panel laminated with oak planks, grain parallel to that of the panel, in going from dry to moist conditions.

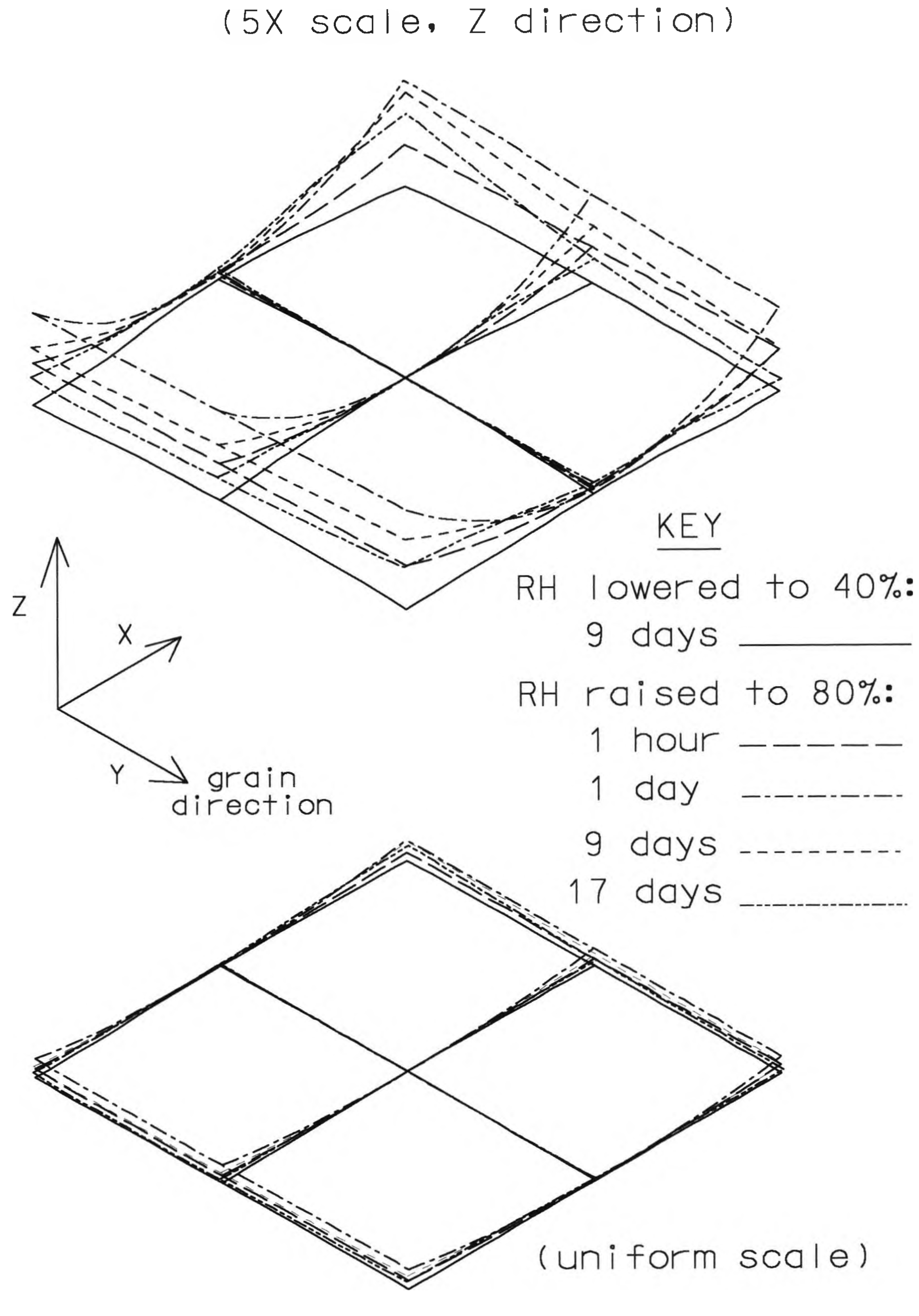


Figure 51. Changes in shape for an oak panel laminated with oak parquets, grain parallel to that of the panel, in going from dry to moist conditions.

framing, thin panels such as these are especially subject to such problems if frame retainers are too rigid. The author has noted many panels with such framing defects. Framed carefully with adeqately flexible retention, panels can be retained safely and with considerable freedom for warp movement. Panel framing considerations have been discussed elsewhere [12, 140].

Besides the foam-cushion tray discussed above, transverse panel expansion was also underestimated in other frame structures, including the "chassis cadre" and cable suspension type. In the latter, the author was entirely responsible for the construction error. Again, some of the panels had to be planed down slightly or they would have been rendered completely useless for this research.

The "chassis cadre" (Reinforcement #21) resembles a grooved frame. However, the behaviour of thinned panels, including the test panels, should not be confused with early Flemish panel paintings in grooved frames. Most such paintings consisted of relatively well-dried, thick and rigid oak panels of radial cut when first framed. Many had moisture permeability roughly equalised by coatings on both sides. If not, the exposed wood surfaces have undergone countless cycles of expansion and contraction, rendering such panels less responsive (see section 2.1). By comparison, the test panels and any thinned panel painting having freshly exposed back surfaces would be more moisture-responsive, warping more quickly and to a greater degree. A too-tight fit could be disastrous.

The brass-angle retainer frame of the "chassis cadre" created two specific problems for the panels. First, as panels contracted under drying conditions, one edge moved within the inner edge of the front flange of the brass-angle. Once free, the exposed panel edge assumed a slight convex warp which caused it to project in front of the plane of the brass frame. On expansion, the exposed edge caught on the brass edge and immediately began to buckle. Thus, the brass-angle did not overlap the panel edge sufficiently to allow for possible contraction of the panel. This would be even more likely with panels of larger dimension across the grain, where buckling and potential splits could be provoked upon panel expansion. Therefore, the front flange of the brass angle should be sized according to the maximum expected contraction of the panel. This problem could occur in any panel whose outer dimensions fall just inside the sight size of the frame.

The second problem was that too little space was allowed for panel thickness between the brass-angle and the wood frame. Besides warping, panels also swell in thickness. Expansion caused oak and pine to fill the space, impeding transverse movement and aggravating out-of-plane distortions in the exposed middle of the panel.

Distortions across the panel were influenced by the greater exposure of the middle relative to the edges, which were covered for about 50mm into the panel by the wooden frame. Moisture permeability was reduced at the edges and in front of the frame so that moisture response was much more rapid in the exposed middle area (Appendix 8, Photo Nos.118-121). With rigid restraint of warp at all edges, raised RH swelled the panel middle, causing considerable distortions there and bending of the panel against the frame's inner edges.

The frame with cable suspension (Reinforcement #17) presented an interesting and unusual approach to reinforcement. The small wood retainers did not develop sufficient friction to cause seizure of the panel as it warped and moved along the wires. However, the basic mechanical relationship between a cable and warp movement is similar to a flexible beam with both ends fixed. This means that freedom of out-of-plane movement is greatest in the middle and less at the longitudinal-grain edges. The panel is more restrained from warp toward the edges, though not as much as with the "chassis cadre", for example, because the option to adjust cable tension individually would allow the degree of restraint to be varied for more moisture-responsive panels or greater inherent curvature. Another potential problem was that the light test panels were prone to vibration during handling. This is a problem with any highly flexible reinforcement. It could be corrected with movement-damping structures.

CHAPTER 4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Unreinforced Panels

Temporary panel deformations during RH changes were strongly affected by oil paint and size layers on one side. Shape changes appear to be consistent with the diffusion and levelling of moisture gradients through the panel section. Buck's "awkward flapping motion" was shown to be a consistent pattern of warp in both transverse- and longitudinal-grain directions, regardless of panel wood type or thickness. Prior to this research, movement parallel to the panel grain was not considered important and accompanying warp was not considered. However, it is considerable and interactions with reinforcements can be expected.

This research showed definitively that thicker panels have a slower rate of wood movement and therefore warp and twist less and more slowly than do thinner panels. Temporary twist during equilibration appeared to be related to differential movement due to grain variation.

4.2 Reinforced Panels

Alteration or replacement of original reinforcements is not so much in question here, since their preservation is an accepted conservation priority. However, reverential admiration of original reinforcements is sometimes encountered, of sliding battens for example, even though they can cause damaging restraint under certain conditions. How to treat such problems without altering the original irreversibly is an important ethical and technical consideration which warrants further research.

The review shows that, much as original reinforcements evolved from fixed rigid structures to sliding structures designed to allow for in-plane movement, so non-original reinforcements have evolved toward structures which allow greater freedom of panel movement in all directions. The trend toward allowing greater freedom reflects a growing realisation of the preservation role of non-original reinforcements for panel paintings which have become more and more fragile. The most recent change has been toward allowing greater freedom of warp movement.

These changes are neither accepted by all nor are they widely understood and practised. Most are current only among a small number of conservators specialised in panel considerations so that more widespread exposure of custodians of paintings to this information could help prevent inappropriate reinforcement and further improve methods. Custodians include primarily museum and public collections administrators and private owners, as well as personnel who handle and transport paintings.

Results of the survey and CE study show in general that the causes of some effects, such as sliding battens seizing from poor construction, either too tight or accidentally fixed with glue during assembly, are more easily identified than others. Generally well-known, these causes need no discussion here. Other causes, such as deformations in balsa laminates, are more difficult to identify clearly or separate from misconceptions. Nonetheless, important information was gained in terms of both general and more specific causes and effects.

Many effects shown by the CE study span different reinforcement types and appear to have similar causes. These will be summarised first, the details of which would benefit from further confirmative research.

Stresses from restraint of panel movement in-plane, that is, restraint in shear, were shown to be an important influence on panel deformations. Such deformations were shown repeatedly and to varying degrees in panels with reinforcements fixed overall or having fixed elements. Transverse-grain effects were more obvious because of greater restrained movement. Such restraint in shear was directed over the entire panel dimension across the grain for fixed battens, parallel to the panel grain for fixed cradle members and in all directions in-plane for laminates. Thus, shear stress was mainly due to differential movement between panel and fixed areas, whether the laminate was relatively static like MDF, or moved to a different degree, as with the balsa laminates or oak plank laminate. The oak laminates showed an important difference in deformation, suggesting they showed wood movement more like the panels.

Where restraint occurred across the panel surface, such as from a fixed batten, fixed lattice or laminate, panel and reinforcement were obliged to bend out-of-plane to reduce in-plane shear stresses between them. For relatively rigid restraints, the direction of bend was always in the opposite direction to that which an unreinforced panel would undergo during the same RH change. Bending of both panel and reinforcement beneath showed that the panel wood must have undergone considerable compressive and tensile stresses.

Many of the effects noted in panel paintings during this research can be related to such shear restraint. For panels with fixed battens, whether original or non-original, twists, concave deformation, splits and/or disjoins, and detached battens were observed. Of these, only splits and/or disjoins did not occur in the test panels, though the degree of deformation left no doubt that panel paintings of thickness similar to the test panels would develop fractures. Also, panel paintings which had been laminated showed delamination, tented flaking and paint losses. Concave deformation, splits, disjoins, and tented flaking in some panels suggest that compressive strain, perhaps contributing to permanent set, may also occur in the panel wood. Again, these effects would be aggravated by shear stress in the plane of the panel.

Most laminates are a case in point. The great deception with such restraints which do not conform to panel movement in shear is that associated stresses may remain in the panel, maintained by high relative stiffness. Also, strains resulting from these stresses may be undetectable by visual inspection alone, at least until the panel or laminate fractures, or delaminates. This gives the false impression that stable and stress-free reinforcement has been achieved. None of the laminates applied here, whether rigid or flexible, would be stable or stress-free under varying RH.

Besides stresses from restraint of movement in-plane, stresses also arise from restraint in bending. Moiré analysis of cradles gave direct evidence of Buck's observation on "free control devices" [19, p. 160]: warp restraint causes "amplified compressive strains on the front ...[and]... amplified tension on the back". A corollary to Buck's observation would be that in-plane stress increases with warp restraint. That is, if a panel is tending to warp, the more rigidly it is restrained flat (in bending), the greater will be its tendency to move in-plane. Further evidence of such amplified stress/strain must await analysis of in-plane movement in battened panels, for example, when areas undergoing different degrees of restraint may be compared to less restrained areas and to movement of unreinforced panels.

Ignoring these points, some panel workers believe that only in-plane movement and not warp need be accommodated by reinforcement, a belief which is also evident in panels which have received rigid sliding structures. This research shows that any reduction of in-plane or warp restraint would decrease risk of unusual stresses such as buckling, twist, and resulting damages. Both restraints occur together with reinforcements having rigid fixed battens, most laminates, and seized battens or cradle members. Resulting increased stresses provoke flaking and splits, and under raised RH, increase compression set.

Besides stress/strain amplification from flattening, the moiré study of cradled panels also showed asymmetry in the strain distribution due to glued and free areas of batten.

These are probably both occurring where flattening is concentrated locally near battens or retainers of any type. Under raised RH, for example, these factors together probably contributed to exaggeration of initial warp followed by a buckling reaction in such areas of battened panels. This would at least partially explain splits, disjoins, and tented flaking noted in exposed areas between battens, whether battens are fixed or sliding, original or non-original. There are other factors of course, such as local grain orientation (Figure 24). Such damages are all too common in cradled panel paintings.

For attached reinforcements, glued members and retainers tended to cause local deformations either soon after application or during RH cycling. The former was attributed mainly to contractile stresses from drying animal glue over larger glued areas of fixed cradle members. The latter occurred with retainers having even small glued areas and was attributed to cyclic effects on wood movement due to differences in moisture response between glued and exposed areas of panel. They are separate effects and would be more apparent in thinner panels.

To reduce contractile stresses from drying, adhesives with greater plasticity and low shrinkage could be used, preferably without water so that the wood is not "locked" into a swelled condition. Adhesives should either be reversible or be made so using a removable interleaf. The area of each adhered surface should be minimised since contractile drying stresses would be greater over larger glued areas.

Cyclic effects are more difficult to prevent. They would affect very thin panels most, making reinforcement a more critical question for such panels. Unattached reinforcements such as trays, though solving the problem, may not provide sufficient restraint to prevent the panel buckling forward. For such panels, more research should be done on such cyclic effects in relation to glued area, adhesive type, on laminates which provide for adequate wood movement overall, perhaps modifications based on the balsa block type, and if these are not adequate, on new forms of reinforcement.

Laminate response to RH-cycling in this research also emphasised how important the influence of moisture exchange is on panel deformations. A balance between moisture permeability of back and front should increase stability, as noted for panels originally coated on both sides, but it is not practical with some reinforcements. With some, not only does the panel still undergo wood movement, but the relative degree of moisture permeability is shifted, greater at the front than the back. Among the test panels, those in foam-cushioned trays were probably sealed most against moisture exchange at both back and edges. Yet, movement and deformations explainable by cyclic moisture exchange occurred in those panels as well.

The pattern of moisture permeability over the panel back can also adversely influence deformations. The "chassis cadre" restricted moisture exchange and movement to the exposed middle area which, when combined with its particular problems of restraint, caused seizure of panel wood movement and subsequent distortions.

4.2.1 Fixed Battens and Lattices

These have the vicissitudes of both restraint in-plane and out-of-plane, as well as leaving exposed areas open to bending stresses. Any change in relative dimensions of panel and reinforcement over time from changes in MC or compression set will cause such stresses and subsequent bending. A substantial decrease of deformations was shown in surveyed panels after removal of such restraints, showing that deformations were largely elastic in nature. The increase in deformations of the panel examined at the Kollektief after thinning the fixed battens can now be explained as a decrease in rigidity during batten thinning in relation to constant shear stress by the battens due to restraint of panel movement in-plane. Complete removal would very likely have eliminated the shear stress and resultant bending, though it would probably have been replaced by some degree of inherent convex warp. Generally, removal of such reinforcements can be recommended.

For original reinforcements of the fixed and rigid type, conditions should be maintained as constant as possible by means of environmentally-controlled enclosures. Fortunately, most panels with nailed original battens have developed some freedom of movement with time, so there is room for limited fluctuation of MC.

4.2.2 Sliding Battens

Farnsworth's experiments with sliding battens on relatively thick, rigid test panels showed the influence of thickness on bending stresses and batten seizure. Thicker panels are more prone to breakage from bending because of the greater distance of each side from the neutral axis of bending. The greater the thickness, the greater the compressive or tensile stresses on each side. The relatively thin, flexible test panels used here were therefore less prone to bending stresses and they bent without generating appreciable friction against sliding structures. Farnsworth's experiments also demonstrated the greater tendency of battens and retainers spaced away from the panel back to cause seizure compared with those constructed nearer the back surface. Von Imhoff [51] referred to a comparative situation when he noted the intensification of mechanical movement by high relative to low cradles.

Two different styles of retainer mechanism were shown here for sliding battens. The sliding flexible lattice and cable suspension reinforcements used different sliding mechanisms. Though the roller-bearing retainers of the rigid sliding battens probably caused least friction, inherent flexibility reduced the effect of friction in other sliding types. Low-friction retainers become less necessary as reinforcement flexibility is increased. If flexibility is sufficient, then it should not be necessary to employ expensive teflon or complicated sliding mechanisms as discussed in some of the reviewed batten designs. Still, some provision for friction reduction should be made.

Though panels with sliding flexible battens showed local distortions and some twist, even the most restrained areas over the battens warped in a similar pattern to unreinforced panels, interrupted only by temporary seizure of the battens as they swelled under high RH. The seizure showed again the danger of imposing restraint on panel movement in-plane. Splits in the panel painting by Boateri (Figure 7), for example, may have been provoked by battens swelling and seizing in the grooves. To the author's knowledge, batten swelling in itself has not been offered as a reason for seizure and damages, more commonly-cited mechanisms having been reviewed in sections 2.1 and 2.3.2(b).

The following are suggested to minimise the chance of batten seizure: increase spacing between batten and retainer; keep the outer batten surface as close to the panel back as possible; allow greater flexibility in the structure. The use of metal or plastic battens would avoid seizure from their swelling, though their flexibility is more difficult to adjust than wood. Aluminium battens, though lightweight, are not the best choice due to friction concerns.

Sprung retainers and flexible battens are both designed to allow for panel warp. While sprung retainers combined with rigid battens tend to concentrate bending stresses at the panel middle around retainers, flexible battens should distribute bending stresses more continuously across the panel. Temporary warps were shown to produce quite regular curves in unreinforced panels (Figures 33b, 36 and 37). Therefore, the closer a flexible batten is made to contact the panel surface along such a curve, the more bending stresses from restraint of temporary convex warp will be distributed along the contact surface rather than being concentrated near the panel middle. The sliding flexible battens examined here made no provision for a regular curvature because their section was constant. Transverse members of the sliding flexible lattice and tray were tapered toward their ends for this purpose [11, 101].

In general, however, sliding flexible battens are a simple, effective approach. They can be easily constructed and applied *in situ* and though not a functional advantage, they have a traditional, pleasing appearance. Simplicity has some very attractive practical advantages. Friction can be overcome by adequate flexibility, liberal tolerance between sliding surfaces, and judicious use of friction-reducing coatings such as harder waxes or graphite.

4.2.3 Cradles

Rigid cradles in their classic form, whether *parquetage du champ* or *parquetage á plat*, are unjustifiable simply in light of the considerable record of damages, backed by moiré analyses of cradle behaviour here, in which in-plane and out-of-plane stresses have been shown to occur. "Washboarding", for example, was shown to be basically due to restraint in bending. If "washboarding" is present, it is a precursor to splits and compression damages. Waiting under the pretext of minimum intervention does not address the problem and will probably only worsen matters with time. It is the author's opinion and experience that cradled panels may appear unstressed because elastic stresses are not visible as deformations or are otherwise difficult to detect. Yet they are present in many cradled panels and they increase risk of damages, especially with cyclic changes in RH.

Cradles could be applied more safely if panels were relatively thick and known to warp very little, perhaps having radially-sawn planks (in itself, not a guarantee of stability), or if RH were relatively constant. However, the risks do not justify the action. The method begins with an increase in MC from flattening or even from gluing which is temporary but significant, provoking subsequent stress and deformation. Members fixed the entire length of the panel and with the grain should be avoided. With changes in panel MC, they have been shown here to cause stresses which would increase with panel dimensions. Also, even with little warp restraint, the intermittent attachment of cradle members and corresponding panel exposure will probably aggravate stresses with changes in RH.

Therefore, for most environments, cradling should be strongly discouraged as a reinforcement option. Efforts should be made to limit potential damage from those still on panels, such as safe methods of permanently freeing sliding members and making them adequately flexible. If a cradled panel shows no sign of excessive restraint under close monitoring over the ambient RH range, but the panel could be self-supporting, then a judgement may be made whether to remove the cradle as a preventative measure or not. If the panel is excessively thin and cradle damages are apparent, then systematic removal [12], followed by replacement with a better reinforcement, should help.

4.2.4 Laminates

In general, laminates are not suitable because of the excessive restraint imposed on panel movement in all directions, especially in-plane, as shown by MDF panel. Tissue and honeycomb-core laminates appear to provoke considerable twist and distortions due to shear stresses in-plane and to their high flexibility. In their tested form, these flexible laminates would not be suitable for thin panel paintings. However, the idea could be explored further. Mechanical and other physical properties of honeycomb-core, such as moisture permeability and adhesive compatibility, can be modified to meet reinforcement requirements by changing the core material (using paper for example), filling the cells with various materials, or by applying various backing laminates.

The two balsa laminates examined here both imposed in-plane restraint, though to different degrees. The balsa block type showed out-of-plane deformations which suggested greater laminate flexibility in the transverse-grain direction, while the balsa plank type deformed more like a rigid laminate. These deformations were maintained until RH was changed so that associated in-plane stresses would be maintained likewise. Such panels are probably always under in-plane and bending stresses, risking the delamination noted in many of the surveyed panels and onset of other cited damages. Therefore, rather than avoiding stresses, as Laurie said [83], such laminates can impose considerable stress.

None of the laminates reduced panel moisture exchange sufficiently to stabilise against movement. Buck and his colleagues had hoped to achieve this, primarily through wax-resin impregnation of the panel. Though impregnation was later discarded, the same intention is evident in the multiple layers of wax-resin adhesive and impregnated fabric in the balsa plank laminate examined here. However, such panels are not, as Kolch put it [44], "thoroughly barricaded" because while the back and usually the edges are covered or coated, the painted side remains exposed to moisture exchange. Typical varnish layers, whether cracked or not, remain relatively moisture permeable [141, p. 151].

A third problem with balsa laminates is the use of heat during application. Heat usage was discouraged in one institution after impregnation with molten wax-resin appeared to cause flaking damages from possible "flexing of the structure" or "drying, and consequent warping" in at least one panel painting. Heat application appeared to release drying stresses in oak planks of the test panels, causing warp changes. Release of stresses developed since the panel's construction can be expected to occur under similar conditions. Also, contraction during cooling and solidification of wax-resin was argued to be a likely cause of in-plane stresses and various bending reactions in the test panels during application. These potential heat-related causes may all be implicated in deformation and flaking of panels laminated with balsa and wax-resin.

If a balsa laminate is to be used, and there are very thinned panels for which it is a very seductive recourse, then the balsa block method described here has some advantages, both practical and preventative, over the plank type. The block type is simpler to apply and remove, can be adapted better to inherent panel deformations, is less rigid, uses less heat and wax-resin, and the blocks and adhesive can be applied in a manner whereby they conform more independently to any adhesive contraction. The author has found that on more dense woods, such as oak, absorption of molten wax-resin applied in this manner is negligible. Remnants can usually be removed sufficiently with poultice techniques to allow for future use of water-based adhesives.

The two oak laminates warped similarly to unreinforced oak, though shear stress was evident in the plank type. The adhesive system used here could be improved. Same-wood parquets, as applied here, are much more difficult to fit to panel curvature than balsa, which can be quickly and easily shaped. Though skepticism is very much in order, analysis begun here should be continued and use of same-wood parquets should be studied further.

4.2.5 Foam-cushion Tray

The foam-cushion tray showed potentially damaging effects from excessive restraint and moisture exclusion. Because it is relatively simple to build, the design has become popular, though care must be exercised. For example, Barrington's version [106] could be expected to cause high stresses in the painting due to restraint of in-plane and warp movement. This can be judged from the size of the paintings described, their stated tendency to warp, and the spacing allowed for panel movement by balsa packing at the edges. Honeycomb panel, "totally stable, immensely strong", was described as "a reference surface against which the painting may move". It may instead prove to be quite the opposite, imposing excessive restraint.

Attention has been given by some practitioners to altering the shape or distribution of foam pads to tailor cushioning. This is usually done in an empirical way, squeezing the pads individually until it is felt that overall support will be correct. However, it is very easy to misjudge and underestimate compressibility. To avoid these problems, it is possible to adequately predict panel movement and make a more objective calculation of the necessary compressibility by using methods such as those described by [11, 101].

4.2.6 Sliding Flexible Lattice and Tray

Considering moisture-related effects and the stresses and distortions discussed with respect to shear and warp restraint, reinforcement should achieve the following: lower moisture exchange moderately on the exposed wood surfaces at the panel back and edges without otherwise changing its pattern; minimise or eliminate shear restraint; provide only enough restraint of warp to prevent excessive bending stresses from handling, etc..

