heritage

MDPI

Article

An Innovative Method Based on In Situ Deformometric Monitoring to Support Decisions for the Structural Restoration of a Historic Panel Painting

Paola Mazzanti [1], Bertrand Marcon [1,2], Linda Cocchi [1], Giacomo Goli [1], Lorenzo Riparbelli [1,*] and Luca Uzielli [1]

[1] DAGRI, University of Florence, 50145 Florence, Italy; paola.mazzanti@unifi.it (P.M.)
[2] LABOMAP, Laboratoire Bourguignon des Matériaux et Procédés, 50501 Cluny, France
* Correspondence: lorenzo.riparbelli@unifi.it

Abstract: This paper describes an innovative method developed by the authors to support basic decisions concerning the structural restoration of a large historical panel painting which had been damaged by inappropriate attachment to a wall and ongoing exposure to severe changes in environmental humidity. The *Lapidazione di Santo Stefano* is a large panel (2.78 × 3.92 m^2) painted by Giorgio Vasari in 1571 and has been housed since then in the Church of Santo Stefano dei Cavalieri in Pisa (Italy). Its wooden support is made of large horizontal planks glued together along their edges and stiffened by vertical, dovetailed crossbeams. The panel was tightly fastened to a church wall with several rigid bolts; due to the moisture cycling produced by rainwater leakage and a subsequent "compression set", it had developed severe tension stresses perpendicular to the grain, resulting in cracks affecting both the wood and the paint layers. To decide how to carry out the structural restoration of the panel, it was necessary to know whether slippage could occur between the panel and crossbeams during seasonal variations in environmental humidity. Without slippage, tensile stresses would be generated in the wood and could produce further cracks and damage the paint layers. An in situ monitoring method for assessing the possibility of slippage was developed and implemented. An analysis of data collected over a period of 6 months before the structural restoration confirmed that adequate slippage was possible; hence, the decision to fully repair the cracks was taken. Monitoring continued for a year after restoration and confirmed the previous findings. This paper describes the monitoring method, the equipment used, the results of its implementation and its value as a preventive conservation tool.

Keywords: panel paintings; dovetailed crossbeams; monitoring; wood shrinkage/swelling; structural restoration; preventive conservation

check for updates

Citation: Mazzanti, P.; Marcon, B.; Cocchi, L.; Goli, G.; Riparbelli, L.; Uzielli, L. An Innovative Method Based on In Situ Deformometric Monitoring to Support Decisions for the Structural Restoration of a Historic Panel Painting. *Heritage* **2024**, *7*, 4193–4205. https://doi.org/10.3390/heritage7080197

Academic Editors: Nikolaos Laskaris, Lamprini Malletzidou, Georgios S. Polymeris and Anastasia Rousaki

Received: 30 June 2024
Revised: 26 July 2024
Accepted: 6 August 2024
Published: 7 August 2024

1. Introduction

1.1. Panel Paintings

A panel painting is a complex structure composed of several paint layers (typically, a ground layer and one or more paint and varnish layers) applied to a wooden support (also called planking) made of one or more boards. Wood is an extremely variable, hygroscopic and anisotropic material. When it is subjected to severe moisture variations, dimensional variations, distortions, stresses and ruptures may occur both in the planking and in the paint layers [1–6]. To control such deformations of the planking, many kinds of crossbeams and back frames have been devised and used [7].

This brief recap highlights the complexity of such artworks and how their handcrafted nature contributes to their uniqueness. The extent of the variety and variability of the deformational behaviour of panel paintings and the complexity of their hygro-mechanical response to climatic variations are supported by the findings in [4]. These characteristics have also been investigated through experimental non-invasive methods developed to monitor the actual hygro-mechanical response of individual historical panel paintings in exhibition rooms [8,9] and restoration laboratories [10,11]. Numerous studies demonstrate the complexity and variability of the behaviour of individual artworks and constitute a still-developing body of scientific knowledge and analyses intended to support the decisions and work of conservators and restorers [5,10–12].

This paper presents an innovative method developed by the authors to provide guidance in planning the structural restoration of a large-scale historic panel painting. Its overly rigid constraints had resulted in severe transverse tensile cracking following major changes in moisture content.

1.2. The Panel Painting

The *Lapidazione di Santo Stefano* by Giorgio Vasari (1571) is a large panel painting, whose planking is made of ten boards of poplar (*Populus alba* L.) 3.5 to 4.0 cm thick, 278 cm wide and 392 cm high. The boards are horizontally oriented and are all as long as the width of the panel (278 cm). They range in width from 27 to 57 cm, except for the upper board, which is only 5 cm wide (Figure 1). Assuming, for poplar, an average density of 380 kg/m^3 and a total volume of the boards of 0.44 m^3, the weight of this planking may be estimated at around 170 kg.