The sliding flexible lattice and sliding flexible tray addressed most of these considerations successfully. Though photogrammetric analysis has not been completed, the tray appeared to allow deformations similar to unreinforced panels. In addition, because of its relatively loose, unpacked rebate, it appeared to slow moisture exchange at the panel back and edges while not sealing them excessively. This suggests that, where an environmentally-controlled vitrine is not possible, a looser tray-like enclosure can provide the advantage of an "imperfect" moisture-barrier while allowing for panel movement. A similar backing panel would improve the lattice or any other reinforcement, if only as part of the frame proper.

The depth of the integral frames of these reinforcements would be considered much too great by the uninformed. Depths were somewhat over-estimated for the test panels and could be reduced further by building thinner spring structures. Still, most clients would still find the depth too great, especially if it projected beyond the frame rebate, a sentiment which will influence acceptance of such reinforcements. Thinking thus and unaware of their vital protective function, persons may discard such frame structures in ignorance [22], along with the lattice if it is unattached. This is a serious problem for unattached reinforcements. The importance of accepting such deeper reinforcements to allow warp can only be achieved by persuasive education.

Though these reinforcements seemed to give adequate protection when handled during the CE study, improper handling, accidental blows and vibrations are a great danger. The same applies to the cable suspension type. The advantages of such flexible reinforcements for panel movement will be wasted if the panel is broken in transit. Rather, the reinforcement will be condemned as too weak and will probably be replaced by yet another excessively restraining alternative. Not by chance have relatively rigid reinforcements been the historical norm for panel paintings.

Flexible reinforcements can be temporarily stiffened during transit and released afterward, provided trained personnel are present. However, trained personnel cannot be guaranteed for all occasions. Again, education of custodians and personnel is a major preventative. Also, it may be possible to prevent excessive bending by limiting flexibility to less than the ideal. This is an important consideration which should be researched further with respect to packing and transport environments.

4.2.7 Perimeter Frames

The three reinforcements classed as perimeter frames showed the importance of allowing adequate space for panel movement and how easily it is underestimated. Despite being built to measure for the test panels by panel specialists, three of four reinforcements with frame structures blocked transverse-grain expansion, partly due to the relatively large RH span imposed. However, similar movement could be expected in panel paintings, no matter what thickness, if they were given long enough to equilibrate to RH of interiors uncontrolled for RH but subject to seasonal extremes. Thin panels would be especially quick to expand. Therefore, generous allowance must be made for panel expansion in all frame structures.

The flexible brass retainers used here were too rigid for the thin test panels. Retainers used to maintain panels in frames, especially softer wood types or under moist conditions, should not be rigid structures, but they should be chosen for flexibility and positioned with care. Framing methods for panels should be researched and developed further.

4.3 Summary

Surveys of panels and treatment records provide a rich source of information. However, most panel work, particularly private work, is neither published nor inscribed in reports. Treatments discussed here represent only a small proportion of those actually done. A few treatment records were sufficiently long and detailed to be useful. It would be helpful if people with an intimate knowledge of a particular collection gained over several years could make an assessment of all the panels, whether treated or not. This should be possible, especially where conservators are on staff. Most private conservators cannot afford the expense of such research, which is a shame.

This research increased understanding of panel movement with changing RH, whether the panel is reinforced or not. It is evident that knowledge of movement in both cases is indispensable when analysing panel/reinforcement interactions. Also, by examining a broad range of panel/reinforcement combinations, the controlled-environment study gave an overall assessment while helping to better understand effects of individual reinforcements. This information is invaluable to conservators for predicting effects of removal or application. A large quantity of data was gathered from which much more can be learned. For example, it would be instructive to compare in-plane movement over fixed areas of reinforcement with movement in the less-restrained areas between.

This research has shown that application of some types of reinforcement can be rejected, partly because better alternatives exist. Fixed reinforcement, whether rigid or flexible, should not be applied because of bending due to shear restraint. Where present, non-original fixed reinforcements should be replaced by less restraining structures. The research showed how some reinforcements could be altered in specific ways to make them more amenable to panel requirements.

Reinforcements which minimised both in-plane and warp restraint allowed some panel movement in all directions, more like unreinforced panels. These included sliding structures, such as flexible battens and the sliding flexible lattice and tray, which if constructed correctly can make in-plane restraint practically inconsequential. These would probably give good results for most panels. For extremely thin or weak panels, design must be more stringent, providing more overall support, as with the flexible lattice-type structures.

Of the laminates, the balsa block type appeared to be the most suitable examined here. With caution, it could be considered as a reinforcement when more flexible and sliding or unattached reinforcements are not an option.

However, balsa laminates exert two types of restraint-shear restraint of in-plane panel movement and bending restraint of warp movement out-of-plane, the former being probably the most dangerous. Therefore, balsa laminates need further study and development.

Though promising, same-wood laminates should be regarded with skepticism until further research can be done.

For all the reinforcements examined, function can be improved while style remains open to creativity. Like architecture, function need not compromise style.

4.4 Comments on Measurement Methods Used

The two main measurement methods used here, digital photogrammetry and moiré fringe analysis, were well-suited to the research demands and constraints of budget, time, and available expertise. The researcher relied on highly specialised technical assistance in both cases. This ensured that both methods were used successfully to capture surface images virtually instantaneously. Also, good quality raking-light photography was useful to appreciate and verify analytical results.

Though the digital photogrammetric technique was limited in coverage to the minimum distance between targets, it was well-suited to comparison of deformation effects between the large number of panel/reinforcement types. The researcher could view, manipulate, and measure the resulting images with the aid of a commercial graphics program. While requiring considerable effort to learn and apply, the program allowed great freedom to explore results.

Moiré fringe analysis was extremely well-suited to exploring overall effects of cradles in greater detail. The technique's simplicity is very attractive for use by conservators *in situ* where expertise is not readily available.

REFERENCES

1 Ulich, R., *History of Educational Thought*, revised edition, American Book Company, New York, (1968) abridged quoth, p.5-6.

2 Gettens, R. J., and Stout, G. L., *Painting Materials. A Short Encyclopaedia*, Dover Publications, New York (1966).

3 Marette, J., *Connaissance des Primitifs par l'Etude du Bois du XIIe au XVIe Siècle*, Editions A.& J. Picard & Cie, Paris (1961).

4 Schießl, U., 'History of structural panel painting conservation in Austria, Germany and Switzerland', paper delivered at *Symposium on The Structural Conservation of Panel Paintings*, Getty Conservation Institute/J. Paul Getty Museum, Malibu, U.S.A. (April 24-28, 1995). (to be published)

5 Stout, G. L., *The Care of Pictures*, Dover Publications, New York (unabridged reprint 1975; originally published 1948).

6 'Code of Ethics & Guidelines for Practice' IN *Directory of The American Institute for Conservation of Historic and Artistic Works* (AIC) (1995) 23.

7 *Statuts: Code de déontologie professionelle*, International Council of Museums (ICOM) (1996) 32.

8 *The Care of Wood Panels,* ed. G. L. Stout, UNESCO, International Council of Museums (ICOM), Rome, *Museum* VIII (1955) 139-194.

9 *Conservation-Restauration des Biens Culturels. Restauration, Dé-restauration, Re-restauration...,* 4ième colloque de l'Association des Restaurateurs d'Art et d'Archéologie de Formation Universitaire (A.R.A.A.F.U.), Paris, 5-7 octobre 1995.

10 Ruhemann, H., *The Cleaning of Paintings. Problems and Potentialities*, Faber and Faber, London (1968).

11 Brewer, A., 'An auxiliary support case history' IN *Hamilton Kerr Institute Bulletin Number 2*, ed. A. Massing, Hamilton Kerr Institute of the Fitzwilliam Museum, Cambridge, England (1994) 61-67.

12 Brewer, A., 'Practical aspects of the structural conservation of large panel paintings', paper delivered at *Symposium on The Structural Conservation of Panel Paintings*, Getty Conservation Institute/J. Paul Getty Museum, Malibu, U.S.A. (April 24-28, 1995). (to be published)

13 Buck, R. D., 'Is cradling the answer?', *Studies in Conservation* 7 (1962) 71-74.

14 Robson, S., Brewer, A., Cooper, M. A. R., Clarke, T., Chen, J., Setan, H. B., Short, T., 'Seeing the wood for the trees- an example of optimised digital photogrammetric deformation detection', paper delivered at *From Pixels to Sequences*, ISPRS Intercommission Workshop, Zurich (March 22-24, 1995) IAPRS (30) Part 5W1.

15 Cooper, M. A. R. and Robson, S., 'Photogrammetric methods for monitoring deformation: Theory, practice and potential' IN *Recent Advances in Experimental Mechanics*, eds. Silva Gomes *et al*, Balkema, Rotterdam (1994) 395-400.

16 Brewer, J. A., and Forno, C., 'Moiré fringe analysis of cradled panel paintings', *Studies in Conservation* 42 (1997) 211-230.

17 Skaar, C., *Wood-water Relations*, Springer-Verlag, Berlin (1988).

18 Dinwoodie, J. M., *Timber, Its Nature and Behaviour*, Van Nostrand Reinhold, Berkshire, England (1981).

19 Buck, R. D., 'Some applications of mechanics to the treatment of panel paintings' IN *Recent Advances in Conservation. Contributions to the IIC Rome Conference, 1961*. ed. G. Thomson, Butterworths, London (1963) 156-162.

20 Raymond Marchant, conservator, Hamilton Kerr Institute, London, private communication (1994).

21 Verougstraete-Marcq, H., and Van Schoute, R., *Cadres et Supports Dans la Peinture Flamande aux 15e et 16e Siecles*, Heure-le-Roman, Louvain (1989).

22 Ian McClure, Director, Hamilton Kerr Institute, Whittlesford, England, private communication (1997).

23 Christa Steinbüchel, Head of Conservation, Wallraf-Richartz-Museum, Köln, private communication (1991).

24 Popova, O., Smirnova, E., Cortesi, P., *Les Icônes. L'histoire, les styles, les thèmes des origines à nos jours*, Éditions Solar, Paris (1996) 18.

25 Castelli, C. and Ciatti, M., 'I supporti lignei dei dipinti e i sistemi di traversatura: un'analisi storica e alcune proposte operative' IN *Il Restauro del Legno. Ricerche e Restauri su Architetture e Manufatti Lignei. Volume II,* ed. Genaro Tampone, Nardini Editore, Florence (1989) 141-154.

26 Kunzelman, D., 'Dal restauro, nuove conoscenze per l'ancona con la 'Maestà' di Montici', *OPD Restauro* 7 (1995) 77-90.

27 Gordon, J. E., *Structures*, Penguin, London (1978).

28 Sobré, J. B., *Behind the Altar Table. The Development of the Painted Retable in Spain, 1350-1500*, University of Missouri Press, Columbia, USA (1989).

29 Lavers, G. M., *The Strength Properties of Timber*, 3rd ed., Building Research Establishment (BRE) Report, Her Majesty's Stationery Office (HMSO), London (1983).

30 Jobling, J., *Poplars for Wood Production and Amenity*, Forestry Commission Bulletin 92, Her Majesty's Stationery Office (HMSO), London (1990).

31 Dr Thomas Brachert, Head of Conservation, Germanisches Nationalmuseum, Nürnberg, private communication (1992).

32 Brachert, T., 'Zur Parkettierungsfrage (The question of cradling)', *Maltechnik* LXI (1955) 7-8.

33 Wehlte, K., *The Materials and Techniques of Painting*, Van Nostrand Reinhold, New York (1982).

34 Wehlte, K., 'Planierung einer Bildtafel als Sonderfall (The flattening of a panel painting- an exceptional case)', *Maltechnik* LXIV (1958) 104-111.

35 Straub, R. E., 'Über die Erhaltung von Holztafelbildern' IN *Über die Erhaltung von Gemälden und Skulpturen*, ed. R. E. Straub, Foetz & Wasmuth Verlag, Zurich/Stuttgart (1963) 107-170.

36 Doerner, M., *Malmaterial und seine Verwendung im Bilde. Nach den Vorträgen an der Akademie der Bildenden Künste in München. Neu herausgegebenvon Toni Roth, maler und Konservator in München. Chemischer und wissenschaftlicher Mitarbeiter Dr. Richard Jacobi*, 9th ed., Enke, Stuttgart (1949).

37 John Farnsworth, Chief Conservator, Westfalisches Amt für Denkmalpflege, Münster, Germany, personal communication (1991).

38 Brandi, C., 'Il Restauro della Maestà di Duccio', *Bolletino dell Istituto Centrale del Restauro* 37-40 (1959).

39 Carità, R., 'Pratica della parchettatura', *Bolletino dell'Istituto Centrale del Restauro* 27-28 (1956) 101-131.

40 Carità, R., 'La parchettatura del dipinto', *Bolletino dell'Istituto Centrale del Restauro* 41-44 (1954) 3-35.

41 Louvre Accession number MI680, Dossier number D652 (1965).

42 Huot, C., unpublished abstracted biography (1995).

43 Bergeon, S., *Science et Patience ou la Restauration des Peintures,* Editions de la Réunion des Musées Nationaux, Paris (1990).

44 Kolch, D., 'A reconstruction system for panel painting supports: A review and evaluation of treatments in the Fogg Museum Laboratory 1927-1952', unpublished report, Center for Conservation and Technical Studies, Fogg Art Museum, Harvard University (1977).

45 Jean-Albert Glatigny, conservator, Institut Royal du Patrimoine Artistique (IRPA), Brussels, private communication (1990).

46 D'Hulst, R., Baudouin, F., Aerts, W., Nieuwenhuizen, J. V. D., Manderyck, M., Goetghebeur, N., Guislain-Wittermann, R., *L'Erection de la Croix Pierre Paul Rubens,* Editions de Lassa, Brussels (1992).

47 Mette Bjarnhof, conservator, Statens Museum for Kunst, Copenhagen, private communication (1991).

48 Castelli, C. and Ciatti, M., 'Proposta di intervento sui particolori supporti lignei' *OPD Restauro* 1 (1989) 108-111.

49 Victor Von Reventlow, conservator, Brooklyn, New York, private communication (1992).

50 Louvre RF.1962-1, Dossier 1503 (1965).

51 H. C. Von Imhoff, conservator, Fribourg, Switzerland, private communication (1990)

52 Bünsche, B., 'Verleimung, planierung und stabilisierung einer verwölbten Holztafel', *Neue Museumkunde*, Volume 19, Number 2 (1976) 139-149.

53 Wolters, C., 'Treatment of warped wood panels by plastic deformation; moisture barriers; and elastic support' IN *Recent Advances in Conservation. Contributions to the IIC Rome Conference, 1961*. ed. G. Thomson, Butterworths, London (1963) 163-64.

54 Castelli, C., 'Proposta di un nuovo tipo di traversa per dipinti su tavola', *OPD Restauro* 2 (1987) 78-80.

55 Castelli, C., Ciatti, M., Parri, M., Santacesaria, A., 'Alcune nuove proposte per i sistemi di sostegno e controllo dei dipinti su tavola' IN *Il Restauro del Legno. Ricerche e Restauri su Architetture e Manufatti Lignei. Volume II*, ed. Genaro Tampone, Nardini Editore, Florence (1989) 290-298.

56 Pietro Gori, conservator, Florence, Italy, private communication (1990).

57 Enrico Guidi, conservator, Vatican City, Italy, private communication (1993).

58 Marussich, G. and Rothe, A., 'Florentine structural stabilization techniques', paper delivered at *Symposium on The Structural Conservation of Panel Paintings*, Getty Conservation Institute/J. Paul Getty Museum, Malibu, U.S.A. (April 24-28, 1995). (to be published)

59 Giovanni Marussich, conservator, Florence, Italy, private communication (1990).

60 'Conservation et restauration. Peintures des musées de Dijon', *Les dossiers du département des peintures* 27, Editions de la Réunion des Musées Nationaux, Paris (1983) 20.

61 Laurie, A. P., *The Painters Methods and Materials*, Dover Publications, New York (1967).

62 Keyselitz, R., "Roste auf Holztafelbildern nach der "Wiener Methode", *Maltechnik* LXVI (1960) 73-75.

63 Kühn, H., *Conservation and Restoration of Works of Art and Antiquities Volume 1*, 2nd ed., Butterworths, London (1986)

64 *Manuel de la Conservation et de la Restauration des Peintures*, Office International des Musées, L'Institut International de Coopération Intellectuelle, Paris (1939).

65 Pease, M., 'A treatment for panel paintings', *The Metropolitan Museum of Art Bulletin*, Volume VII, Number 1 (1948) 119-124.

66 Dunkerton, J., Roy, A., and Smith, A., 'The unmasking of Tura's 'Allegorical Figure': A painting and its concealed image', *National Gallery Technical Bulletin* 11 (1987) 5-35.

66 Robinson, M., and Robinson, P., 'The treatment of cradled panel paintings' IN *Managing Restraint in Panels*, Association of British Picture Restorers Conference (ABPR), London (1996) 24-27.

67 'Conservation record No. NG249', unpublished report excerpt, National Gallery, London (1888).

68 Eastlake, C. L., *Methods and Materials of Painting of the Great Schools and Masters,* Dover, London, Volume 1 (1960) (first published as *Materials for a History of Oil Painting*, Longman, Brown, Green, and Longmans, London (1847)).

69 Ruhemann, H., *The Cleaning of Paintings. Problems and Potentialities*, Faber and Faber, London (1968).

70 The Roberson Archive of the Hamilton Kerr Institute, PB.24-1993, University of Cambridge, Whittlesford, England.

71 Papari, T. V., 'Methodes de conservation des peintures anciennes', *Mouseion* 16 (1931) 8-17.

72 Bauer-Bolton, V., 'La conservation des peintures de chevalet. Les supports et les fonds', *Mouseion*, Office International des Musées, Paris, Vol. 23-24 (1933) 68-91.

73 Rosen, D., 'Notes on the preservation of panel pictures', *The Journal of the Walters Art Gallery,* Baltimore (1941) 123-127.

74 Packard, E. C. G., and Kirby, J. C., 'The structure of some south German panel paintings', *The Journal of the Walters Art Gallery* 10 (1947) 91-101.

75 Buck, R. D., 'Some applications of rheology to the treatment of panel paintings', *Studies in Conservation.* 17 (1972) 1-11.

76 Kozlowski, R., 'A new cradle model', *Studies in Conservation* 7 (1962) 56-66.

77 Mayer, R., *The Artist's Handbook of Materials and Techniques*, 3rd ed., Faber and Faber, London (1973).

78 Verougstraete-Marcq, H., and Van Schoute, R., *Cadres et supports dans la peinture flamande aux 15e et 16e siecles.* Heure-le-Roman (1989).

79 Lebas, F. J. M., conservator, Museum für Kunst und Gewerbe, Hamburg, private communication (1993).

80 Caption on back of raking-light photograph, Service de Restauration des Musées de France (SRMF), Dossier 1066, negative number 9302 (1958).

81 Déon, H., *De la Conservation et de la Restauration des Tableaux*, Paris (1851) (reprint by Gutenberg (1981) of original manuscript).

82 Suhr, W., 'A built-up panel for blistered paintings on wood', *Technical Studies in the Field of Fine Arts* 1 (1932) 29-34.

83 Laurie, A. P., 'The warping of panels', *The Museums Journal* 32 (April, 1932, to March, 1933) 389-391.

84 Service de Restauration des Musées de France (SRMF) Dossier 055 (1967).

85 Bradley, M. C., *The Treatment of Pictures*, Art Technology, Cambridge, U.S.A. (1950).

86 Glatigny, J.-A., 'Le doublage au balsa de panneaux peints' IN *La Conservation du Bois dans le Patrimoine Culturel*, Journées d'Etude de la SFIIC, Besancon-Vesoul (November 1990) 177-181.

87 Volle, N., 'Recherches de supports inertes pour les peintures sur bois' IN *Traitement des Supports Travaux Interdisciplinaires,* Journées sur la Conservation Restauration des Biens Culturel, Association des Restaurateurs d'Art et d'Archeologie de Formation Universitaire (A.R.A.A.F.U.), Paris (November 1989) 11-22.

88 Lucas, A. W., 'The transfer of easel paintings' IN *Recent Advances in Conservation. Contributions to the IIC Rome Conference, 1961.*, ed. G. Thomson, Butterworths, London (1963) 165-168.

89 Brachert, T., 'Die Solothurner Madonna von Hans Holbein aus dem Jahr 1522', *Maltechnik* (1972) 6-21.

90 Smith, A., Reeve, A., and Roy, A., 'Francesco del Cossa's 'S. Vincent Ferrer'', *National Gallery Technical Bulletin* 5 (1981) 45-57.

91 Röttger, G., 'Die Verleimung einer dünnen Bildtafel und ihre Doublierung mit Balzaholzielsten', *Maltechnik* 73 (1967) 13-17.

92 Lebas, F. J. M., 'Parquetage d'un relief 'L'Annonciation' attribué à Martin Schaffner' IN *Symposium on Structural Work on Paintings On Wood Panel*, Getty Conservation Institute/J. Paul Getty Museum, Malibu, U.S.A. (April 24-28, 1995). (to be published)

93 Fritz Rieber, conservator and instructor, Institut für Technologie de Malerei, Staatliche Akademie der bildenden Künste, Stuttgart, private communication (1992).

94 Imhoff, H. C. von, 'Reinforcing a thin panel painting', IN *Conservation of Wood in Painting and the Decorative Arts*, Preprints, Congress of the International Institute for Conservation of Historic and Artistic Works (IIC), Oxford (1978) 157-163.

95 Gerry Hedley, lecturer, Department of Conservation and Technology, Courtauld Institute of Art, private communication (1990).

96 Simon Bobak, conservator and instructor, Hamilton Kerr Institute, London, private communication (1993).

97 'Conservation record No. 908', unpublished report excerpt, Volume II, p.1, National Gallery, London (1949).

98 Gordon, J. E., *The New Science of Strong Materials or Why You Don't Fall Through the Floor*, 2nd ed., Pelican Books, London (1976).

99 Samet, W. H., 'An evaluation of wood panel painting conservation of The Walters Art Gallery: 1934-1980', *Preprints of papers presented at the sixteenth annual meeting of The American Institute for Conservation of Historic and Artistic Works*, New Orleans, Louisiana (June 1-5, 1988).

100 Brewer, A., 'Aluminium devices as temporary helpers for panel structural work' IN *Hamilton Kerr Institute Bulletin Number 2*, ed. A. Massing, Hamilton Kerr Institute of the Fitzwilliam Museum, Cambridge, England (1994) 73-76.

101 Marchant, R. T., 'The development of a flexible attached auxiliary support', paper delivered at *Symposium on The Structural Conservation of Panel Paintings*, Getty Conservation Institute/J. Paul Getty Museum, Malibu, U.S.A. (April 24-28, 1995). (to be published)

102 Bobak, S., 'A flexible unattached auxiliary support', paper delivered at *Symposium on The Structural Conservation of Panel Paintings*, Getty Conservation Institute/J. Paul Getty Museum, Malibu, U.S.A. (April 24-28, 1995). (to be published)

103 Stolow, N., and Sack, S. P., 'A micro-climate for a Fayum painting', *Studies in Conservation* 23 (1978) 47-56.

104 Brough, J., and Dunkerton, J., 'The construction of panel trays for two paintings by the Master of Cappenberg', *National Gallery Technical Bulletin* 8 (1984) 63-70.

105 A viewing of the video-tape can be arranged by contacting Anthony Reeve at the National Gallery, London.

106 Barrington, M., 'Panel trays', *Conservation News*, United Kingdom Institute for Conservation (UKIC) 46 (November 1991) 14-15.

107 Ciatti, M., Director, Laboratori di Restauro, Opificio Delle Pietre Dure, Florence, private communication (1990).

108 Barkas, W. W., *The Swelling of Wood Under Stress*, Her Majesty's Stationary Office (HMSO), London (1949).

109 Stamm, A. J., *Wood and Cellulose Science*, Ronald Press, New York (1964).

110 Tiemann, H. D., *Wood Technology*, Pitman, New York (1944).

111 Daniel Jaunard, conservator, Service de Restauration des Musées de France (SRMF), Versailles, private communication (1990).

112 Patrick Mandron, conservator, Service de Restauration des Musées de France (SRMF), Versailles, private communication (1990).

113 'Conservation record NG.3076', unpublished report excerpt, National Gallery, London (1950) 8.

114 Raymond Marchant, conservator, Hamilton Kerr Institute, London, private communication (1993).

115 Nieri Pierluigi, conservator, DAMBRA Restauro, Florence, private communication (1990).

116 Brandi, C., 'Teoria del Restauro', Piccola Biblioteca Einaudi, Torino (1977) (first published 1963).

117 Robert Hayes, advisor on environmental control, Colebrooke Consulting Ltd., personal communication (1993).

118 Buck, R. D., 'The use of moisture barriers on panel paintings' *Studies in Cnservation* 6 (1961) 9-19.

119 Thomson, G., *The Museum Environment*, 2nd ed., Butterworths, International Institute for Conservation of Historic and Artistic Works (IIC), London (1986).

120 Sarah Staniforth, advisor on paintings conservation and environmental control, The National Trust, England, private communication (February, 1997).

121 Stevens, W. C., 'Rates of change in the dimensions and moisture contents of wooden panels resulting from changes in the ambient air conditions', *Studies in Conservation* 6 (1961) 21-25.

122 Richard, M., 'Factors affecting the dimensional responses of wood' in *Conservation of Wood in Painting and the Decorative Arts*, Preprints, Congress of the International Institute for Conservation of Historic and Artistic Works (IIC), Oxford (1978) 131-136.

123 Brewer, J. A., 'Effect of selected coatings on moisture sorption of selected wood test panels with regard to common panel painting supports', *Studies in Conservation* 36 (1991) 9-23.

124 Bodig, J., and Jayne, B. A., *Mechanics of Wood and Wood Composites*, Van Nostrand Reinhold, New York (1982).

125 Reeve, A. M., 'Structural conservation of panel paintings at The National Gallery, London', paper delivered at *Symposium on The Structural Conservation of Panel Paintings*, Getty Conservation Institute/J. Paul Getty Museum, Malibu, U.S.A. (April 24-28, 1995). (to be published)

126 Goldstein, M., Simonetti, G., and Watschinger, M., *Complete Guide to Trees and Their Identification,* Macdonald and Co., Milan (1984).

127 Klein, P., and Bauch, J., 'Analyses of wood from Italian paintings with special reference to Raphael' IN *The Princeton Raphael Symposium*, eds. J. Shearman and M. B. Hall, Princeton University Press, Princeton, U.S.A. (1990) 85-92.

128 Of 26 thinned and reinforced panels surveyed, thickness was from 2-5mm, mean 4+/-1mm, with transverse-grain dimensions 165-1210mm, mean 570+/-280mm.

129 Bergeon, S., Emile-Mâle, G., Baÿ, O., and Huot, C., 'La restauration des supports de bois de la peinture: deux cents ans d'histoire en France, du 18ème siècle au Louvre jusqu'à la collection Campana et aux années 1970's', paper delivered at *Symposium on the Structural Conservation of Panel Paintings*, The Getty Conservation Institute/The J. Paul Getty Museum, Malibu, U.S.A. (April 24-28, 1995). (to be published)

130 Brewer, A., 'A consolidation\filler system for insect-damaged wood' IN *Hamilton Kerr Institute Bulletin Number 2*, ed. A. Massing, Hamilton Kerr Institute of the Fitzwilliam Museum, Cambridge, England (1994) 68-72.

131 *Handbook of Hardwoods*, second edition, revised by R.H. Farmer, Her Majesty's Stationery Office (HMSO), London (1972).

132 Karpowiscz, A., 'In-plane deformations of films of size on paintings in the glass transition region', *Studies in Conservation* 33 (1989) 67-74.

133 Arney, J. S., and Stewart, D., 'Surface topography of paper from image analysis of reflectance images', *Journal of Imaging Science and Technology* 37 (1993) 504-509.

134 Forno, C., 'Moiré methods in strain measurement' IN *Optical Methods in Engineering Metrology*, ed. D. C. Williams, Chapman and Hall, London (1993) 339-384.

135 Paoletti, D., Schirripa Spagnolo, G., 'Automated digital speckle pattern interferometry contouring in artwork surface inspection', *Optical Engineering* 32 (1993) 1348-1353.

136 Bertani, D., Cetica, M., and Molesini, G., 'Holographic tests on the Ghiberti panel, 'The Life of Joseph'', *Studies in Conservation* 27 (1982) 61-64.

137 *Microstation Version 5*, Bentley Systems, Exton, Pennsylvania, USA (1993).

138 *A Handbook of Softwoods*, Building Research Establishment (BRE) Report, Her Majesty's Stationery Office (HMSO), London (1977).

139 Anthony Reeve, conservator, National Gallery, London, private communication (1993).

140 McClure, I., 'The framing of wooden panels', paper delivered at *Symposium on the Structural Conservation of Panel Paintings*, The Getty Conservation Institute/The J. Paul Getty Museum, Malibu, U.S.A. (April 24-28, 1995). (to be published)

141 Feller, R. L., Stolow, N., Jones, E. H., *On Picture Varnishes and Their Solvents*, National Gallery of Art, Washington D. C., (1971).

APPENDICES

Appendix 1: Interviews

Date, Country	City-Location	Hostpersons
autumn 1990, Italy	Florence- Laboratorio del Restauro (Uffizi Gallery, others)	Diane Kunzelman, Ezio Buzzegoli
	DAMBRA Restauro (private)	Nieri Pierluigi
	Studio Gori (private)	Pietro Gori
	(private)	Giovanni Marussich
	Opificio Delle Pietre Dure e Laboratori di Restauro	Dr Marco Ciatti Ciro Castelli
summer 1993	Rome- Vatican Museums	Dr Fabrizio Mancinelli, Enrico Guidi, Marcello Monterocce
	Istituto Centrale del Restauro	Dr Mara Nimmo
autumn 1990, Belgium	Brussels- Institut Royal du Patrimoine Artistique	Liliane Masschelein-Kleiner Jean-Albert Glatigny
France	Versailles- Service de Restauration des Musées de France	Daniel Jaunard, Patrick Mandron
	Paris- Atelier Claude Huot (private)	Claude Huot
Switzerland	Basel- Historisches Museum	H.-C. von Imhoff
	Bern- Fachklasse für Konservierung und Restaurierung	Volcker Schaible
autumn 1991, Netherlands	Amsterdam- Rijksmuseum	Martin Bijl
	Kollektief	IJsbrand Hummelen Liesbeth Abraham
	Haarlem- Frans Halsmuseum	Ella Hendriks

	Den Haag- Mauritshuis	Jørgen Wadum, Carol Pottasch
	Maastricht- Stichting Restauratie Atelier Limburg	Anne van Grevenstein
summer 1991, Denmark	Copenhagen- Statens Museum for Kunst	Mette Bjarnhof
	Det Kongelige Danske Kunstakademi Konservatorskolen	Mette Bjarnhof, Puccio Speroni, Mikkel Scharff
Germany	Münster- Westfälisches Amt für Denkmalpflege	John Farnsworth
	Hamburg- Museum für Kunst und Gewerbe	Frédéric Lebas
	Kunsthalle	Eva Keochakian
	Köln- Wallraf-Richartz-Museum	Christa Steinbüchel
autumn 1992	Stuttgart- Statsgalerie	Friedrich Schmidt
	Staatliche Akademie der bildenden Künste	Fritz Rieber
	Nürnberg- Germanisches Nationalmuseum	Dr Thomas Brachert
Austria	Vienna- Akademie der bildenden Künste	Prof. G. Kaspar Pia Geusau
	Kunsthistorisches Museum	Prof. G. Kaspar
	Bundesdenkmalamt, Abteilung für Restaurierung und Konservierung von Denkmalen	Dr Manfred Koller, Franz Höring
Czechoslovakia	Prague- various	Ladislav Kryl
1990-1991, England	London- The Tate Gallery	Roy Perry
1991-1993	The National Gallery	Anthony Reeve David Thomas Peter Scullard
	The Courtauld Institute, Department of Technology and Conservation	Robert Bruce-Gardner Alan Phenix
	Conservation Unit, Kenwood House	Jim Dimond

winter 1992, USA	Malibu- The J. Paul Getty Museum	Mark Leonard
	Los Angeles- County Museum	Shelley Svoboda
	San Diego- Balboa Art Conservation Center	Elizabeth Court
	New York- Metropolitan Museum of Art	George Bisacca
	Hispanic Society of America Museum	George Papadopulos
	Studio Grassi (private)	Marco Grassi
	Brooklyn- (private)	Victor von Reventlow
	Cambridge- Fogg Art Museum	Gianfranco Pocobene
	Boston- Museum of Fine Arts	James Wright Gianfranco Pocobene
	Washington, D.C.- National Gallery of Art	Mervin Richard
	Smithsonian Institution Conservation Analytical Laboratory	Marion Mecklenberg Melvin Wachowiak
	Baltimore- Walters Art Gallery	Melanie Gifford

COLLECTION **Trinity Hall, University of Cambridge**

PANEL PAINTING TITLE **Visitation**

artist **Maso da San Friano**

medium **oil**

conservation record number **HKI194**

accession number

provenance **Italian 16th c.**

execution date

height **4.09m** *width* **2.48m** *thickness* **.04m**

wood type **poplar** *grain orientation* **vertical**

original back? **yes**

auxiliary support? **yes**

auxiliary support type class **battens- rigid; intended to slide**

auxiliary support type

auxiliary support/back description **boards half-lapped by 15-16 cm to make height; 8 planks each about 34 cm width; loose tenon inserts in joints dowelled from front; 2 dovetail-inset battens tapered right to left when viewed verso**

general condition **poor**

flaking paint? **yes**

warping? **yes**

warp description

splitting; disjoining? **yes**

back coated? **no**

other

thinned? **no**

catalogue/publication(s) **HKI Bulletin No. 2**

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Appendix 3: Controlled-environment Room Description

The room (Figure 29) was built within an enclosed workshop which allowed nested construction with insulating advantages. The surrounding workshop space was adequately sealed against air draughts, the floor consisting of polyurethane-painted chipboard panels laid over a rigid foam which acted as a leveller, moisture seal, and thermal insulator from concrete beneath. Within the CE room, another floor of 1/2 inch (12.5mm) fibreboard panels was laid to provide some buffering of applied humidity changes.

A wooden framework (16X8X8ft high (4900X2440X2440mm)) with entrance was built. Two double-glazed windows on one side allowed communication with the photogrammetric-equipment operator. Outside walls were 3/8in (10mm) plywood lined inside with 2in (50mm) polystyrene insulation panels and sealed inside with thick black polyethylene sheet, including the roof, to create a black interior to enhance target contrast. Polystyrene insulating panels were laid on the roof from above. The workshop was lit from above with several banks of fluorescent-tube lamps. To admit top-light to the CE room, gaps were left in its roof directly below two workshop lamp fixtures and clear polyethylene sheet was stapled over the entire roof to provide an adequate seal.

Heat was provided inside the CE room by a thermostat-controlled oil heater unit. Relative humidity was controlled by a floor-model fan-circulated drum humidifier and a warm-air activated dehumidifier mounted near the ceiling with separate humidistats mounted on a wooden panel and located about halfway up the wall. A small electric fan was mounted beside them and run continually. Between measurements, panels were stored on shelves where they were separated by tensioned string dividers.

The CE room was thus effective, simply and economically constructed, and easily disassembled into re-usable elements.

Appendix 4: Test Panel Codes and Weights

Reinforcement Code	Reinforcement Type	Sample Code	Panel Weight (g)		Weight of Ground	Panel Thickness (mm)
			before ground	after ground		
	oak					
1	wood only	O1	841.8	841.8	0.0	3.3
2	sized only	O2	877.4	877.4	0.0	3.3
3	sized and grounded	O8	881.6	919.6	38.0	3.3
7	tissue/BEVA	O13	873.6	910.2	36.6	3.3
8	battens: fixed and rigid	O14	847.7	883.1	35.4	3.3
9	battens: sliding and rigid	O4	851.2	887.1	35.9	3.3
10	battens: sliding and flexible	O12	852.2	888.9	36.7	3.3
11	lattice: fixed and rigid	O18	865.4	909.3	43.9	3.3
12	lattice: sliding and rigid (cradle)	O9	838.9	876.2	37.3	3.3
13	lattice: sliding and flexible	O6	857.1	900.6	43.5	3.3
14	tray: sliding and flexible lattice	O5	836.8	874.3	37.5	3.3
15	tray: foam-cushion	O3	887.8	929.6	41.8	3.3
16	perimeter frame: rebated	O19	799.6	844.3	44.7	3.3
17	cable suspension	O17	777.1	822.6	45.5	3.3
18	laminate: balsa planks	O15	841.4	877.5	36.1	3.3
19	laminate: balsa blocks	O16	844.0	877.9	33.9	3.3
20	laminate: MDF	O11	873.9	913.7	39.8	3.3
21	perimeter frame: chassis cadre	O10	865.4	903.6	38.2	3.3
22	laminate: oak planks	O7	839.9	879.4	39.5	3.3
23	laminate: oak parquets	O21	843.9	885.1	41.2	3.3
		mean=	849.8		39.2	
	standard deviation=		26.5		3.5	
	poplar					
1	wood only	P21	398.2	399.8	1.6	3.3
2	sized only	P1	384.9	384.8	-0.1	3.3
3	sized and grounded	P17	393.2	443.6	50.4	3.3
3	sized and grounded	P22				10.0
3	sized and grounded	P23				20.0
4	laminate: OX honeycomb/PVA	P2	381.4	437.9	56.5	3.3
8	battens: fixed and rigid	P11	389.6	430.8	41.2	3.3
9	battens: sliding and rigid	P3	382.4	448.5	66.1	3.3
10	battens: sliding and flexible	P15	385.9	439.6	53.7	3.3
11	lattice: fixed and rigid	P7	399.7	465.9	66.2	3.3
12	lattice: sliding and rigid (cradle)	P12	393.2	451.2	58.0	3.3
13	lattice: sliding and flexible	P18	388.4	444.4	56.0	3.3
15	tray: foam-cushion	P5	391.9	442.2	50.3	3.3
16	perimeter frame: rebated	P6	399.0	457.1	58.1	3.3
17	cable suspension	P10	390.9	439.8	48.9	3.3
18	laminate: balsa planks	P4	393.9	448.7	54.8	3.3
19	laminate: balsa blocks	P9	393.2	431.8	38.6	3.3
20	laminate: MDF	P14	394.2	450.8	56.6	3.3
21	perimeter frame: chassis cadre	P19	388.4	443.2	54.8	3.3
		mean=	391.1		54.0	
	standard deviation=		5.4		7.6	

Reinforcement Code	Reinforcement Type	Sample Code	Panel Weight (g)		Weight of Ground	Panel Thickness (mm)
			before ground	after ground		
		linden				
1	wood only	L22	571.3	570.2	-1.1	3.3
2	sized only	L1	569.3	567.3	-2.0	3.3
3	sized and grounded	L9	591.9	643.7	51.8	3.3
5	laminate: OX honeycomb/epoxy	L13	603.4	652.5	49.1	3.3
8	battens: fixed and rigid	L6	577.9	626.0	48.1	3.3
9	battens: sliding and rigid	L16	582.9	636.0	53.1	3.3
10	battens: sliding and flexible	L18	579.4	629.4	50.0	3.3
11	lattice: fixed and rigid	L5	583.7	628.0	44.3	3.3
12	lattice: sliding and rigid (cradle)	L7	587.6	651.0	63.4	3.3
13	lattice: sliding and flexible	L14	588.3	640.5	52.2	3.3
15	tray: foam-cushion	L4	611.6	668.4	56.8	3.3
16	perimeter frame: rebated	L11	583.2	628.3	45.1	3.3
17	cable suspension	L12	588.5	641.8	53.3	3.3
18	laminate: balsa planks	L19	580.8	640.5	59.7	3.3
19	laminate: balsa blocks	L3	594.8	640.3	45.5	3.3
20	laminate: MDF	L17	596.9	652.0	55.1	3.3
21	perimeter frame: chassis cadre	L2	588.2	634.1	45.9	3.3
		mean=	587.0		51.6	
	standard deviation=		9.3		5.6	
		pine				
1	wood only	S22	667.6	667.0	-0.6	3.3
2	sized only	S14	574.0	574.7	0.7	3.3
3	sized and grounded	S19	631.4	672.9	41.5	3.3
6	laminate: HEX honeycomb/epoxy	S17	652.6	699.5	46.9	3.3
8	battens: fixed and rigid	S15	584.6	624.3	39.7	3.3
9	battens: sliding and rigid	S5	550.4	599.6	49.2	3.3
10	battens: sliding and flexible	S6	604.0	654.0	50.0	3.3
11	lattice: fixed and rigid	S21	548.4	588.9	40.5	3.3
12	lattice: sliding and rigid (cradle)	S13	601.9	643.9	42.0	3.3
13	lattice: sliding and flexible	S9	579.6	631.4	51.8	3.3
15	tray: foam-cushion	S11	628.5	683.8	55.3	3.3
16	perimeter frame: rebated	S18	577.9	619.5	41.6	3.3
17	cable suspension	S2	658.5	699.1	40.6	3.3
18	laminate: balsa planks	S10	565.6	617.6	52.0	3.3
19	laminate: balsa blocks	S3	567.4	618.2	50.8	3.3
20	laminate: MDF	S16	635.2	689.7	54.5	3.3
21	perimeter frame: chassis cadre	S12	586.2	627.7	41.5	3.3
		mean=	600.8		46.5	
	standard deviation=		38.1		5.7	

Appendix 5: Panel Construction

Oak and pine had been air-dried, then kiln-dried to MC of about 14%, then stacked under cover until sale. Poplar was selected from planks from one tree. They had been air-dried under cover for at least one year. All acquired planks were stacked with stickers between layers and under interior conditions for about six months with intermittent low heating. Each plank was then re-sawn with a bandsaw into three planks, ranging from 6 to 8mm thickness, planed on one edge, sawn to width, planed on the other edge, stickered again and allowed to equilibrate for about six weeks. Planks were then sanded both sides to uniform thickness of 4.00mm using a wide-belt sanding machine and cut to length, each yielding up to three pieces at least 610mm long. Joining edges were planed straight and square to widths of 200.0mm using hand planes and a shooting-board. Planks were joined in a purpose-built press, oriented with annual rings alternating in adjacent planks, using urea formaldehyde resin. After drying, panels were machine-sanded diagonally across opposite corners and on both sides with 80-grit abrasive to a final thickness of 3.30mm. Perimeter dimensions were then finished to 600.0mm on each side with a radial-arm saw.

Two additional poplar panels, 10.0mm and 20.0mm thick, were prepared similarly.

Appendix 6: Reinforcement Construction

Where considered necessary, diagrams accompany descriptions.

Over-extended Honeycomb-core Laminate (Reinforcement #4)

Materials

non-wet strength tissue

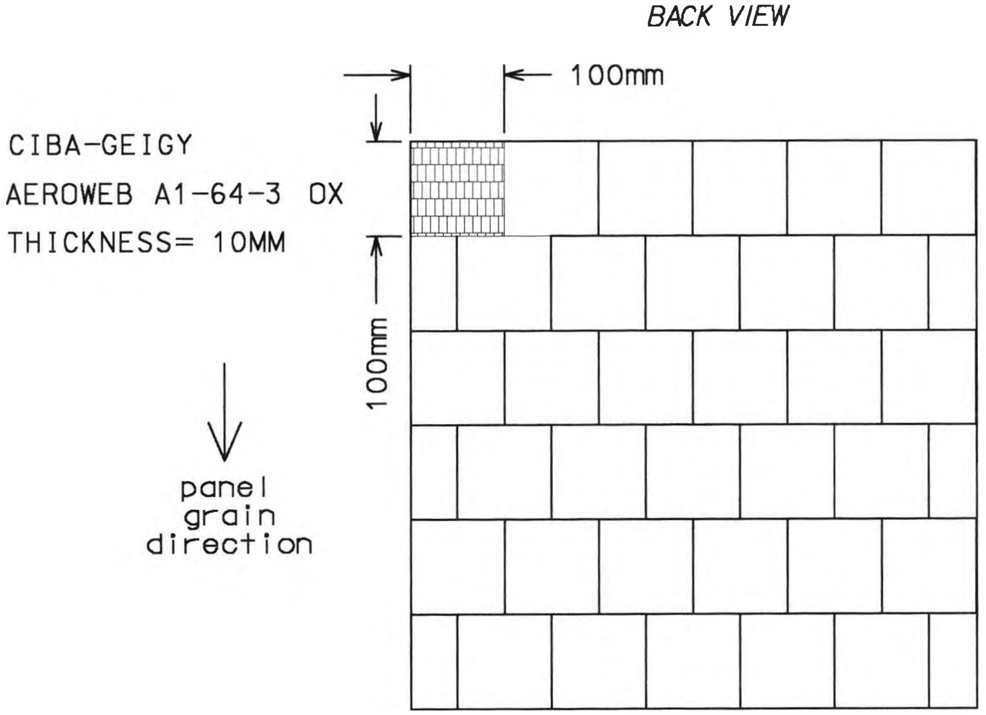
heat-activated adhesive (BEVA371, undiluted)

over-extended honeycomb-core made from phenolic-resin coated
polyamide (Ciba Geigy AEROWEB A1-29-3 OX)

polyvinyl-acetate dispersion adhesive (EVOSTIK Resin W)

release film (MELINEX)

Diagram



Construction

The core consisted of rectangular cells with the shorter axis of each cell aligned with one axis of the supplied sheet, called the horizontal axis in this thesis. The sheet was more easily stretched in one direction than the other, with a Poisson ratio of about -0.4 parallel to the horizontal axis. It was considered important that any movement of the panel in the transverse-grain direction should affect its behaviour as little as possible in the longitudinal-grain direction. If transferred to the core laminate, its Poisson's effect would influence restraint in such a way. To minimise passive strain of the laminate in the longitudinal-grain direction, the horizontal axis was aligned parallel to the transverse-grain direction.

A tissue release layer was applied (see Paper Tissue Strips, Reinforcement #7, below). The adhesive was mixed (2 parts:1 part by volume) with water to achieve a lower viscosity so that it would flow down the cell wall and form a meniscus for a more secure bond.

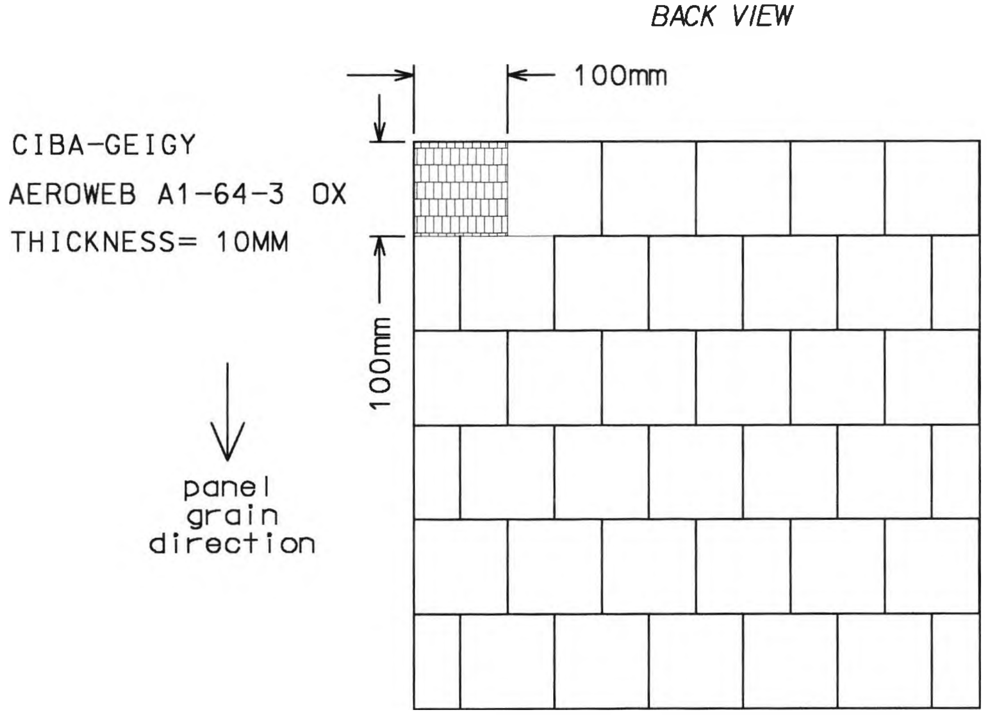
Squares of core were cut with one edge parallel to the horizontal axis of the hexagonal cell. A film of adhesive about 0.5mm thick was spread on a stretched sheet of release film using a toothed spatula. Each square was then placed with one side in the adhesive and swivelled round until a meniscus coated the cell walls uniformly to a height of about 1mm. With the cell horizontal axis parallel to the transverse-grain direction, each square was then carefully positioned on the panel back in a brick-like pattern and weighted lightly overall. The adhesive produced a variable gap at each cell center.

Over-extended Honeycomb-core Laminate (Reinforcement #5)

Materials

non-wet strength tissue
heat-activated adhesive (BEVA371, undiluted)
over-extended honeycomb-core, phenolic-resin coated polyamide (Ciba
    Geigy AEROWEB A1-29-3 OX)
epoxy/microballoon mortar (Ciba Geigy Araldite XD759
    mixed 4 parts to one by weight with Araldite GY1823,
    then combined with phenolic resin microballoons)
release film (MELINEX)

Diagram



Construction

The same as for Reinforcement #4, except that an epoxy/microballoon mortar was used instead of PVA. A film of mortar about 0.5mm thick was spread on a stretched sheet of release film with a toothed spatula. Each square was then placed with one side in the mortar and swivelled round until a meniscus coated the cell walls uniformly to a height of about 1mm. With the cell horizontal axis parallel to the transverse-grain direction, each square was then carefully positioned on the panel back in a brick pattern and weighted lightly overall. The mortar flowed to produce about a 2mm (average) exposed gap at each cell center. This ensured that the epoxy was porous to moisture and decreased its stiffness from that of a continuous film.

Hexagonal Honeycomb-core Laminate (Reinforcement #6)

Materials

non-wet strength tissue

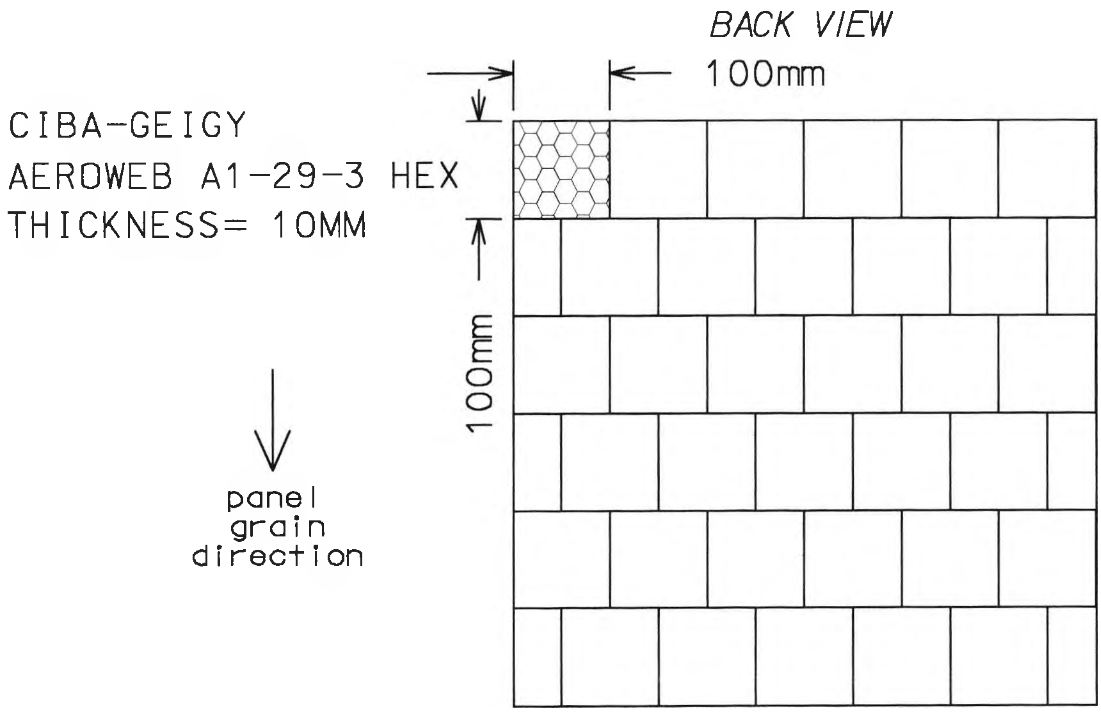
heat-activated adhesive (BEVA371, undiluted)

hexagonal honeycomb-core, phenolic-resin coated polyamide (Ciba Geigy AEROWEB A1-29-3 HEX)

epoxy/microballoon mortar (Ciba Geigy Araldite XD759 mixed 4 parts to one by weight with Araldite GY1823, then combined with phenolic resin microballoons)

release film (MELINEX)

Diagram



Construction

The core consisted of hexagonal cells so that one pair of opposite apices of each cell were aligned with one axis of the supplied sheet, which in this thesis is called the horizontal axis. The sheet was more easily stretched in one direction than the other, suggesting a Poisson ratio less than 1 parallel to the horizontal axis. This was measured at about -0.9. It was considered important that any movement of the panel in the transverse-grain direction should affect the panel as little as possible in the longitudinal-grain direction. If transferred to the core laminate, its Poisson's effect would influence restraint in such a way. Therefore, it would be desirable that passive strain of the laminate in the longitudinal-grain direction be minimised. Therefore, the horizontal axis was aligned parallel to the transverse-grain direction.

A tissue release layer was applied (see Paper Tissue Strips, below).

Squares of core were cut with one edge parallel to the horizontal axis of the hexagonal cell. A film of mortar about 0.5mm thick was spread on a stretched sheet of release film with a toothed spatula. Each square was then placed with one side in the mortar and swivelled round until a meniscus coated the cell walls uniformly to a height of about 1mm. With the cell horizontal axis parallel to the transverse-grain direction, each square was then carefully positioned on the panel back in a brick pattern and weighted lightly overall. The mortar flowed to produce about a 2mm (average) exposed gap at each cell center. This ensured that the epoxy was porous to moisture and decreased its stiffness from that of a continuous film.

Paper Tissue Strips (Reinforcement #7)

Materials

non-wet strength tissue
heat-activated adhesive- (BEVA371, undiluted)

Construction

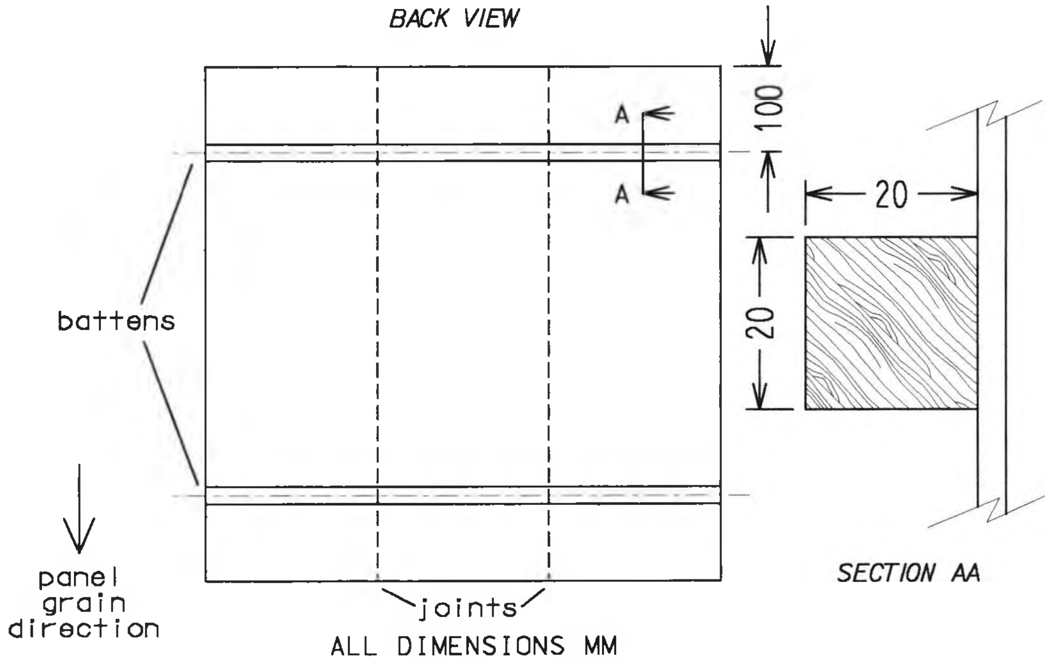
Strips of non-wet strength tissue were cut to width (varied from 80-120mm) by first wetting along a straight-edge with a sable-hair brush and then tearing to produce frayed edges. Strips were dried and thoroughly impregnated with heat-activated adhesive by brush, allowed to dry, then each strip was heat-tacked to the panel back, parallel to the grain direction and overlapped slightly with the adjacent strip. Good adhesion was assumed when the paper/adhesive/panel bond darkened and became more transparent. The panel wood absorbed heat quickly from the hot-spatula, which had to be kept at 120C and allowed occasional intervals to regain heat. Overhanging tissue at the panel edges was turned, heat-tacked, and trimmed flush with the panel face.

Fixed Rigid Battens (Reinforcement #8)

Materials

Scots pine (*Pinus sylvestris* L.) planks
animal glue (TROBAS brand, 12 g/100 ml distilled water)

Diagram



Construction

For each panel, two square-section battens were sawn with the grain and planed smooth. Each was heated (70C) on the gluing face with an electric clothes-iron, hot glue applied by brush, then pressed onto the panel and weighted for at least 15h. Adhesion to the more absorptive woods (eg. poplar) may have been poorer.

Sliding Rigid Battens (Reinforcement #9)

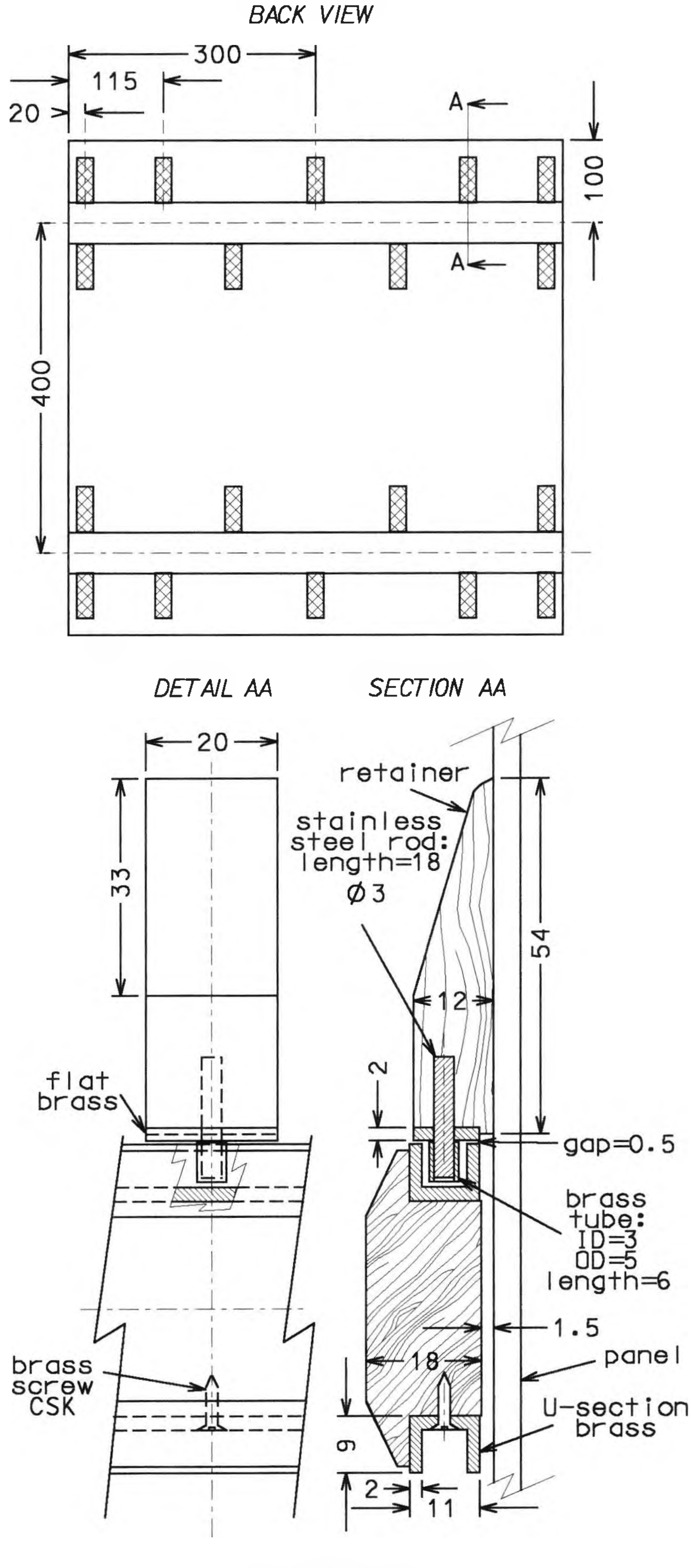
Materials

wood- utile (*Entandophragma utile* (Dawe & Sprague) Sprague) or South American mahogany (*Swietenia* sp.) planks
polyvinyl-acetate dispersion adhesive (EVOSTIK Resin W)
epoxy wood filler- (ARALDITE)
brass, flat stock
brass tubing
brass U-section
stainless steel rod
brass screws, countersunk

Construction

For each panel, two battens were sawn with the grain, rebated with a power router and bevelled with a hand plane. U-section brass strips were cut to length, glued (epoxy) and reinforced with countersunk screws into each rebate. Retainers were supplied by C. Huot. Each had been rebated at end-grain, flat brass set-in and glued (epoxy), drilled through the brass and into the wood, and a steel rod glued in (epoxy) as a spindle. Brass tubing was cut to the length of the projecting spindle and slid onto it. Battens were positioned, spaced about 1.5mm from the panel back with card and temporarily clamped. Retainers were glued (PVA) to the panel with the indicated tolerances and left to dry at least 15h.

Diagram



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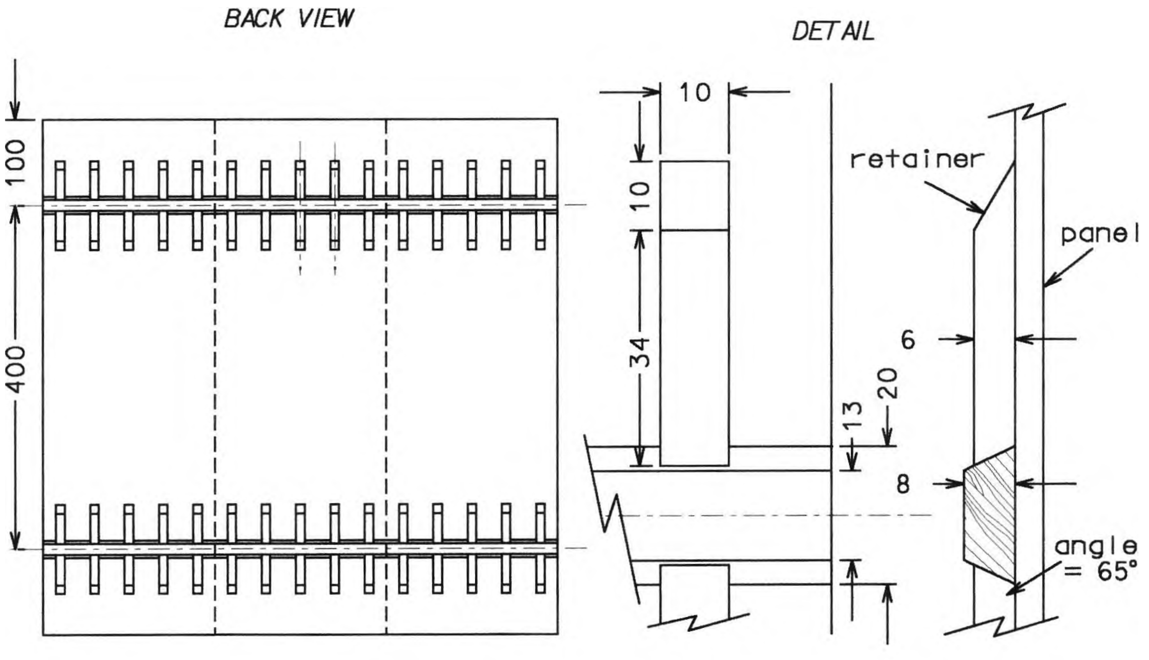
Sliding Flexible Battens (Reinforcement #10)

Materials

Afrormosia (*Pericopsis elata* van Meewen) wood planks
polyvinyl-acetate dispersion adhesive (EVOSTIK Resin W)
paraffin wax

Diagram



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Construction

For each panel, two battens were sawn with the grain and finished with a hand plane. Paraffin was rubbed on the contact surfaces and polished vigorously with cork. The panel was laid on a table, each batten clamped to it and all retainers along one side of the batten glued to the panel. Battens were then unclamped and set away from retainers by a tolerance equal to two thicknesses of typewriter paper, reclamped and retainers on the other side glued and allowed to dry for at least 15h before removing clamps.

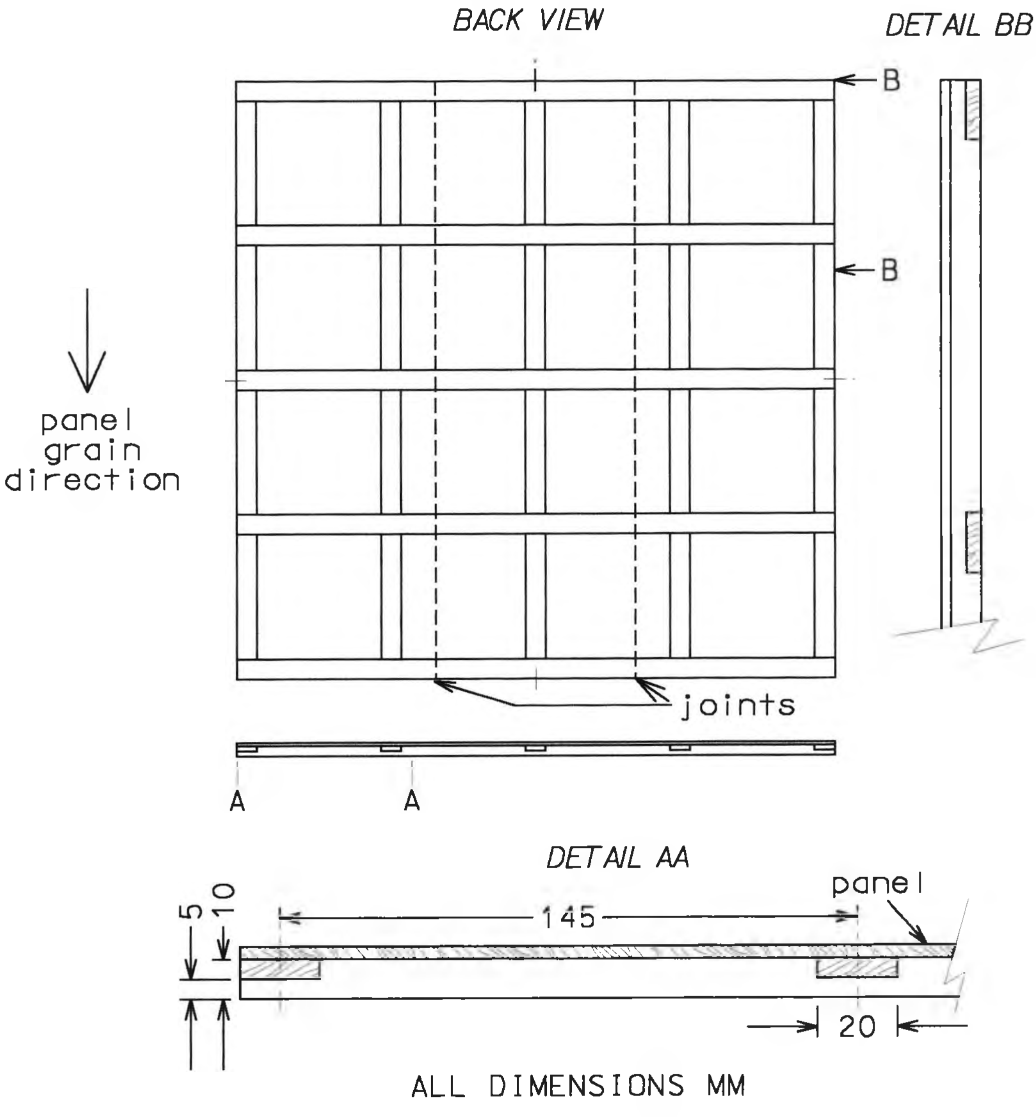
Fixed Lattice (Reinforcement #11)

Materials

oak (*Quercus* sp.) planks, radially sawn.

animal glue (TROBAS brand, 12 g/100 ml distilled water)

Diagram



Construction

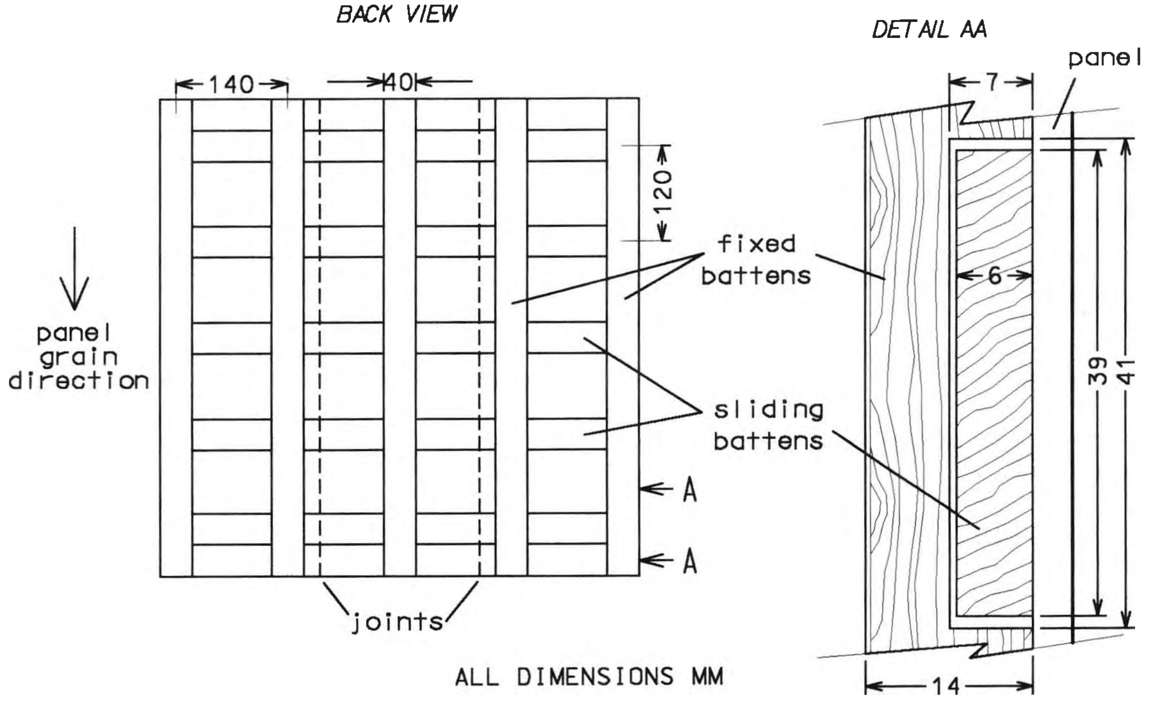
For each panel, an oak lattice was prepared from the same oak planks as the panels, planed and thicknessed. Channels in the fixed members were cut with a jig and radial-arm saw. Members to be glued parallel to the panel grain were heated (70C) on the gluing face with an electric clothes-iron, hot glue applied by brush, then pressed onto the panel and weighted for at least 15h. Cross-members were treated similarly and the lattice and panel weighted immediately under 1/2in (12mm) plywood panel and weights. Adhesion to the more absorptive woods (eg. poplar) may have been poorer.

Sliding Rigid Lattice (Cradle) (Reinforcement #12)

Materials

oak (*Quercus* sp.) planks, radially sawn.
animal glue (TROBAS brand, 12 g/100 ml distilled water)

Diagram



Construction

Cradles were constructed to function as the design was originally intended. Sliding members were made sufficiently loose so as to not swell and bind in the channels. During attachment of the fixed members, glue seepage was carefully avoided to prevent accidental gluing of the sliding members.

For each panel, an oak cradle (low type, or *parquetage à plat)* was prepared from the same wood source as the oak panels. Fixed and sliding members were cut from planed and thicknessed planks. Channels in the fixed members were cut with a jig and power router set-up. Fixed members were then glued to the panels with animal glue with the two outside sliding members positioned first and clamped to guide alignment. Each fixed member was heated (70C) on the gluing face with an electric clothes-iron, hot glue applied by brush, then pressed onto the panel and weighted for at least 15h. Adhesion to the more absorptive woods (eg. poplar) may have been poorer. Sliding members were planed to their final section dimensions after the fixed members were attached to ensure at least the tolerance shown in the diagram.

Sliding Flexible Lattice (Reinforcement #13)

Materials

Sitka spruce (*Picea sitchensis* (Borg) Carr.) planks,
radially sawn
polyvinyl-acetate dispersion adhesive (EVOSTIK Resin W)
closed-cell polyethylene foam (PLASTAZOTE)

Construction

Most elements were constructed of Sitka spruce, chosen for its straight grain and particular, consistent bending properties. Retainers were the same wood as the panel. All elements were joined with PVA dispersion.

For all four panels, battens were cut parallel to the grain with their radial surfaces on the largest face. Retainers were cut from a

Diagram (dimensions)

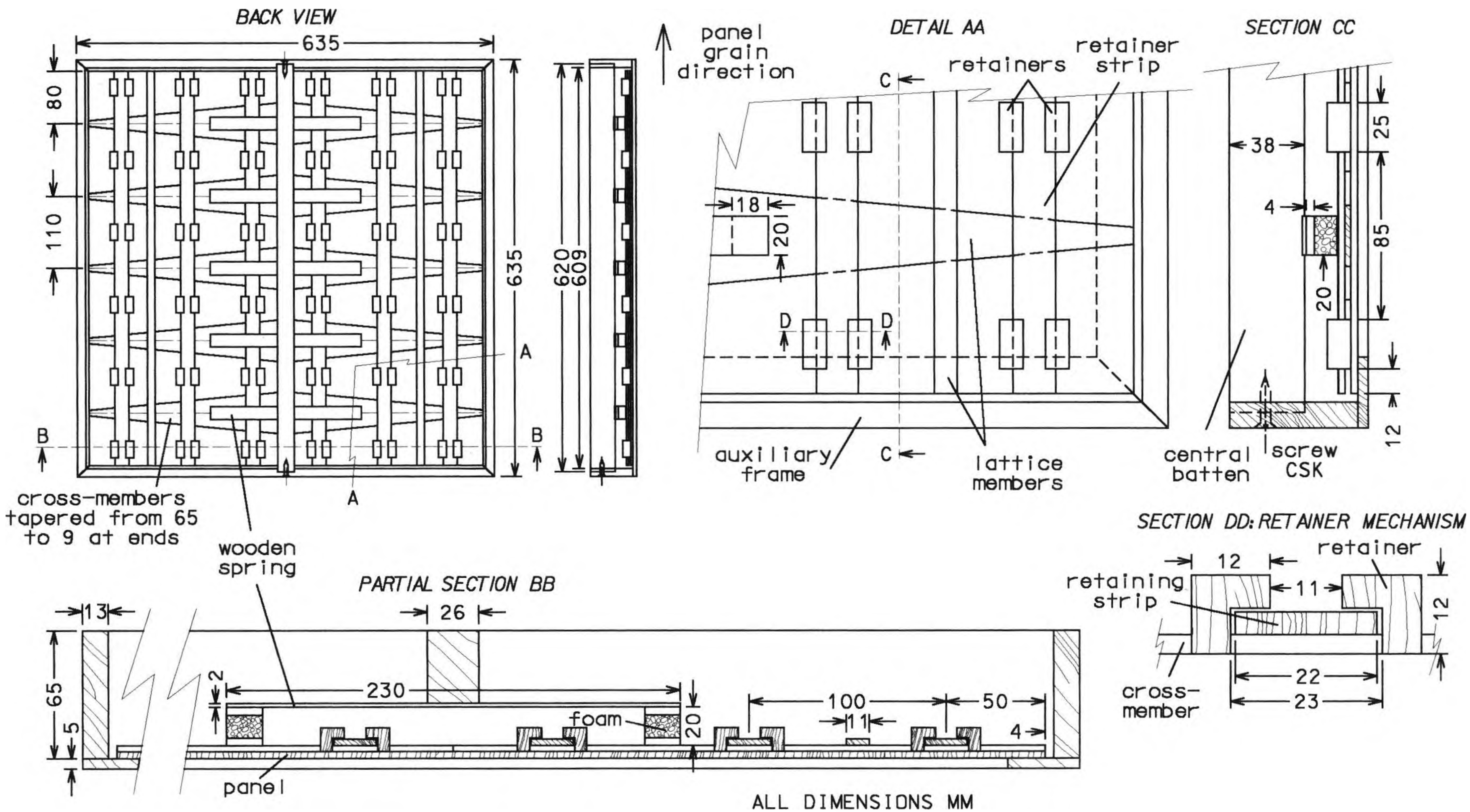
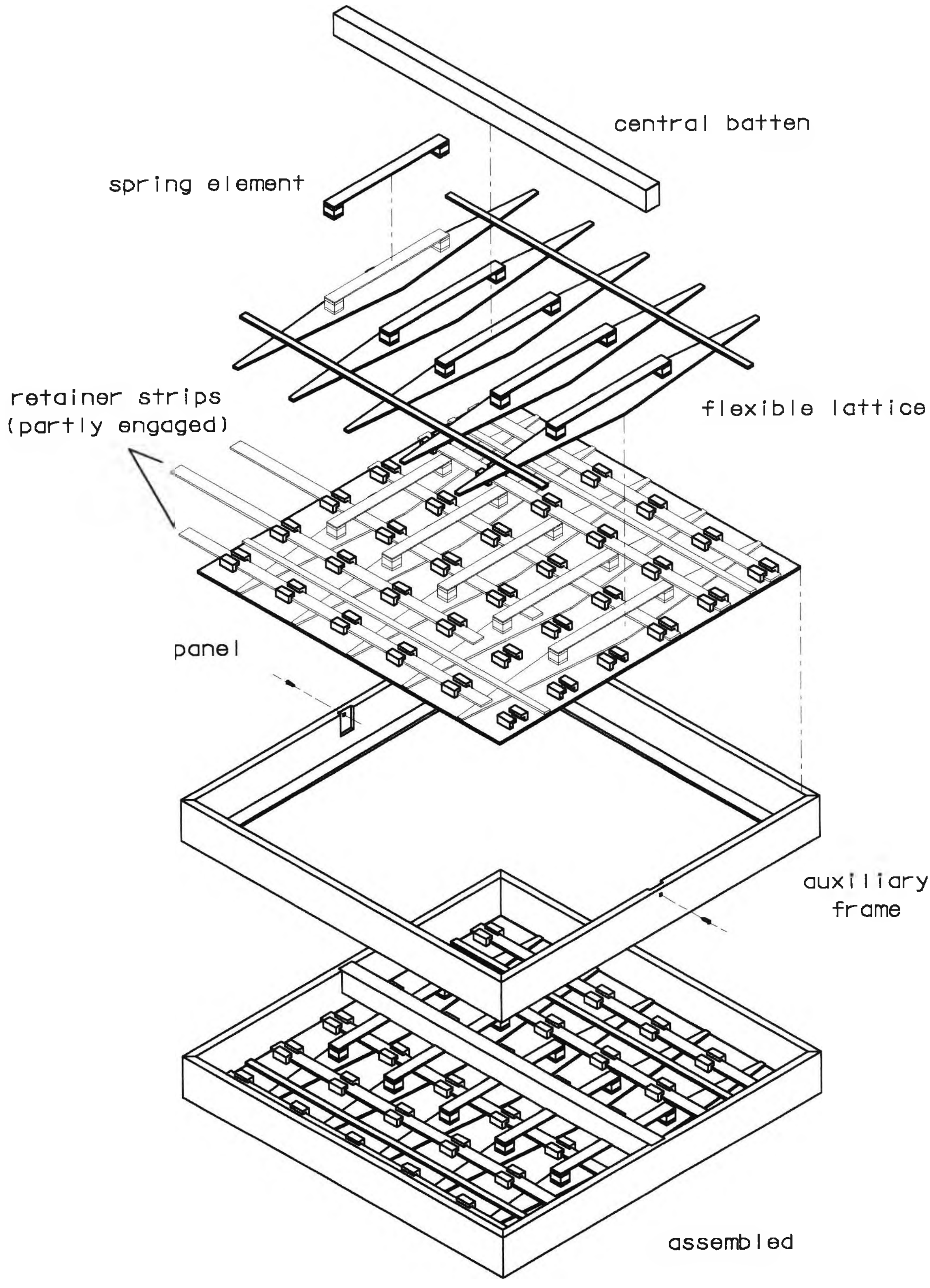


Diagram (assembly)



rebated, square-section batten. The lattice was built from five tapered cross-members laid across the panel grain and glued to two rectangular-section members lying perpendicular to the grain. The cross-members were thinned and tapered according to beam theory based on a maximum safe deflection which would occur from the weight of the panel if it were laid flat and supported at each longitudinal-grain edge. The taper, here decreasing from center by about 0.2 mm per mm length, was based on a change in section of a beam supported at both ends which would produce a uniform curve from an evenly distributed load.

The lattice was held against the panel back by evenly spaced, flexible wood retainer strips oriented with the panel grain. These were slid through small wood retainers glued to the panel back with grains parallel to the panel. The lattice could be removed by disengaging the retainer strips.

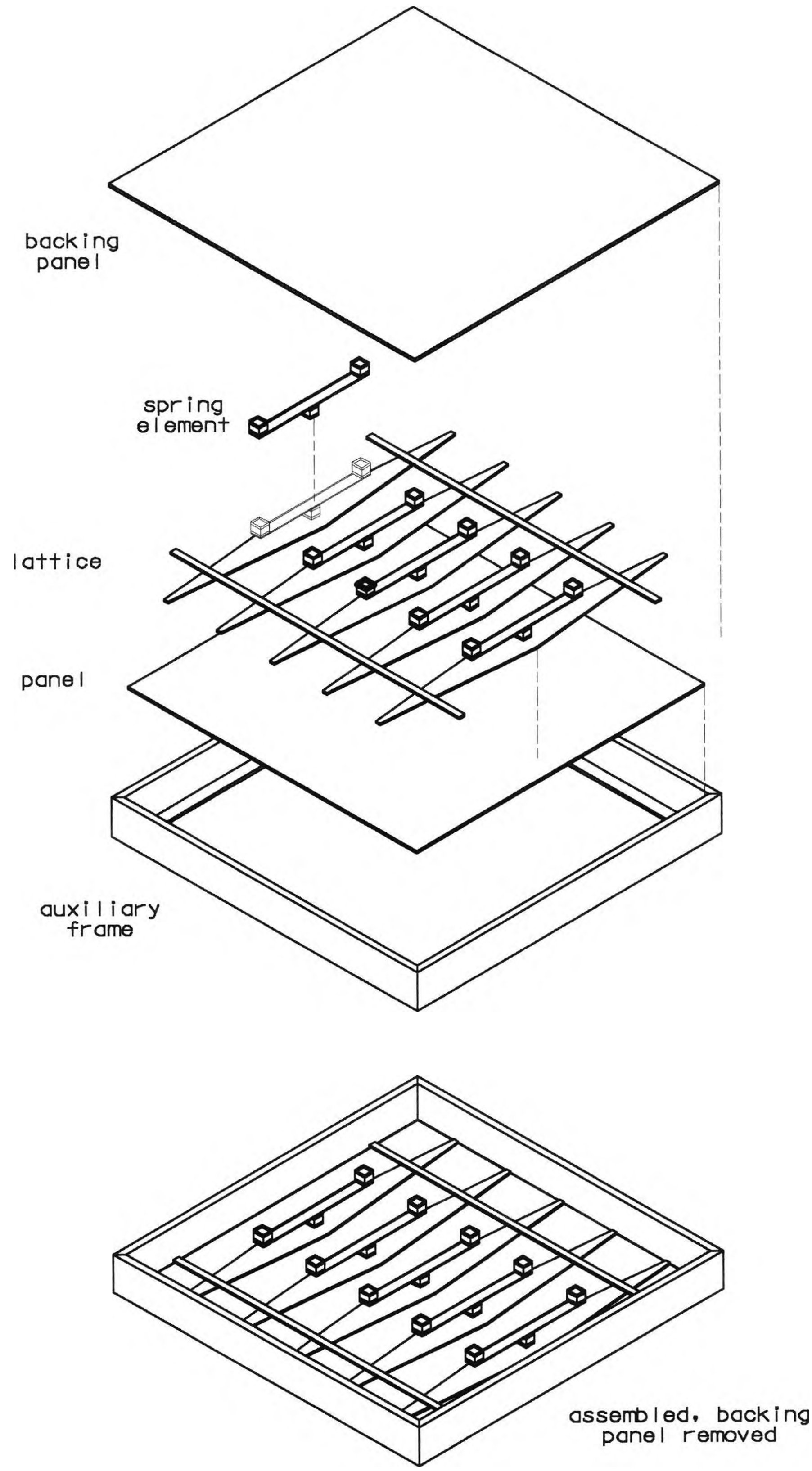
An auxiliary frame was constructed with a rebate depth and width slightly greater than the maximum expected panel warp and transverse expansion, respectively, for a range of about 40%RH. The panel was held in the inner frame with a central rigid batten positioned parallel to the panel grain and bearing on the central third of the lattice via a type of leaf spring. Thin wooden strips, one for each tapered batten and 1/3 its length, were centered and attached by each end to the batten to act as "springs" to accommodate concave warp. Closed-cell foam (EVAZOTE) was used for a flexible joint between the ends of the spring and the batten to prevent the fixed-end condition of typical glued joints which would stiffen the spring excessively.

Sliding Flexible Tray (Reinforcement #14)

Materials

Sitka spruce (*Picea sitchensis* L.) planks, radially sawn
polyvinyl-acetate dispersion adhesive (EVOSTIK Resin W)
closed-cell polyethylene foam- (PLASTAZOTE)
tray backing panel, polystyrene foam-core/paper-skin
sandwich (FOMECOR)

Diagram (assembly)



Construction

A lattice was constructed as for the sliding flexible lattice (Reinforcement #13) to provide a flexible cushion for the panel which was in contact but not attached. The panel and lattice were retained within an auxiliary frame by a backing panel intended to prevent handling and frame stresses and buffer the effect of rapid RH changes. The auxiliary frame's depth was based on panel movement and warp anticipated for an RH range of about 40%, including any warp restraint provided by the reinforcement.

Foam-cushion Tray, National Gallery type (Reinforcement #15)

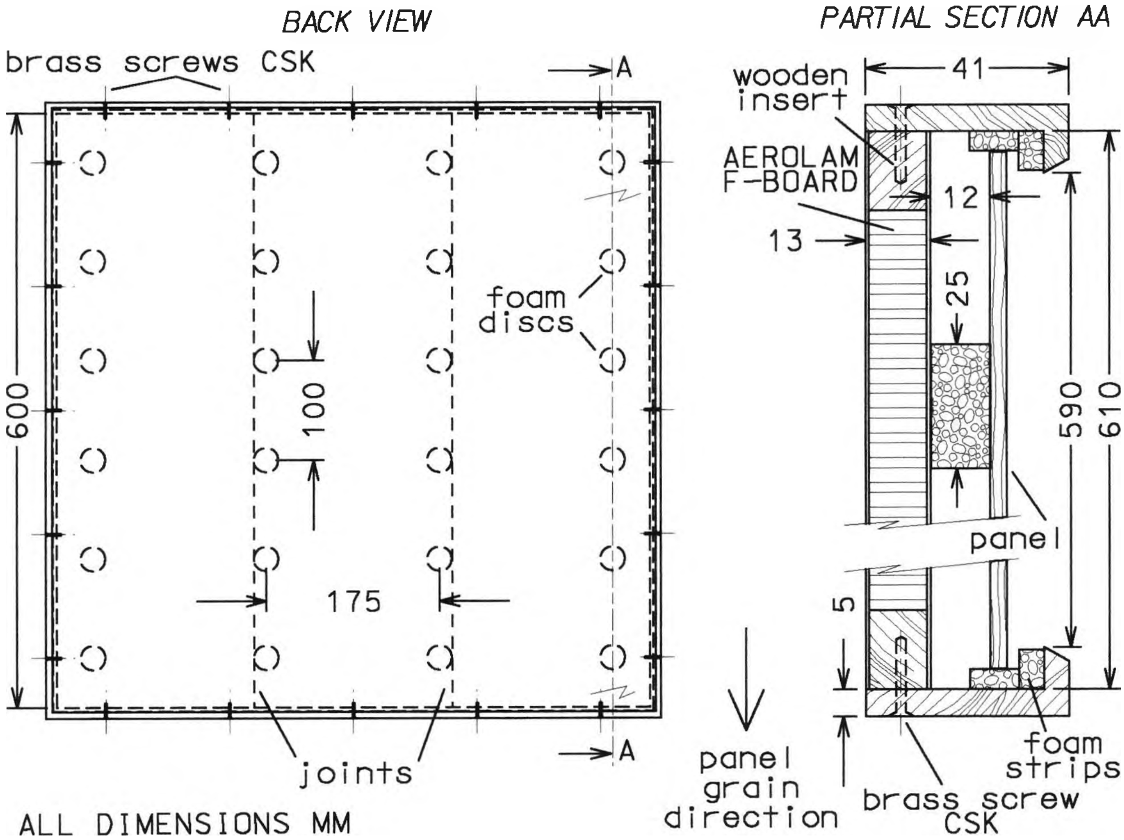
Materials

tray backing panel- AEROLAM honeycomb panel (aluminium-core/epoxy-impregnated fibre-glass skins, 1/2in (12mm) thick
cedar wood edge inserts
oak wood rebated retaining frame
neoprene rubber adhesive (EVOSTIK)
polyvinyl-acetate dispersion adhesive (EVOSTIK Resin W)
epoxy-resin adhesive (ARALDITE 2003)
foam discs, rebate padding- closed-cell polyethylene foam (PLASTAZOTE LD24)
brass screws, countersunk

Tools

Hand-tools can be used. Helpful alternatives include power jigsaw, power router with 1/2in (12mm) diameter tungsten-carbide blade, bandsaw and table-saw. Framing corner-clamps are recommended.

Diagram



Construction

The honeycomb-core backing panel was measured, marked and cut to the panel painting dimensions plus 1/8in (3mm) all-around (that is, panel dimensions plus 1/4in (6mm) total) using a power jigsaw with tungsten-carbide blade. The aluminium honeycomb-core was cut out of the backing panel edges to a depth of about 1/2in (12mm) using a power router with tungsten-carbide blade. Inserts of cedar wood were glued (epoxy resin adhesive) into the gaps and finished flush to provide a substrate onto which the rebated retaining frame was screwed.

Oak strips were rebated to allow a front flange that would overlap the test-panel edges at the front by at least 1/4in (6mm) all around. The depth of the side flange of the rebate (outside dimension) was calculated as the sum of the front flange thickness (1/8in (3mm)) plus the rebate foam strip thickness (1/8in (3mm)) plus the panel thickness (3/16in (5mm)) plus an allowance for the expected deflection of the painting (1/2in (6mm) was allowed here) plus the base panel thickness (1/2in (6mm)) plus about 1/8in (3mm) extra for planing to finished size. The rebated frame members were mitred, glued, and finished. Foam strips the width of the front rebate flange were cut and adhered to the inside with neoprene rubber adhesive.

Foam discs, 1in (25mm) diameter by 1/2in (12mm) depth, were cut to support the panel. A grid-like pattern of discs was chosen, the intersections marked on the base panel and the discs glued on with neoprene rubber cement. With the painting inverted in the rebated frame, the final rebate depth was marked and the excess planed away. The rebated frame was then positioned on the empty tray and screw holes were drilled and countersunk. The frame was removed, the painting was placed on the foam discs, the frame re-positioned and screwed to the tray base.

Rebated Frame, Brass Retainers (Reinforcement #16)

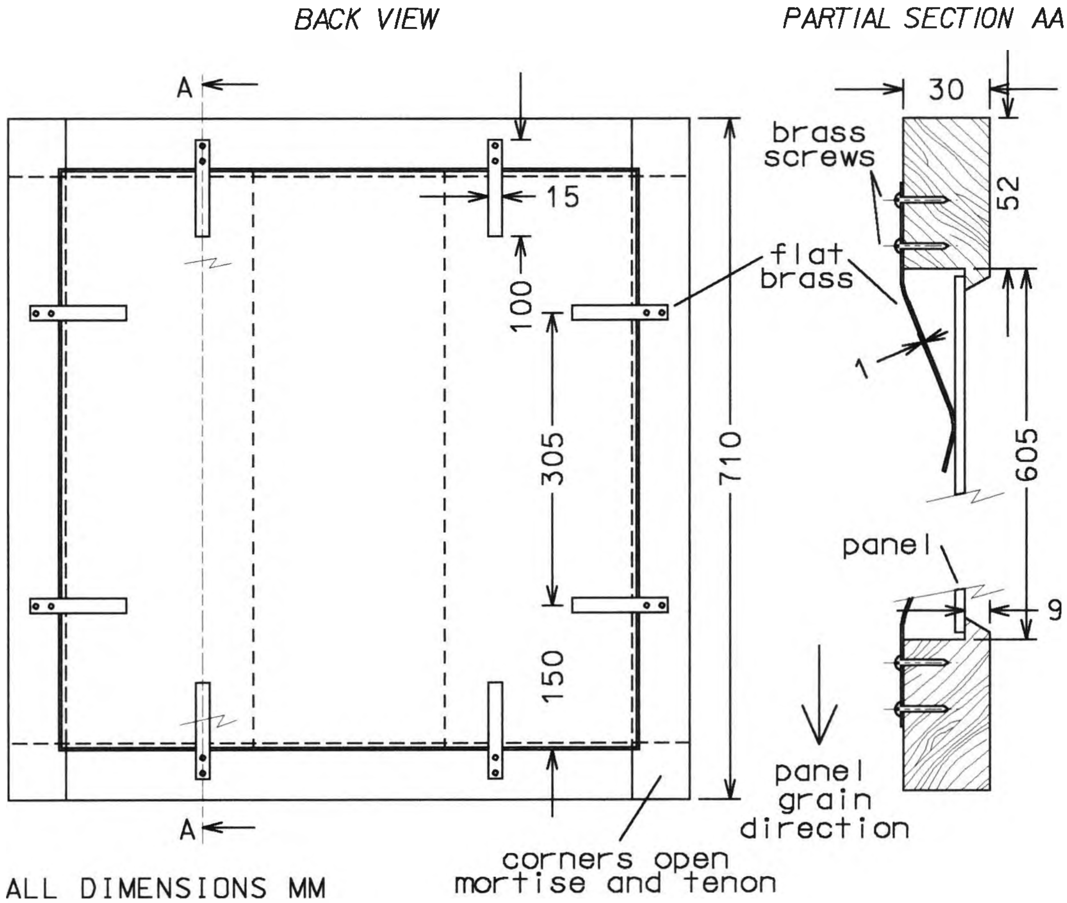
Materials

Scots pine (*Pinus sylvestris* L.) planks
polyvinyl-acetate dispersion adhesive (EVOSTIK Resin W)
rectangular brass mending plates
brass wood screws, round head

Construction

Frame members were cut and joined with open mortise-and-tenons, glued and clamped. Rebates were cut with a power router and the corners finished square with a chisel. The frame was bevelled at the front along the inner (sight) edge to allow for the angles of camera interrogation. The panel was placed in the rebate. Eight brass plates were bent in the same way, two positioned along each side, those along the panel end-grain edges bent to just contact the panel surface, those along the longitudinal-grain edges bent to leave a 1-2mm gap, then screwed to the frame.

Diagram



Cable Suspension (Reinforcement #17)

Materials

Scots pine (*Pinus sylvestris* L.) planks

polyvinyl-acetate dispersion adhesive (EVOSTIK Resin W)

woven stainless steel cable, 1mm diameter

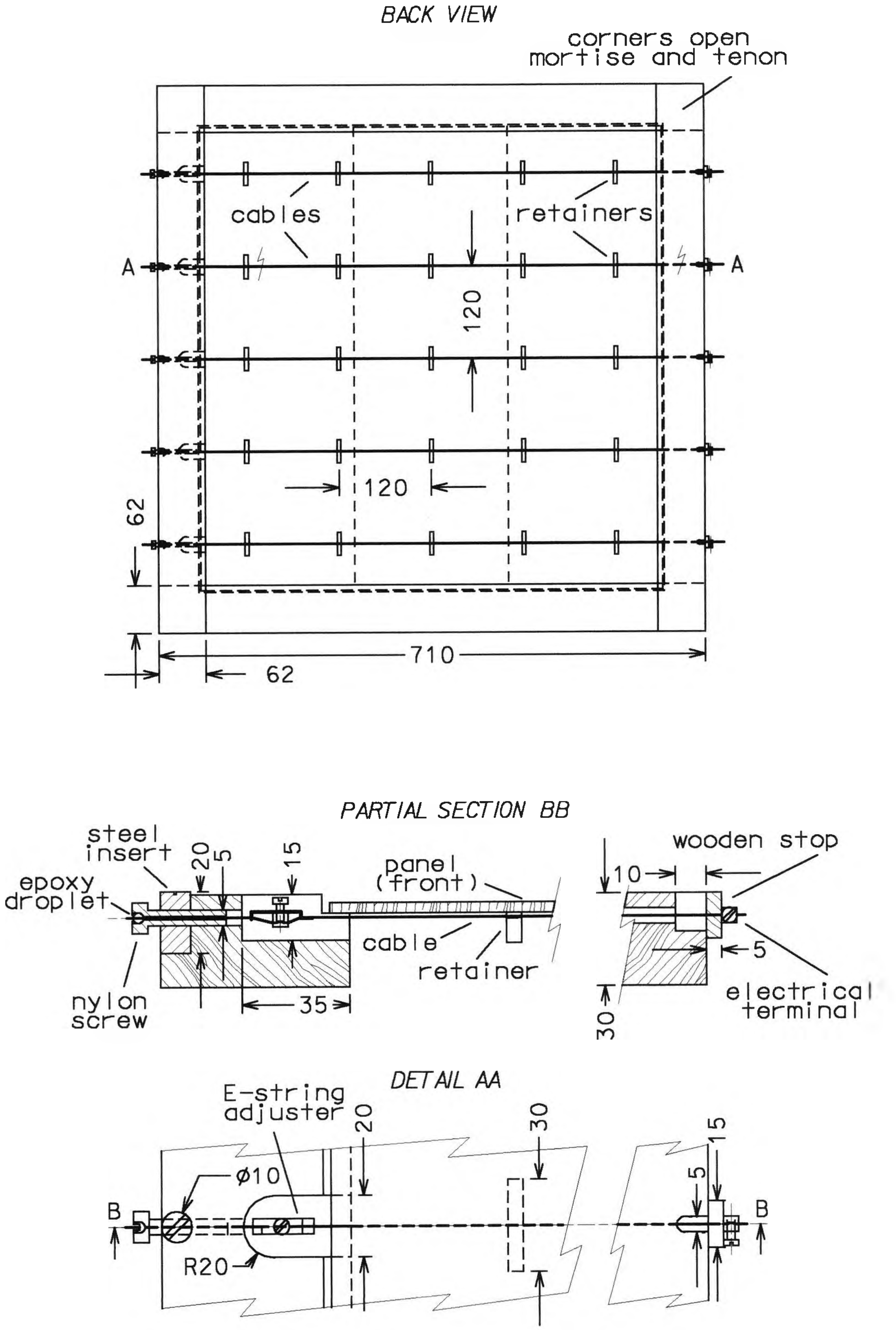
machine-threaded nylon bolts, 25mm X 6mm

machine-threaded zinc-coated steel inserts

brass electrical terminals

violin E-string adjusters, chrome-plated

Diagram



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Construction

The wood was cut to oversized thickness, planed, sawn to length, holes drilled and slots cut with a power router, and the corners cut to form open mortise-and-tenon joints which were glued and clamped. The frame was then planed and sanded to finished dimensions, an inner rebate routered all around and its corners finished.

For each frame, five lengths of wire were cut to 70mm each. For each wire, a droplet of epoxy resin was applied near one end and the wire hung vertically until set. The other end of thewire was passed through a hole drilled the length of the center of a nylon screw, through a hole on one and then the other side of the frame and through a brass electrical terminal. The nylon screw was inserted, turned in the length of its thread, the opposite end of the wire pulled taught and tightly screwed in place using the electrical terminal as a stopper. Tension was applied first by turning the nylon screw outward, then an E-string adjuster was attached to the exposed wire in the frame slot and turned to the exact tension desired. All wires on all frames were "tuned" by ear to the same pitch.

To mount the panels on the wires, retainers were cut from oak using the bandsaw, the panel placed face-down on a horizontal surface and shimmed upward to contact the wires. Retainer positions were marked on the panel back along each wire and the retainers glued to the panel.

Balsa Plank Laminate (Reinforcement #18)

Materials

heat-activated adhesive (BEVA 371 in white spirit, 2:1 by volume)
coarse-woven cotton fabric (cheesecloth or hessian)
balsa planks, 1000mm long X100X12
wax-resin adhesive/mortar-
    adhesive- unrefined beeswax, dammar resin
    mortar- to molten adhesive, add sawdust sifted
    through 1mm-wide mesh (mostly coniferous wood from dried timber)
linen canvas- medium weight

Tools

hot-iron with thermostat control
hot-spatula with thermostat control
transformer
cold-iron
double-boiler and hot-plate
large ladle
several weights, or screw-press
staple gun
wide bristle-brushes
stretching loom
release film (MELINEX)

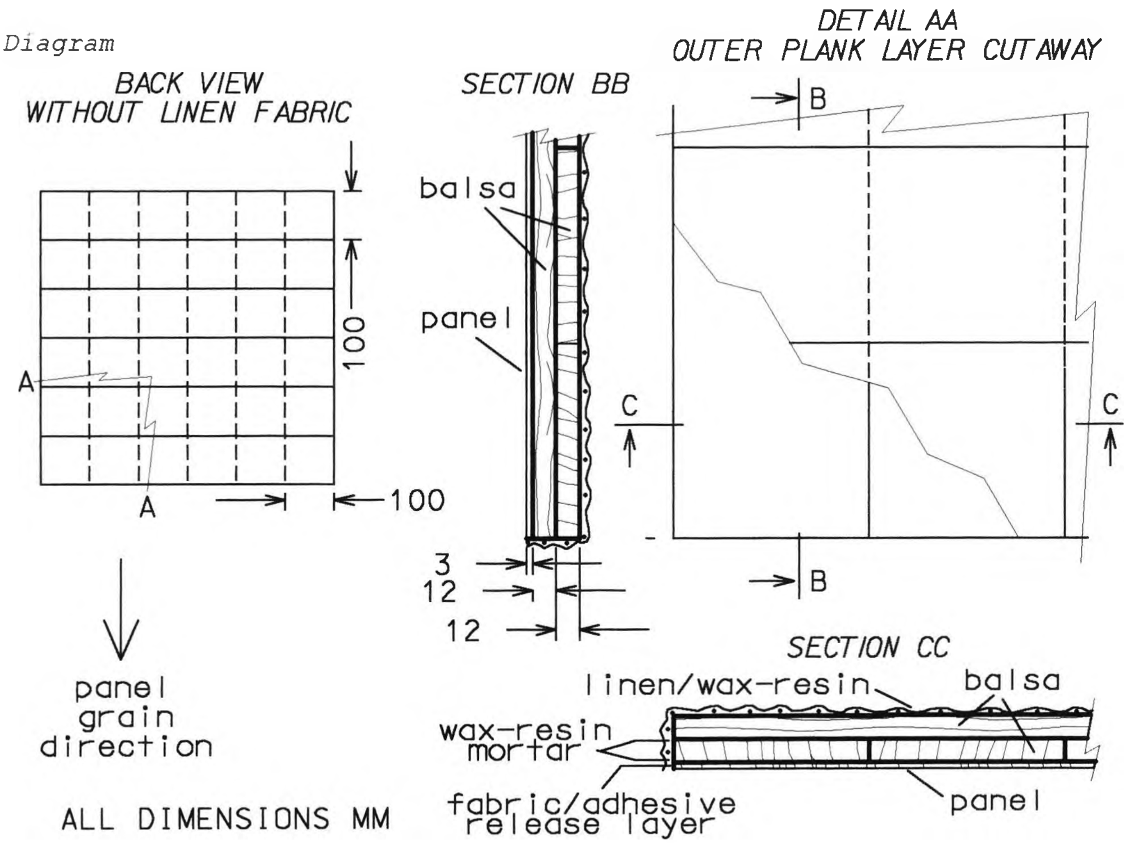
Construction

Noting the panel dimensions, a stretching loom was chosen that allowed a piece of coarse-woven fabric to be stretched so that an area about 50mm larger than the panel was accessible by brush on both sides. The fabric was stretched by hand with moderate tension, turning the edges round to the opposite loom-face and stapling them there. Heat-activated adhesive (BEVA371) was heated to solution in a double-boiler and several coats applied by brush to both sides of the fabric until the weave remained filled by adhesive when thoroughly dry, allowing each coat to dry past the touch-dry stage before applying another.

A working panel of blockboard or plywood, at least 100mm larger than the panel dimensions on all sides, was covered with release film on one side. The panel mock-up was placed face-down on top of the film. The prepared fabric was cut from the loom, stretched loosely over the panel back and the fabric edges stapled to the working panel. A hot-spatula was set to about 100c and the fabric was thoroughly adhered to the back of the painting.

Wax-resin was meanwhile prepared in a double-boiler. The beeswax was melted from smaller blocks and the dammar added (3:1 by weight) and stirred until thoroughly mixed. A volume was prepared that was well in excess of that necessary in the final layer structure. This was done to allow for run-out under pressure, to minimize gaps in the adhesive layers. Once mixed, sifted sawdust was stirred in to make a thicker

Diagram



mortar. It is not possible to state exact proportions, but when molten, the mortar flowed but was not "runny".

Using a hand mitre-saw, each balsa plank was prepared by making parallel cuts along the full length of one large face, at about 30mm intervals, and halfway through its thickness. Though not done as such here, the planks would normally first be cut to excess length, attached, and the intermittent cuts made before repeating the process with the second balsa layer, done to reduce restraint effects of the balsa in its grain direction. The planks were cut to length, allowing about 10-15mm excess at each end.

Prior to adhesion, all planks were heated on one side on a vacuum hot-table set to about 60C under a release film to extend the time available to set the planks in the molten mortar.

The panel was placed, face-down, on a flat working surface (a plywood panel, for example), and secured to it by stapling the edges of the fabric. Usually, the painting would have been faced for protection prior to application of the balsa. This was not done to the test panels.

Beginning at one edge, the mortar was applied with a ladle and spread to a thickness averaging 3-4mm in the general area of the first plank using a broad spatula. The first plank was immediately laid and pressed into the mortar as quickly as possible. Enough pressure was applied by hand, with a slight lateral movement, to squeeze out some of the mortar, level the plank, and expel air bubbles remaining in the adhesive layer. The plank was then moved to its final position to overlap the panel edges equally at each plank end and along the side edge. More mortar was applied to the next area and the next plank aligned within 2-3mm of the previous plank. No attempt was made to completely fill the gap between the planks. This would be done when the subsequent balsa layer or fabric was applied.

The first layer of planks was applied with grain parallel to the panel grain, the second with grain perpendicular. Once these had cooled to room temperature, a wax-resin-impregnated linen canvas was adhered to the back and edges of the entire laminate.

After cooling, the balsa planks were trimmed to the panel edges, first with a crosscut handsaw, then finished with a coarse sandpaper or rasp, with care taken to avoid contacting the panel edges. The back balsa laminate can be chamfered to prevent denting.

Normally, the first balsa layer would be allowed to cool in place overnight under a release layer and a flat panel with some weights on top, before applying the next layer. This was not done for the test panels because of time constraints. Instead, the second balsa layer was immediately applied, weighted, and the whole allowed to cool for three days before applying the linen fabric.

Prior to applying the fabric, the release layer would normally be turned around the back and tacked to the balsa with a hot iron. This would allow it to be utilised in future, if necessary. This was not done for the test panels, as the extruded, cooled mortar made it difficult to separate the release layer without tearing the fabric. This would have been avoided if the fabric had extended further at the edges to prevent the mortar from flowing around the release layer.

To apply the linen fabric, molten wax-resin was brushed onto the outer balsa surface and the panel edges. A piece of linen, cut to excess dimensions, was placed on the wax-resin with the threads aligned parallel to the panel edges and adhered to the balsa with a heated iron. Once fully impregnated, the fabric surface was immediately cooled with a cold-iron to achieve a maximum area of adhesion. The fabric was adhered to the balsa and panel edges and the corners folded neatly, then trimmed flush with the front edge of the panel using a scalpel and re-tacked where necessary.

Balsa Block Laminate (Reinforcement #19)

Materials

balsa planks (1000mm long X100X13)
wax-resin adhesive (proportions by weight)
  unbleached, refined beeswax, 3 parts
  dammar resin, 2 parts
  Multiwax 445, 1 part

Tools

clothes iron
hot-plate
aluminium-foil tray to heat wax-resin
masking tape- 25mm width

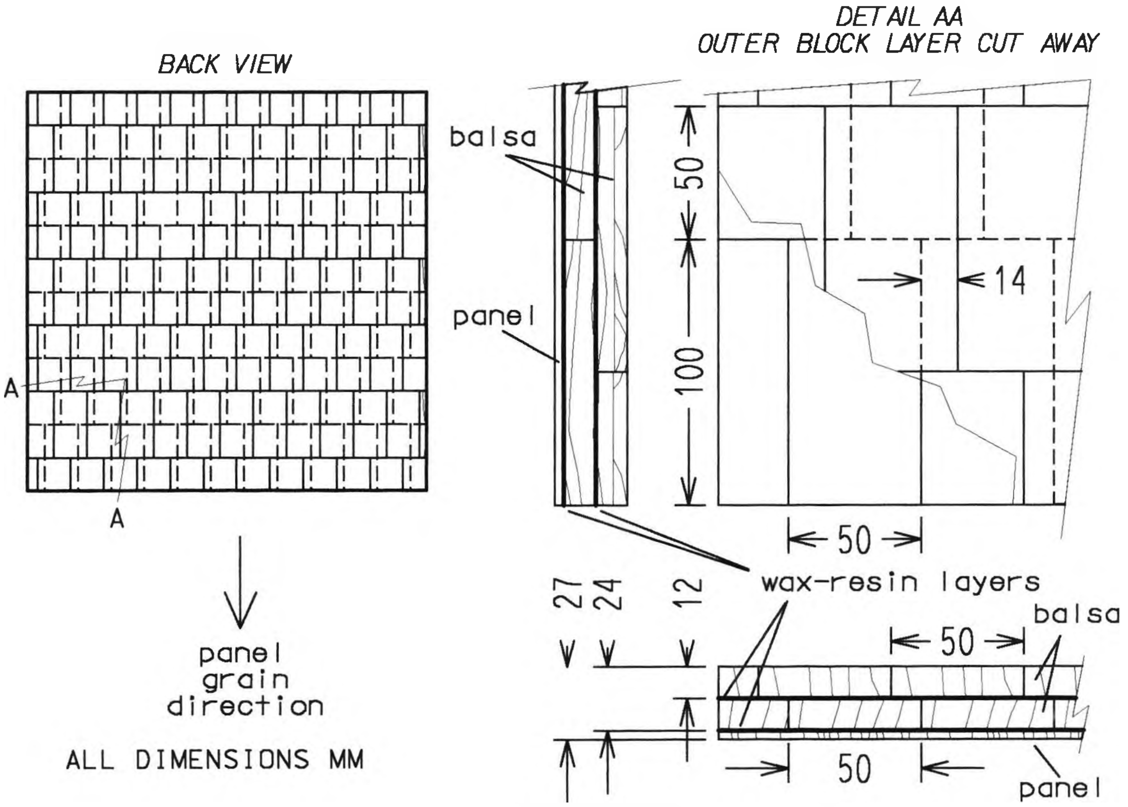
Construction

Balsa planks were rip-sawn to uniform widths of 50.mm from which rectangular blocks of 100.mm length were cut.

Wax-resin adhesive was made by melting the beeswax and MULTIWAX in a double-boiler then adding the dammar resin, stirring occasionally. The molten mixture was poured in shallow pans, scored, and when cool, broken into blocks.

Each panel was placed face-down on a flat surface protected by waxed kraft-paper. The panels were not faced, though this might be done for a real painting. Blocks of adhesive were melted in a foil pan on a hot-plate at about 90°C. A clothes-iron was heated to about 120C.

Diagram



A pattern of blocks was planned for two layers, with the blocks' grain laid parallel to the panel grain. All joints of the first layer lying parallel to the panel grain were bridged by the blocks of the second layer, staggering the blocks of a layer by half their length and width.

To adhere the balsa, a short tab of masking-tape was attached to one large side of a block. Held by the tab, the opposite surface was heated against the clothes-iron for about 5 seconds without causing the block to dry too much and warp toward the heated side. The block was then held in a horizontal plane, dipped in the molten adhesive to about 1-2mm depth, then immediately transferred in a steady motion to the panel back. The block was placed as close to its intended position as possible with a slight rolling pressure to eliminate air pockets beneath, then seated with a slight pressure and wiggling motion. There was about 5 seconds in which to position the block after it contacted the panel and before cooling caused the adhesive to solidify.

The first line of blocks was positioned with the end-grain edges aligned with one end-grain edge of the panel. Each block was positioned as closely as possible to the previous and pressed down slightly so that the top surfaces were more or less in-plane. Pressure was minimised to avoid causing "spring-back" and air gaps. Three or four adjacent lines of blocks were applied progress simultaneously. To maintain flat bonding surfaces, any expressed adhesive was scraped away before it could cool and become difficult to remove. No attempt was made to adhere adjacent block faces to each other. The molten adhesive rarely exuded from the top surface during positioning. If so, it was scraped flush with the surface.

One layer was applied per day. No attempt was made to finish the laminate "in one go". The blocks were applied at an RH of 57+/-3%. The temperature of the controlled-environment room rose to about 25C when elements were heated during which the humidity was held steady.

Medium-density Fibreboard (MDF) Laminate (Reinforcement #20)

Materials

medium-density fibreboard panel, 12mm thick
non-wet strength tissue
heat-activated adhesive (BEVA371, undiluted)
epoxy/microballoon mortar (Ciba Geigy Araldite XD759
mixed 4 parts to one by weight with Araldite GY1823,
then combined with phenolic resin microballoons)

Construction

MDF was conditioned for 2 weeks at the same RH as the panels. A tissue release layer was applied to the panel back (see Paper Tissue Strips, Reinforcement #7).

A thin layer of epoxy mortar was scraped across the MDF panel as a size. A thicker layer (about 0.5mm depth) was applied with a toothed scraper. The panel back was laid on, one edge first, then the other edge was slowly lowered to contact the mortar to avoid air gaps. To apply even weight overall until the mortar set, a 12mm-thick soft polyurethane foam was laid on, then an 18mm-thick plywood panel, then three iron-bar weights (30lb each) were uniformly distributed on top. The mortar was cured for 12h.

"Chassis Cadre" (Reinforcement #21)

Materials

wood planks (utile (*Entandophragma utile* (Dawe and Sprague) Sprague) or South American mahogany (*Swietenia* sp.))

wood glue (AEROLITE KL urea formaldehyde two-part powder/liquid resin)

brass right-angled section

brass wood screws, countersunk

Teflon (polytetrafluoroethylene) pressure-sensitive tape

Tools

(for wood portion, see Sliding Rigid Battens, Reinforcement #9)

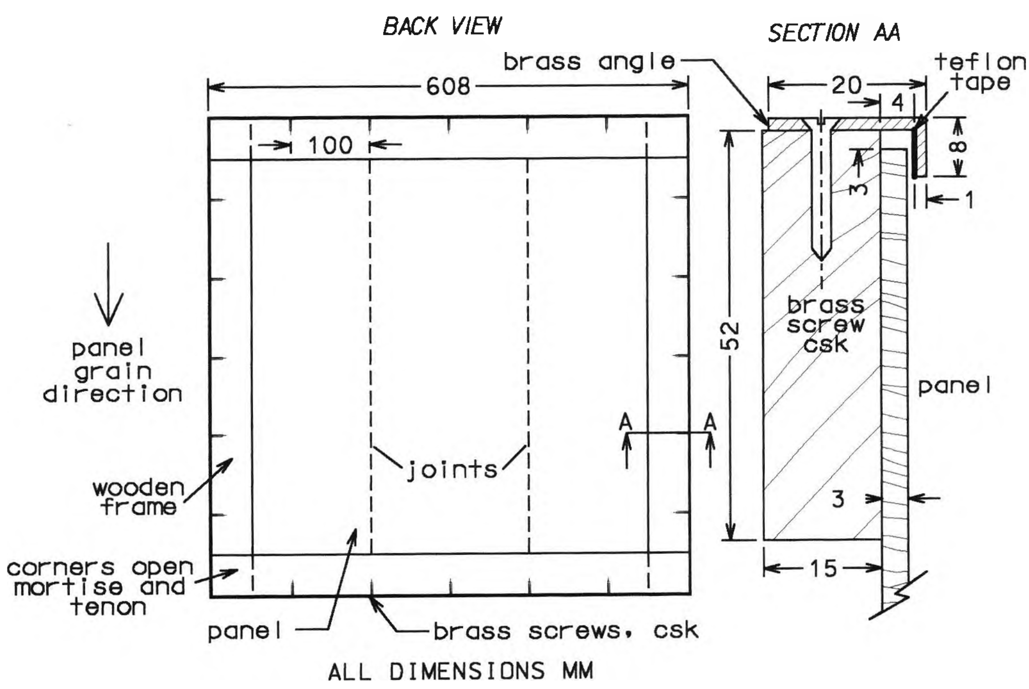
brazing solder

flux

butane or similar blow-torch

mitre-saw with blade for soft metal

Diagram



Construction

For each panel, wooden frame members were sawn to width and length, corners joined with open mortise-and-tenons, then glued and clamped windlass-style. Inner edges of members were bevelled for appearance, outer edges planed and sanded to dimensions, and the exposed surfaces waxed and rubbed to finish.

The brass angle was measured, marked and cut to length of two adjacent sides and mitred at each end. The middle joint was marked and mitres cut with bandsaw, leaving a joining layer intact. A jig was cut from a blockboard panel to the inner dimensions of the brass frame. One side of the brass angle was fixed to the jig with heat-resistant tape (called duct or gaffer tape). The middle joint was heated with a butane flame until slightly soft and slowly bent to a 90-degree angle, then soldered with high-brass content silver solder. This was repeated with the opposite brass angle. The mitred ends of each brass angle were aligned and fixed to the jig with tape and soldered. All corners were filed to finish. The side flanges were then drilled, countersunk and the wooden frame was drilled to receive the screws. Teflon-tape was applied to the side flange of the bottom rebate, and with the panel in place, the rebate was screwed to the wooden frame.

Oak Plank Laminate (Reinforcement #22)

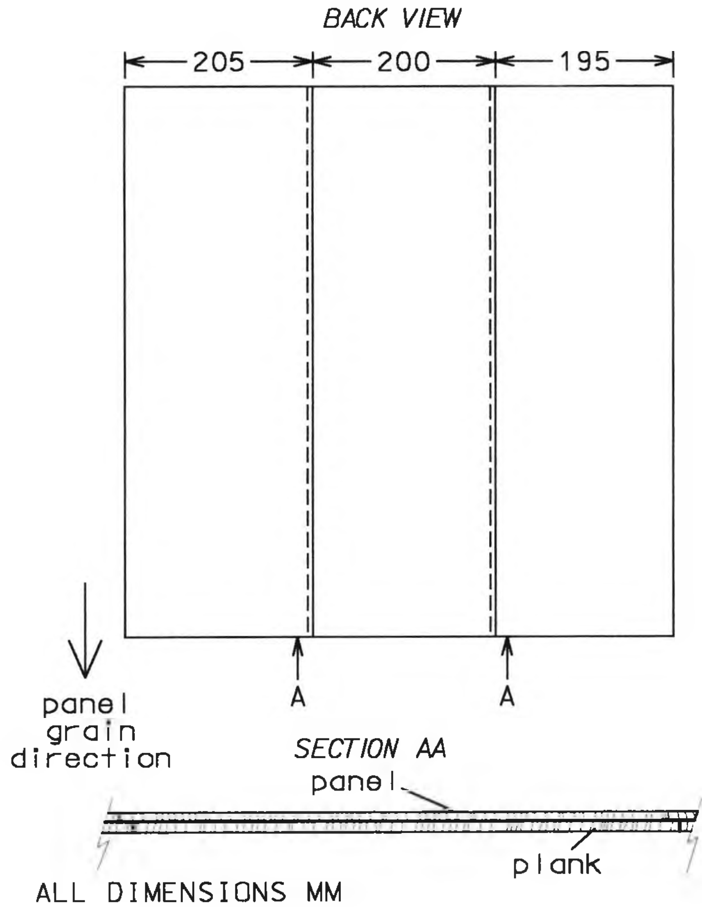
Materials

oak planks (4.00mm thick, radially sawn)
non-wet strength tissue
heat-activated adhesive- (BEVA371, undiluted)
epoxy/microballoon mortar (Ciba Geigy Araldite XD759
mixed 4 parts to one by weight with Araldite GY1823,
then combined with phenolic resin microballoons)

Construction

The panel was placed face-down and tissue, peviously impregnated with heat-activated adhesive and dried, was applied (as in Reinforcement #7). Epoxy mortar (about 0.5mm thick) was spread on the panel back with a toothed spatula. The laminate planks were to be positioned with their joints offset about 10mm to one side of the panel joints to prevent weakness. Each plank was laid on the mortar, one edge first, then slowly lowered to contact overall to avoid creating air gaps. Some mortar was expressed between each laminate plank to form a glued joint. The epoxy was left to cure for 12h with the panel weighted under a 12mm-thick soft polyurethane foam, an 18mm-thick plywood panel, then three iron-bar weights (30lb(14kg) each) uniformly distributed on top.

Diagram



Oak Parquet Laminate (Reinforcement #23)

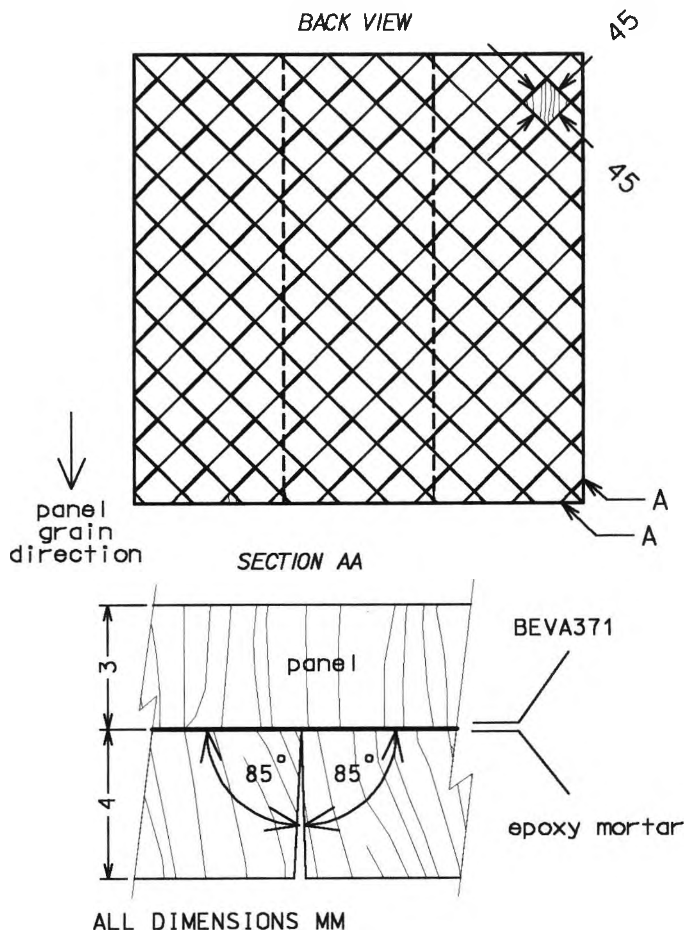
Materials

oak planks (4.00mm thick, radially sawn)

heat-activated adhesive (BEVA371)

epoxy/microballoon mortar (Ciba Geigy Araldite XD759
mixed 4 parts to one by weight with Araldite GY1823,
then combined with phenolic resin microballoons)

Diagram



Construction

The oak planks were sawn diagonally to form parquet-like squares with one set of opposite corners lying parallel to the grain. The edges were sawn with an acute chamfer angled about 5 degrees from the vertical.

The panel was placed face-down and a film of heat-activated adhesive was applied as an isolation/release layer to the back surface only. Epoxy mortar (about 0.5mm thick) was spread on the panel back with a toothed spatula. The parquets were applied in diagonal lines, edge to edge and beginning at one corner. Gaps between the chamfers were not filled with mortar. The mortar was left to cure for 12h.

Appendix 7: Paper entitled "Moiré Fringe Analysis of Cradled Panel Paintings"

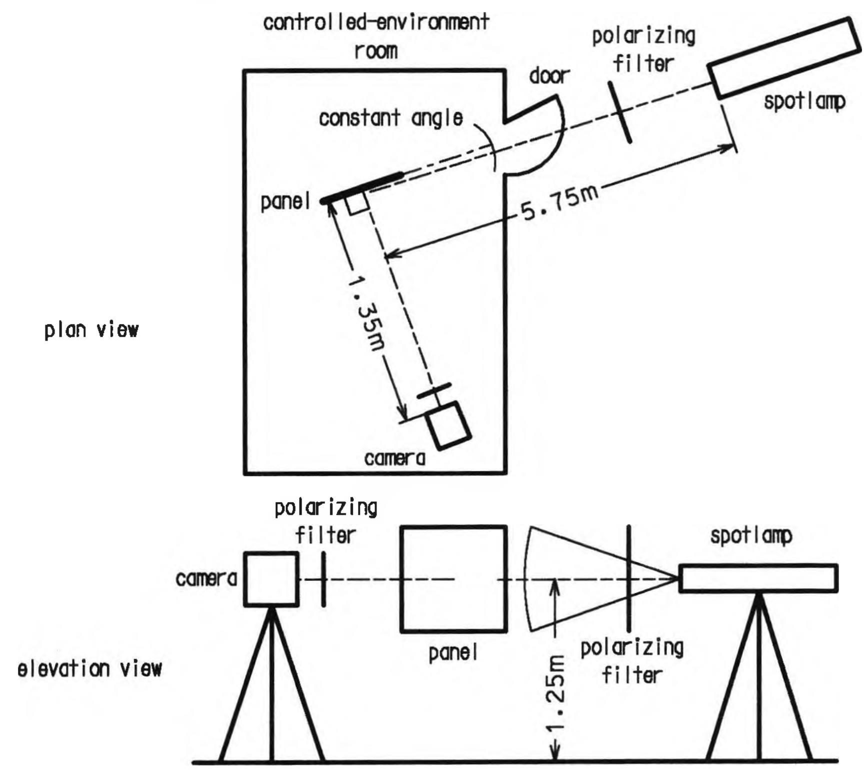
(see pocket at end)

Appendix 8- Raking-light Photographs

Three times during humidity cycling, surface contours of the panels were recorded qualitatively in low-angle raking light. Photographs were taken before, during, and after cycling, those during cycling taken in the middle of a period of high RH. Raking light was projected horizontally from a theater spot lamp [1000 watt Solo CSI Followspot] through a plane-polarizing filter. The angle of incidence to the panel surface was adjusted to a constant minimum angle. Photographs were taken with a Hasselblad 80mm lens onto Kodak XP2 (2X2 inch) black and white film using a Cokin plane-polarizing filter to minimise light scatter from the panel surface. Negatives were printed 1 to 1 onto Ilford photographic paper. A diagram of the set-up is shown below.

The photographs in this Appendix show the panels with grain vertical and with the raking-light source at the left. Labels identify each test panel with a photograph number (top), then (bottom) by reinforcement, then panel wood type, then the sample code from Appendix 4.

Diagram



Before Cycling of Relative Humidity

1

wood only
panel wood:oak
sample code:101

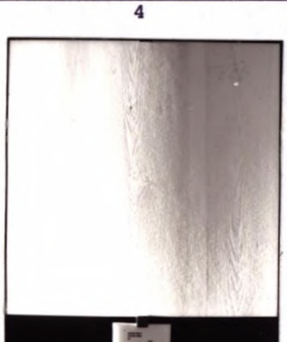
2

wood only
panel wood:poplar
sample code:1P22

3

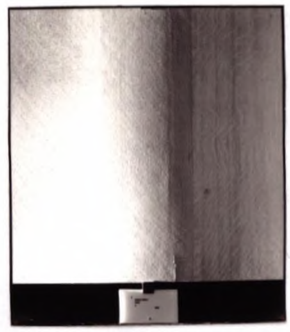
wood only
panel wood:linden
sample code:1L22

4



wood only
panel wood:Scots pine
sample code:1S22

5



sized only
panel wood:oak
sample code:202

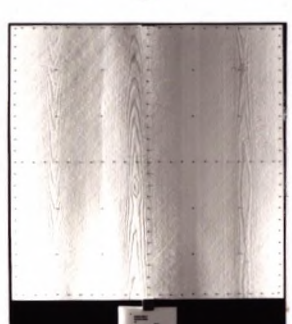
6

sized only
panel wood:poplar
sample code:2P1

7

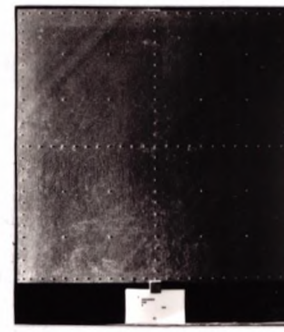
sized only
panel wood:linden
sample code:2L1

8



sized only
panel wood:Scots pine
sample code:2S14

9

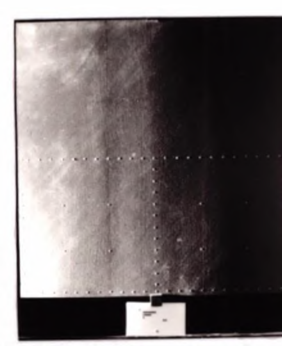


sized & grounded
panel wood:oak
sample code:308

10

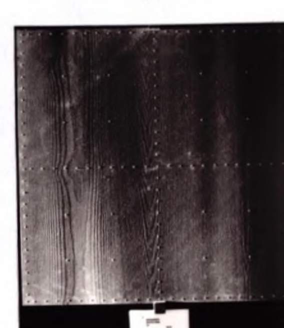
sized & grounded
panel wood:poplar
sample code:3P17

11



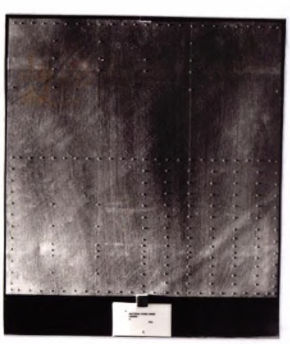
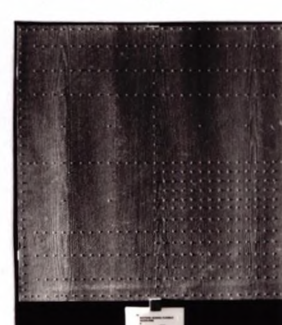
sized & grounded
panel wood:linden
sample code:3L9

12



sized & grounded
panel wood:Scots pine
sample code:3P22

Before Cycling of Relative Humidity

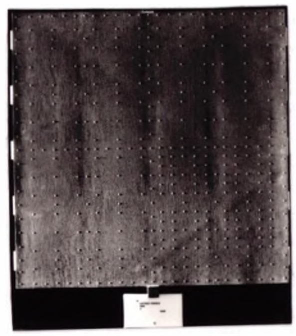
13  **battens:fixed & rigid** **panel wood:oak** **sample code:8O14**	17  **battens:sliding & rigid** **panel wood:oak** **sample code:9O4**	21  **battens:sliding & flexible** **panel wood:oak** **sample code:10O12**
14  **battens:fixed & rigid** **panel wood:poplar** **sample code:8P11**	18  **battens:sliding & rigid** **panel wood:poplar** **sample code:9P3**	22  **battens:sliding & flexible** **panel wood:poplar** **sample code:10P15**
15  **battens:fixed & rigid** **panel wood:linden** **sample code:8L6**	19  **battens:sliding & rigid** **panel wood:linden** **sample code:9L16**	23  **battens:sliding &** **flexiblepanel wood:linden** **sample code:10L18**
16  **battens:fixed & rigid** **panel wood:Scots pine** **sample code:8S15**	20  **battens:sliding & rigid** **panel wood:Scots pine** **sample code:9S5**	24  **battens:sliding & flexible** **panel wood:Scots pine** **sample code:10S6**

Before Cycling of Relative Humidity

25

lattice:fixed & rigid
panel wood:oak
sample code:11O18

29



lattice:cradle
panel wood:oak
sample code:12O9

33

lattice:sliding & flexible
panel wood:oak
sample code:13O6

26

lattice:fixed & rigid
panel wood:poplar
sample code:11P7

30

lattice:cradle
panel wood:poplar
sample code:12P12

34

lattice:sliding & flexible
panel wood:poplar
sample code:13P18

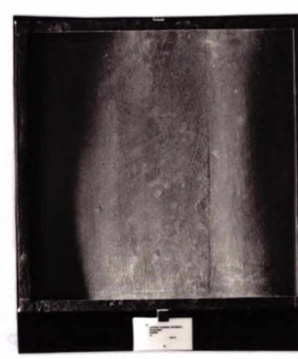
27

lattice:fixed & rigid
panel wood:linden
sample code:11L5

31

lattice:cradle
panel wood:linden
sample code:12L7

35



lattice:sliding & flexible
panel wood:linden
sample code:13L14

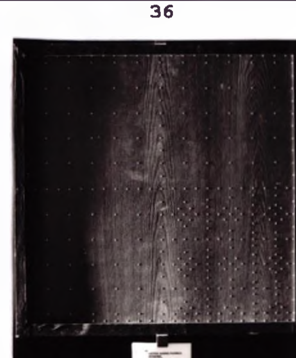
28

lattice:fixed & rigid
panel wood:Scots pine
sample code:11S21

32

lattice:cradle
panel wood:Scots pine
sample code:12S13

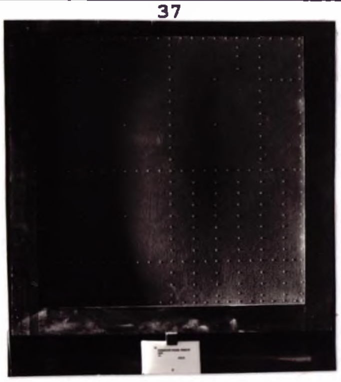
36



lattice:sliding & flexible
panel wood:Scots pine
sample code:13S9

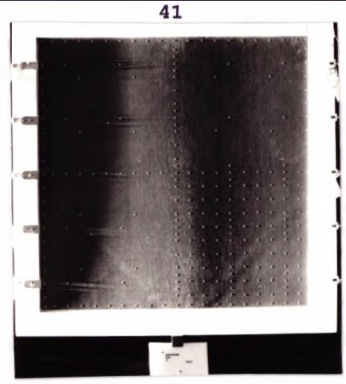
Before Cycling of Relative Humidity

37



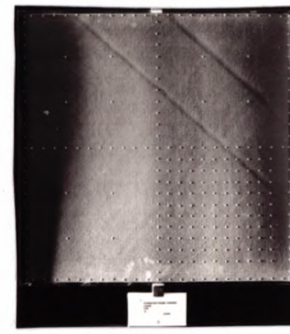
rebated frame
panel wood:oak
sample code:16019

41



cable suspension
panel wood:oak
sample code:17017

45

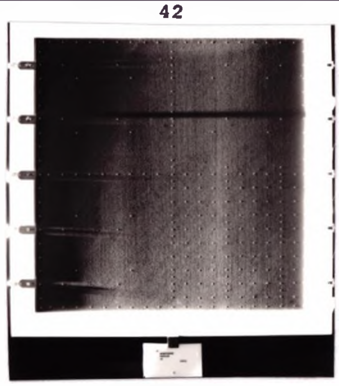


"chassis cadre"
panel wood:oak
sample code:21010

38

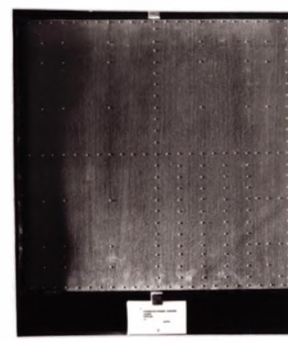
rebated frame
panel wood:poplar
sample code:16P6

42



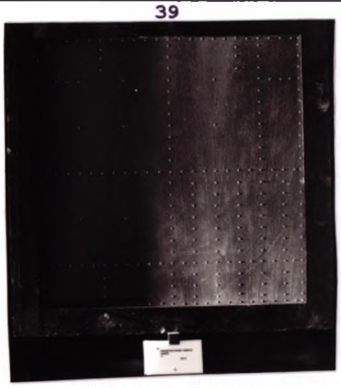
rebated frame
panel wood:poplar
sample code:17P10

46



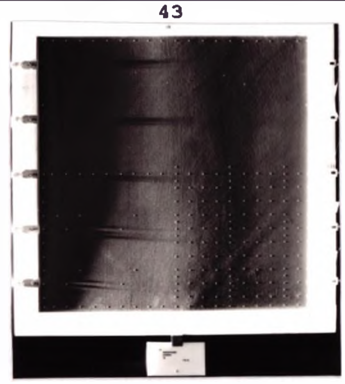
"chassis cadre"
panel wood:poplar
sample code:21P19

39



rebated frame
panel wood:linden
sample code:16L11

43

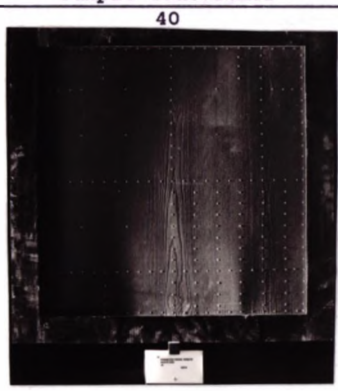


rebated frame
panel wood:linden
sample code:17L12

47

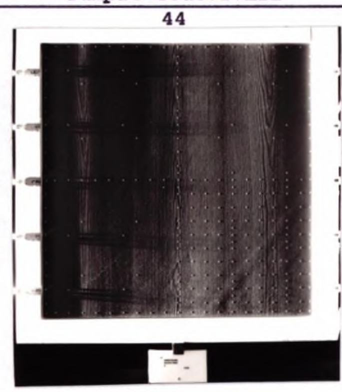
"chassis cadre"
panel wood:linden
sample code:21L2

40



rebated frame
panel wood:Scots pine
sample code:16S18

44

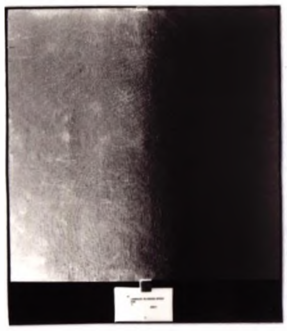
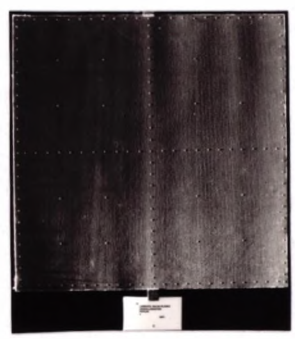
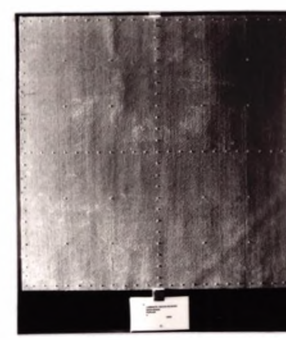
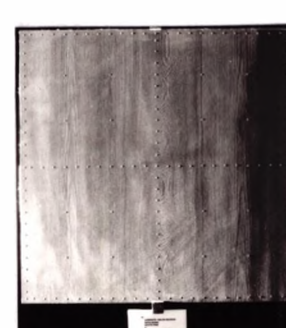


rebated frame
panel wood:Scots pine
sample code:17S2

48

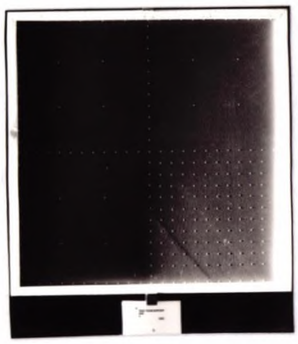
"chassis cadre"
panel wood:Scots pine
sample code:21S12

Before Cycling of Relative Humidity

49	53	57
		
laminate:MDF panel wood:oak sample code:20O11	laminate:balsa planks panel wood:oak sample code:18O15	laminate:balsa blocks panel wood:oak sample code:19O16
50	54	58
		
laminate:MDF panel wood:poplar sample code:20P14	laminate:balsa planks panel wood:poplar sample code:18P4	laminate:balsa blocks panel wood:poplar sample code:19P9
51	55	59
		
laminate:MDF panel wood:linden sample code:20L17	laminate:balsa planks panel wood:linden sample code:18L19	laminate:balsa blocks panel wood:linden sample code:19L3
52	56	60
		
laminate:MDF panel wood:Scots pine sample code:20S16	laminate:balsa planks panel wood:Scots pine sample code:18S10	laminate:balsa blocks panel wood:Scots pine sample code:19S3

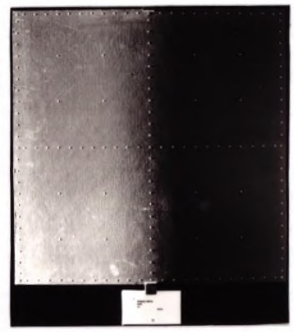
Before Cycling of Relative Humidity

61



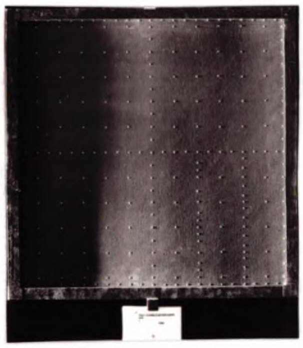
tray:foam-cushion
panel wood:oak
sample code:1503

65



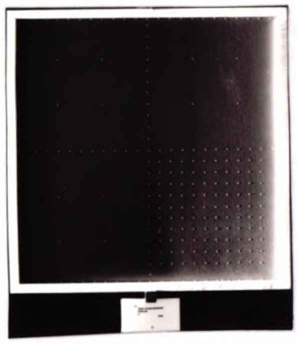
laminate:tissue/BEVA
panel wood:oak
sample code:7013

69



tray:sliding & flexible
panel wood:oak
sample code:1405

62



tray:foam-cushion
panel wood:poplar
sample code:15P5

66

laminate:OXhoneycomb/PVA
panel wood:poplar
sample code:4P2

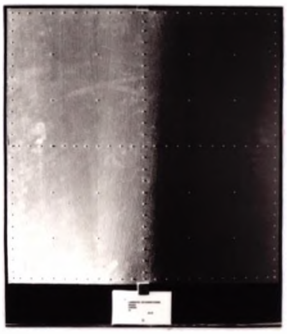
70

sized&grounded:10mm thick
panel wood:poplar
sample code:3P22

63

tray:foam-cushion
panel wood:linden
sample code:15L4

67

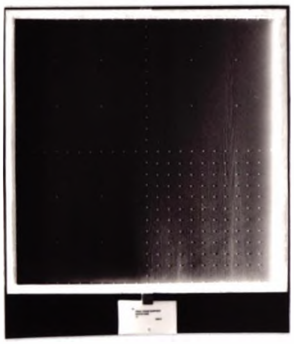


laminate:OXhoneycomb/epoxy
panel wood:linden
sample code:5L13

71

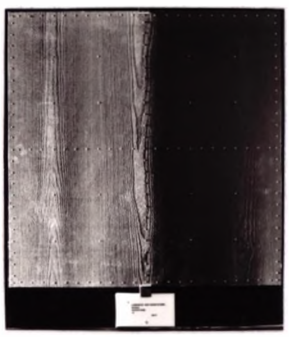
sized&grounded:20mm thick
panel wood:poplar
sample code:3P23

64



tray:foam-cushion
panel wood:Scots pine
sample code:15S11

68



laminate:HEXhoneycomb/epoxy
panel wood:Scots pine
sample code:6S17

Before Cycling of Relative Humidity

72

(panel to be built)

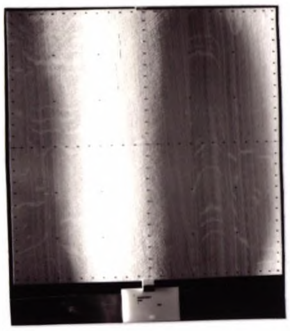
laminate:oak planks
panel wood:oak
sample code:2207

73

(panel to be built)

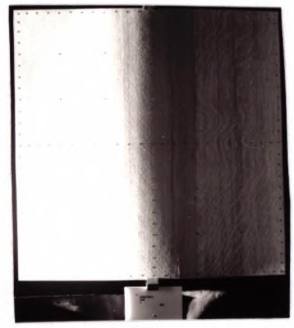
laminate:oak parquets
panel wood:oak
sample code:23021

74



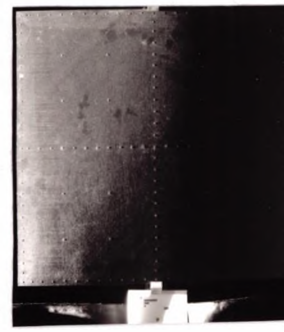
wood only
panel wood:oak
sample code:101

78



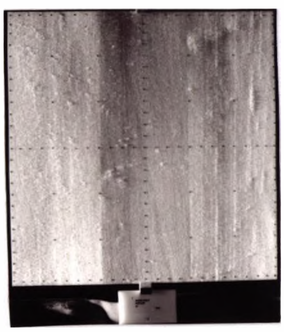
sized only
panel wood:oak
sample code:202

82



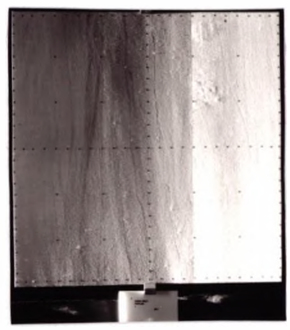
sized & grounded
panel wood:oak
sample code:308

75



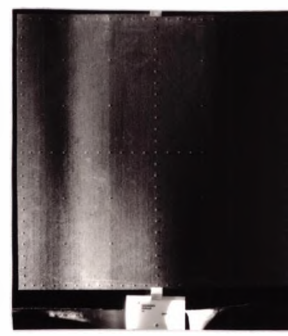
wood only
panel wood:poplar
sample code:1P22

79



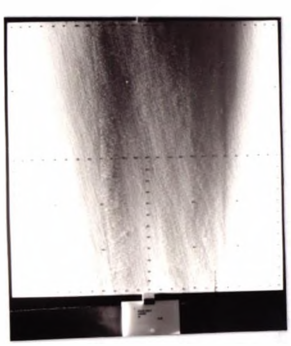
sized only
panel wood:poplar
sample code:2P1

83



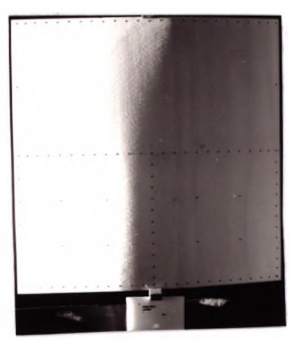
sized & grounded
panel wood:poplar
sample code:3P17

76



wood only
panel wood:linden
sample code:1L22

80

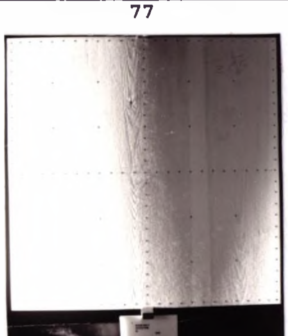


sized only
panel wood:linden
sample code:2L1

84

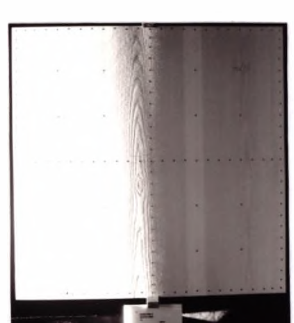
sized & grounded
panel wood:linden
sample code:3L9

77



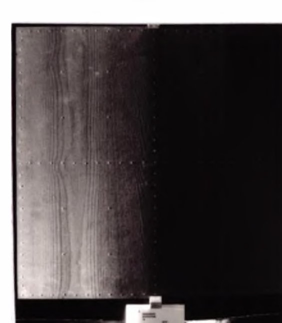
wood only
panel wood:Scots pine
sample code:1S22

81



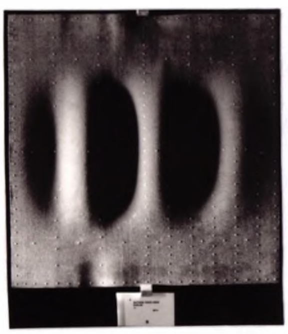
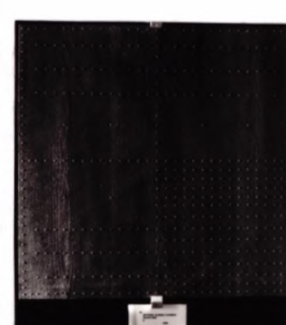
sized only
panel wood:Scots pine
sample code:2S14

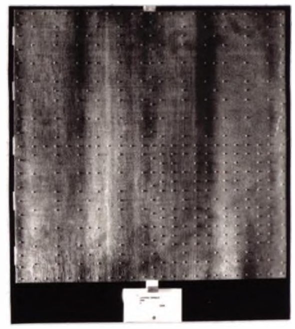
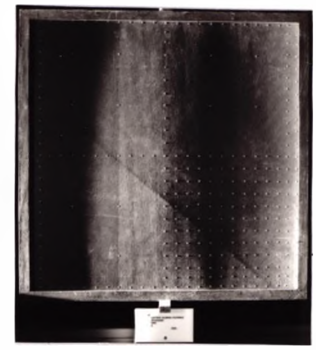
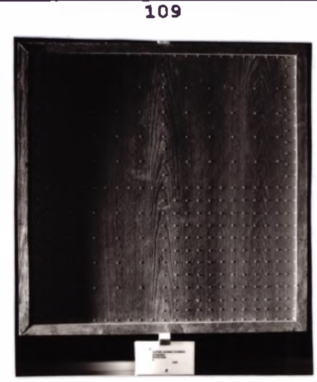
85

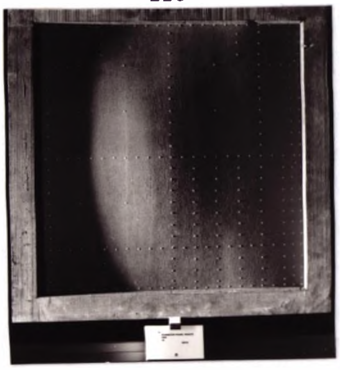
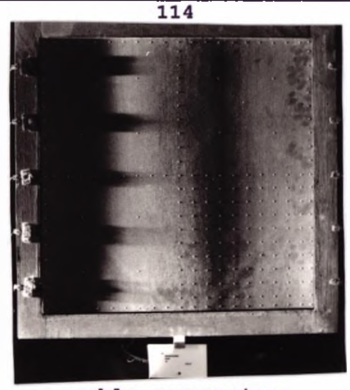
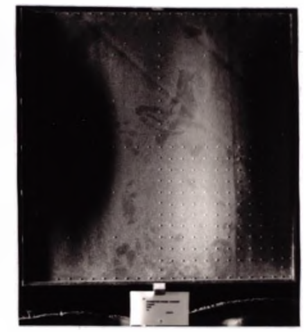
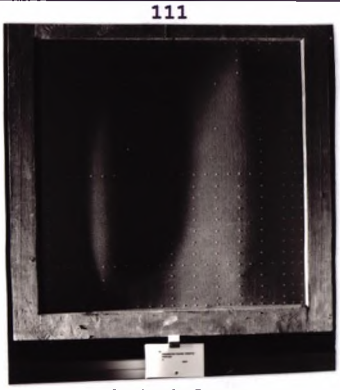
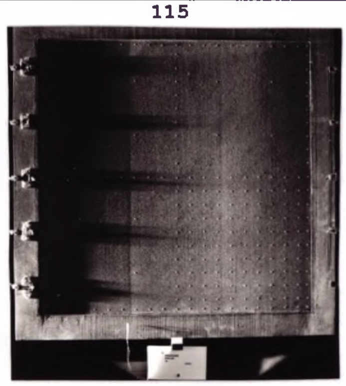
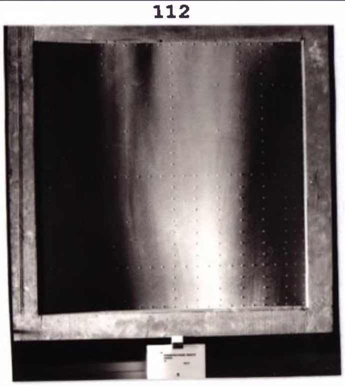
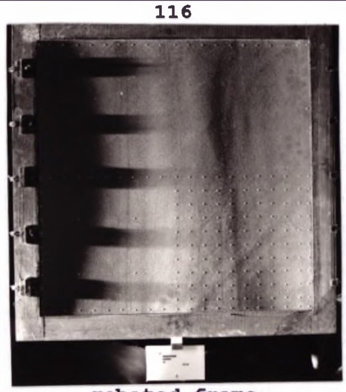
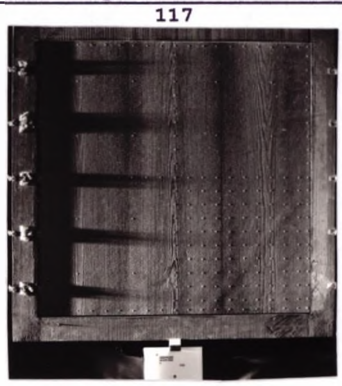


sized & grounded
panel wood:Scots pine
sample code:3P22

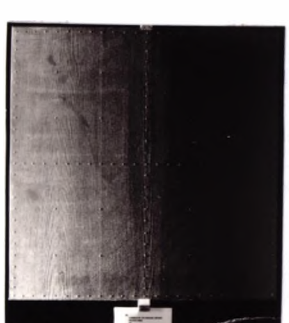
During Period of High Relative Humidity

86  battens:fixed & rigid panel wood:oak sample code:8O14	90  battens:sliding & rigid panel wood:oak sample code:9O4	94  battens:sliding & flexible panel wood:oak sample code:10O12
87  battens:fixed & rigid panel wood:poplar sample code:8P11	91  battens:sliding & rigid panel wood:poplar sample code:9P3	95  battens:sliding & flexible panel wood:poplar sample code:10P15
88  battens:fixed & rigid panel wood:linden sample code:8L6	92  battens:sliding & rigid panel wood:linden sample code:9L16	96  battens:sliding & flexiblepanel wood:linden sample code:10L18
89  battens:fixed & rigid panel wood:Scots pine sample code:8S15	93  battens:sliding & rigid panel wood:Scots pine sample code:9S5	97  battens:sliding & flexible panel wood:Scots pine sample code:10S6

98  lattice:fixed & rigid panel wood:oak sample code:11018	102  lattice:cradle panel wood:oak sample code:1209	106  lattice:sliding & flexible panel wood:oak sample code:1306
99  lattice:fixed & rigid panel wood:poplar sample code:11P7	103  lattice:cradle panel wood:poplar sample code:12P12	107  lattice:sliding & flexible panel wood:poplar sample code:13P18
100  lattice:fixed & rigid panel wood:linden sample code:11L5	104  lattice:cradle panel wood:linden sample code:12L7	108  lattice:sliding & flexible panel wood:linden sample code:13L14
101  lattice:fixed & rigid panel wood:Scots pine sample code:11S21	105  lattice:cradle panel wood:Scots pine sample code:12S13	109  lattice:sliding & flexible panel wood:Scots pine sample code:13S9

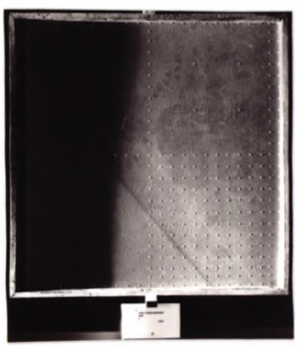
110  rebated frame panel wood:oak sample code:16O19	114  cable suspension panel wood:oak sample code:17O17	118  "chassis cadre" panel wood:oak sample code:21O10
111  rebated frame panel wood:poplar sample code:16P6	115  rebated frame panel wood:poplar sample code:17P10	119  "chassis cadre" panel wood:poplar sample code:21P19
112  rebated frame panel wood:linden sample code:16L11	116  rebated frame panel wood:linden sample code:17L12	120  "chassis cadre" panel wood:linden sample code:21L2
113  rebated frame panel wood:Scots pine sample code:16S18	117  rebated frame panel wood:Scots pine sample code:17S2	121  "chassis cadre" panel wood:Scots pine sample code:21S12

During Period of High Relative Humidity

122  laminate:MDF panel wood:oak sample code:20011	126  laminate:balsa planks panel wood:oak sample code:18015	130  laminate:balsa blocks panel wood:oak sample code:19016
123  laminate:MDF panel wood:poplar sample code:20P14	127  laminate:balsa planks panel wood:poplar sample code:18P4	131  laminate:balsa blocks panel wood:poplar sample code:19P9
124  laminate:MDF panel wood:linden sample code:20L17	128  laminate:balsa planks panel wood:linden sample code:18L19	132  laminate:balsa blocks panel wood:linden sample code:19L3
125  laminate:MDF panel wood:Scots pine sample code:20S16	129  laminate:balsa planks panel wood:Scots pine sample code:18S10	133  laminate:balsa blocks panel wood:Scots pine sample code:19S3

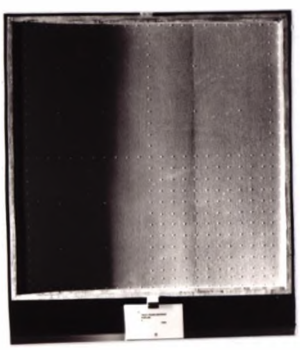
During Period of High Relative Humidity

134



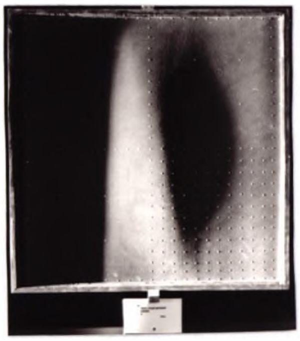
tray:foam-cushion
panel wood:oak
sample code:1503

135



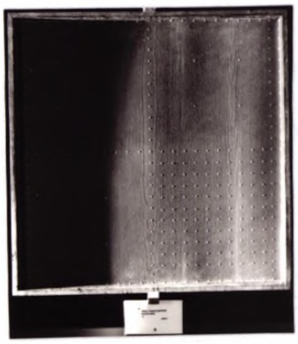
tray:foam-cushion
panel wood:poplar
sample code:15P5

136



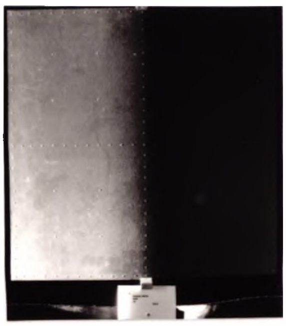
tray:foam-cushion
panel wood:linden
sample code:15L4

137



tray:foam-cushion
panel wood:Scots pine
sample code:15S11

138



laminate:tissue/BEVA
panel wood:oak
sample code:7013

139

laminate:OXhoneycomb/PVA
panel wood:poplar
sample code:4P2

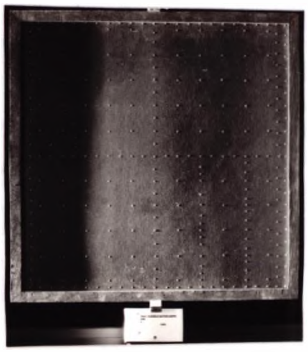
140

laminate:OXhoneycomb/epoxy
panel wood:linden
sample code:5L13

141

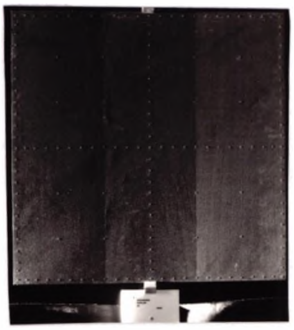
laminate:HEXhoneycomb/epoxy
panel wood:Scots pine
sample code:6S17

142



tray:sliding & flexible
panel wood:oak
sample code:1405

143



sized&grounded:10mm thick
panel wood:poplar
sample code:3P22

144

sized&grounded:20mm thick
panel wood:poplar
sample code:3P23

145

laminate:oak planks
panel wood:oak
sample code:2207

146

laminate:oak parquets
panel wood:oak
sample code:23021

After Cycling of Relative Humidity

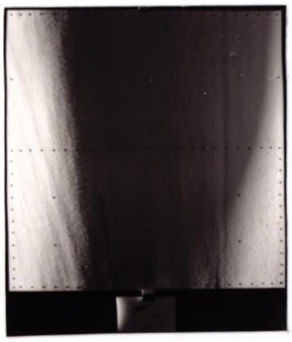
147

wood only
panel wood:oak
sample code:101

148

wood only
panel wood:poplar
sample code:1P22

149



wood only
panel wood:linden
sample code:1L22

150

wood only
panel wood:Scots pine
sample code:1S22

151

sized only
panel wood:oak
sample code:202

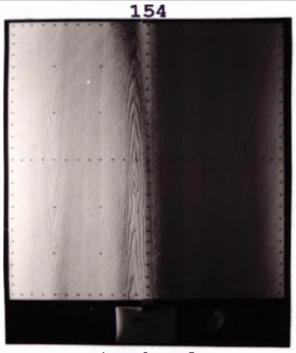
152

sized only
panel wood:poplar
sample code:2P1

153

sized only
panel wood:linden
sample code:2L1

154



sized only
panel wood:Scots pine
sample code:2S14

155

sized & grounded
panel wood:oak
sample code:308

156

sized & grounded
panel wood:poplar
sample code:3P17

157

sized & grounded
panel wood:linden
sample code:3L9

158

sized & grounded
panel wood:Scots pine
sample code:3P22

159

battens:fixed & rigid
panel wood:oak
sample code:8014

163

battens:sliding & rigid
panel wood:oak
sample code:904

167

battens:sliding & flexible
panel wood:oak
sample code:10012

160

battens:fixed & rigid
panel wood:poplar
sample code:8P11

164

battens:sliding & rigid
panel wood:poplar
sample code:9P3

168

battens:sliding & flexible
panel wood:poplar
sample code:10P15

161

battens:fixed & rigid
panel wood:linden
sample code:8L6

165

battens:sliding & rigid
panel wood:linden
sample code:9L16

169

battens:sliding &
flexiblepanel wood:linden
sample code:10L18

162

battens:fixed & rigid
panel wood:Scots pine
sample code:8S15

166

battens:sliding & rigid
panel wood:Scots pine
sample code:9S5

170

battens:sliding & flexible
panel wood:Scots pine
sample code:10S6

171

lattice:fixed & rigid
panel wood:oak
sample code:11O18

175

lattice:cradle
panel wood:oak
sample code:12O9

179

lattice:sliding & flexible
panel wood:oak
sample code:13O6

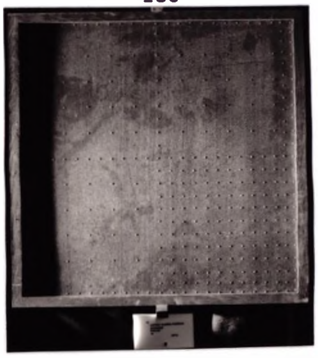
172

lattice:fixed & rigid
panel wood:poplar
sample code:11P7

176

lattice:cradle
panel wood:poplar
sample code:12P12

180



lattice:sliding & flexible
panel wood:poplar
sample code:13P18

173

lattice:fixed & rigid
panel wood:linden
sample code:11L5

177

lattice:cradle
panel wood:linden
sample code:12L7

181

lattice:sliding & flexible
panel wood:linden
sample code:13L14

174

lattice:fixed & rigid
panel wood:Scots pine
sample code:11S21

178

lattice:cradle
panel wood:Scots pine
sample code:12S13

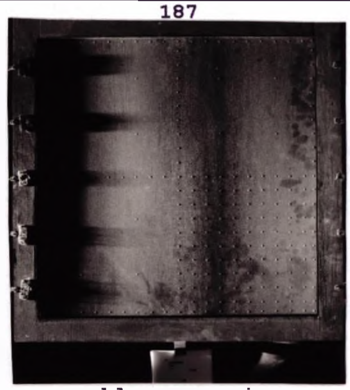
182

lattice:sliding & flexible
panel wood:Scots pine
sample code:13S9

183

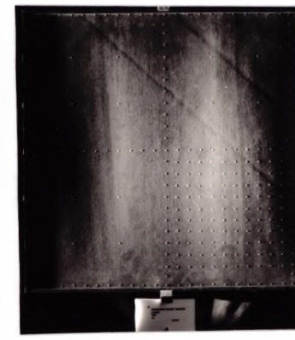
rebated frame
panel wood:oak
sample code:16O19

187



cable suspension
panel wood:oak
sample code:17O17

191

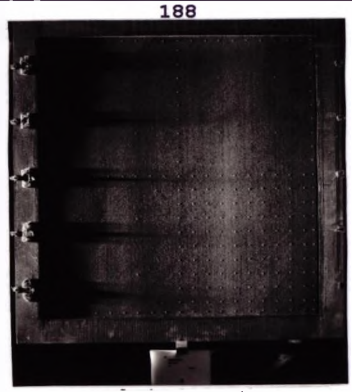


"chassis cadre"
panel wood:oak
sample code:21O10

184

rebated frame
panel wood:poplar
sample code:16P6

188



cable suspension
panel wood:poplar
sample code:17P10

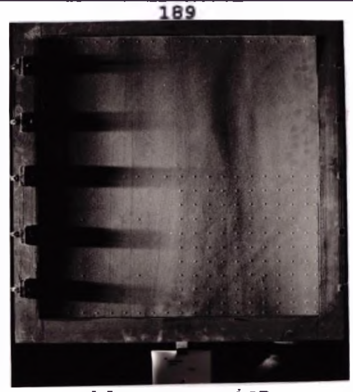
192

"chassis cadre"
panel wood:poplar
sample code:21P19

185

rebated frame
panel wood:linden
sample code:16L11

189



cable suspension
panel wood:linden
sample code:17L12

193

"chassis cadre"
panel wood:linden
sample code:21L2

186

rebated frame
panel wood:Scots pine
sample code:16S18

190

cable suspension
panel wood:Scots pine
sample code:17S2

194

"chassis cadre"
panel wood:Scots pine
sample code:21S12

After Cycling of Relative Humidity

195  laminate:MDF panel wood:oak sample code:20O11	199  laminate:balsa planks panel wood:oak sample code:18O15	203  laminate:balsa blocks panel wood:oak sample code:19O16
196  laminate:MDF panel wood:poplar sample code:20P14	200  laminate:balsa planks panel wood:poplar sample code:18P4	204  laminate:balsa blocks panel wood:poplar sample code:19P9
197  laminate:MDF panel wood:linden sample code:20L17	201  laminate:balsa planks panel wood:linden sample code:18L19	205  laminate:balsa blocks panel wood:linden sample code:19L3
198  laminate:MDF panel wood:Scots pine sample code:20S16	202  laminate:balsa planks panel wood:Scots pine sample code:18S10	206  laminate:balsa blocks panel wood:Scots pine sample code:19S3

After Cycling of Relative Humidity

207  tray:foam-cushion panel wood:oak sample code:1503	211  laminate:tissue/BEVA panel wood:oak sample code:7013	215  tray:sliding & flexible panel wood:oak sample code:1405
208  tray:foam-cushion panel wood:poplar sample code:15P5	212  laminate:OXhoneycomb/PVA panel wood:poplar sample code:4P2	216  sized&grounded:10mm thick panel wood:poplar sample code:3P22
209  tray:foam-cushion panel wood:linden sample code:15L4	213  laminate:OXhoneycomb/epoxy panel wood:linden sample code:5L13	217  sized&grounded:20mm thick panel wood:poplar sample code:3P23
210  tray:foam-cushion panel wood:Scots pine sample code:15S11	214  laminate:HEXhoneycomb/epoxy panel wood:Scots pine sample code:6S17	

218

laminate:oak planks
panel wood:oak
sample code:2207

219

laminate:oak parquets
panel wood:oak
sample code:23021

Appendix 9- Materials and Suppliers

Temperature, humidity sensors, Squirrel type data logger: Grant Instruments (Cambridge) Ltd., Barrington, Cambridge CB2 5QZ, England.

Humidistats: Colebrooke Consulting Ltd., Diamonds, Bells Yew Green, East Sussex TN3 9AX, England; Exeter Environmental Systems, Dudshall Cottages, Church Lane, Cheriton Bishop, Devon EX6 6NY, England.

Calibration salts, Novasina Sensorcheck SC-33 and SC-75: Humitec Ltd., Horsham, Sussex RH13 6DE, England.

Oil heater, 1kW model P.100: Dimplex (UK) Ltd., Millbrook, Southampton SO9 2DP, England.

Humidifier, Century 3 Type: Andrew Sykes, Premier House, Darlington Street, Wolverhampton WV1 4JJ, England.

Dehumidifier, Model M50: Munters Ltd., Blackstone Road, Huntingdon PE18 6EF, England.

Oak and lime wood: North Heigham Sawmills, Paddock Street, Norwich NR2 4TW, England.

Pine wood: Fitchett and Woollacott Ltd., Willow Road, Lenton Lane, Nottingham NG7 2PR, England.

Poplar wood: N.P. Timber Ltd., Kettering, Northamptonshire, England.

Urea formaldehyde wood glue, Aerolite KL resin: Dynochem UK Ltd., Duxford, Cambridge CB2 4QB, England.

Panel sanding: Camweavers Ltd., 84 Duxford Road, Whittlesford, Cambridge CB2 4NH, England.

Glue size, animal hide glue, 300 bloom-gram jelly strength: Lymfabriek Trobas B.V., Steenstraat 9, Dongen- Postbus /4, S100AA Dongen, Netherlands.

Spray gun, Chiron SG90E PN2 blower unit; : Chiron-Werke GmbH & Co. KG, Weimarstraße 66/11, D-7200 Tuttlingen, Germany.

Linseed oil paints, Foundation White 261 SL A Series 1, Ivory Black 117 SL Series: Winsor & Newton Ltd., Wealdstone, Harrow, Sussex HA3 5RH, England.

Non-wet strength tissue: Alliance Paper, Unit 2, Lion Court, The Highway, London E19 HT, England.

BEVA371 heat-activated adhesive: Preservation Equipment Ltd., Church Road, Shelfanger, Diss, Norfolk IP2 2DG, England.

AEROWEB and AEROLAM honeycomb-core and panels: Ciba Bonded Structures, Duxford, Cambridge CB2 4QA, England.

EVOSTIK Resin W poly-vinyl acetate dispersion wood glue and EVOSTIK neoprene rubber adhesive: Evode Ltd., Common Road, Stafford ST16 3EH, England.

MELINEX polyester film: Polyester Converters Ltd., Trade Services Division, 49-53 Glengall Road, Peckham, London SE15 6NP, England

ARALDITE epoxy resins and wood filler: Ciba Plastics, Duxford, Cambridge CB2 4QA, England.

Phenolic resin microballoons: Structural Polymer Systems Ltd., Cowes, Isle of Wight PO31 7EU, England.

PLASTAZOTE foam: BXL Plastics Ltd., Mitcham Road, Croydon, Surrey CR9 3AL, England.

FOMECOR sandwich panel: Atlantis Artist's Materials, Gulliver's Wharf, 105 Wapping Lane, London E1 9RW, England.

brass mending plates: J. Shiner and Sons Ltd., 8 Windmill Street, London W1P 1HF, England.

balsa wood: Solarbo Ltd., Commerce Way, Lancing, West Sussex BN15 8TE, England.

TEFLON pressure-sensitive tape: TEMP-R-TAPE, manufactured by CHR Industries, Incorporated, and distributed by Polypenco Limited, 83 Bridge Road East, Welwyn Garden City, Hertfordshire, AL7 1LA, England.

theatre spot lamp: Ancient Lights Ltd., The Old Maltings, Ditton Walk, Cambridge CB5 8PY, England.

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MOIRÉ FRINGE ANALYSIS OF CRADLED PANEL PAINTINGS

Al Brewer and Colin Forno

Summary—*Cradle-related effects, such as 'washboarding' and tented flaking, were investigated by computer-aided moiré fringe analysis of panel models subjected to cycled changes in relative humidity. In-plane and out-of-plane displacements were recorded and compared for cradled and unreinforced panel models. These results were related to the behaviour of actual cradled panel paintings. Results indicate that restraint of warping increases in-plane strain due to swelling, and the strain distribution is in close correspondence with cradle restraint. Compressive strain, recorded over the fixed battens, and out-of-plane distortions in the exposed panel areas are discussed in relation to deformations and damages in cradled panel paintings.*

Introduction

Generally, cradles have been applied to flatten and/or reinforce panel paintings, which have often been thinned to facilitate flattening and cradle attachment. The principle of cradling, or parquetage, dates back to at least 1770, when Rubens's *La Kermesse*, in the Louvre, was cradled by L. Hacquin [1, 2]. About 100 years later, W. Morrill indicated a reluctance to thin and cradle a painting in a note to the Keeper of the National Gallery in London [3]:

> '. . . The panel itself is very much out of shape or uneven on the surface. I mean, to alter which, it would require to be planed down and parquetted but I think we might do without parquetting this time unless you require the surface to be more level than it is at present.'

Morrill had considerable experience in treating panels, and his words reflect an awareness of the potential problems.

In recent years, a project has been conducted at the Hamilton Kerr Institute, University of Cambridge, to investigate the effects of overall reinforcements on the preservation of panel paintings. Measurement methods were sought to record panel movements in three dimensions, while not interfering with their response to controlled changes of relative humidity (RH). Using panel models, most reinforcement types including cradles were analyzed using digital photogrammetry; the results of this study will be published in due course. However, it was considered necessary to focus more closely on cradles, using a second analytical technique to try to isolate localized panel response to humidity changes over and between the battens; the results from this separate study are presented here.

Moiré techniques were chosen as appropriate for this study since they are non-contacting and offer an adequate displacement sensitivity. Using unreinforced and cradled panel models, specific objectives were to investigate the relationship between wood movement (as defined by Stevens [4]) and restraint effects, including rate and forms of deformation following a sudden change in RH, and more permanent deformations associated with compression set in the wood [5]. A better understanding of these effects should clarify some panel/reinforcement interactions and provide a more sound basis for the treatment of cradled panels in particular. Finally, results are related to the development of 'washboarding' (Figure 1) and related flaking (Figure 2) in real panel paintings.

Panel models

Panel construction

Two types of panel model were constructed. To allow comparisons between a cradled and an unreinforced state, they were made as similar as possible except that one was cradled (Figure 3). Each panel consisted of three oak planks of similar cut, sized and coated with lead white in linseed oil on one side. Though not intended to reproduce any particular historical example, they shared some general material and structural characteristics of northern European panel paintings of the late seventeenth and early eighteenth centuries. Based on examples of similar cradled paintings, the panel dimensions were large enough across the grain, and sufficiently thin, to show movement-related interactions. A square format was chosen to allow some construction simplification.

Most cradled paintings were originally thicker panels. Over several years, panel paintings develop particular internal stress distributions. Thinning dis-

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