(**a**) (**b**)

Figure 1. The *Lapidazione di Santo Stefano* by Giorgio Vasari (1571): (**a**) the painting after the restoration performed in 2012–2013; (**b**) the panel's back face with the monitoring instruments installed. (Photographs are courtesy of the Soprintendenza *BAPSAE di Pisa e Livorno* and the restorers Nadia Presenti and Mario Verdelli.).

The ten horizontal boards are glued together along their edges and stiffened by three vertical dovetailed crossbeams (Figure 1b). The crossbeams are made of silver fir (*Abies alba* Mill.). Their cross-sections at mid-length are approximately 70 $\times$ 110 mm^2; for all three crossbeams, both the entire section and the width of the dovetail are tapered by approximately 2 to 3 cm over the length of 392 cm, that is, by approximately 0.5 to 0.8%. The weight of each crossbeam is estimated at around 13 kg, assuming an average density of 440 kg/m^3 for silver fir.

In her extensive description of the painting and its history, Macripò [13] mentions several restorations of the pictorial layers but no structural restorations before that described in this paper.

1.3. The Dovetailed Crossbeams

The main functions of the crossbeams are (i) to effectively counteract the tendency of both the individual boards and the entire panel to warp because of moisture variations, and (ii) to provide a structural reinforcement during handling, which is particularly useful for larger panel paintings.

Until recently, the dimensioning of crossbeams was decided by carpenters and restorers based on their intuition and experience; only recently [11], using appropriate finite-element digital models (FEMs), scientific criteria and methods have been developed to dimension crossbeams based on the hygro-mechanical characteristics of individual panels.

For this panel painting, the connection between planking and crossbeams was made from the beginning by the so-called dovetailed system, which was widely used from the fifteenth century in central Italy [7]. This system ensures that each crossbeam is continuously connected to the planking along its entire width. The dovetailed face of the crossbeam (Figure 2) is inserted into a corresponding dovetail-shaped groove opened in the back face of the panel. Typically, the crossbeam is slightly tapered to facilitate its insertion into the groove and its tightening against the boards.

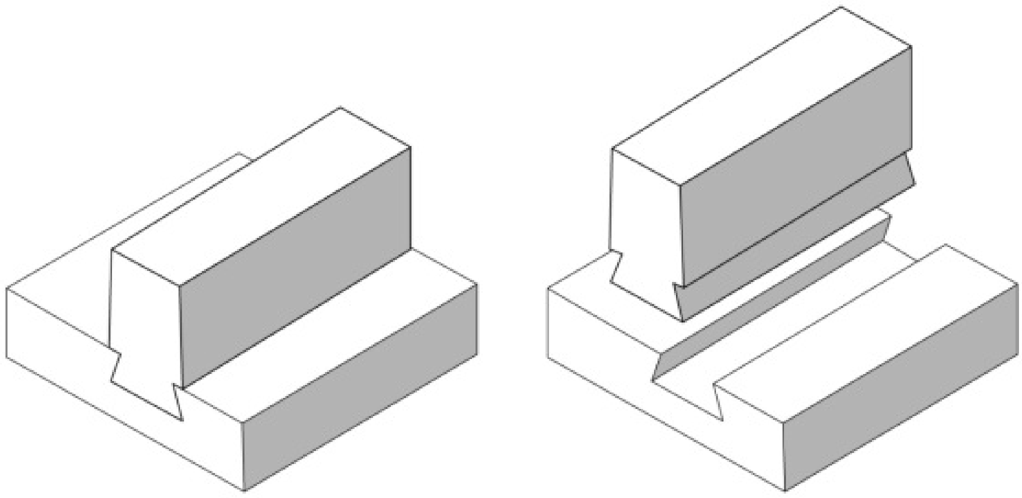

Figure 2. Assembled and exploded sketches of a dovetailed connection between panel and crossbeam.

In theory, this type of connection could allow the two elements it connects to slide between each other. However, in reality, such slippage can be partially or completely prevented by friction between the contacting surfaces.

A more in-depth mechanical analysis, not carried out in this paper, would confirm what intuition and experience show: that these friction forces opposing slippage can reach very high values depending on various factors, including the wood species involved, the smoothness and anatomical direction of the contacting surfaces and, above all, the magnitude of the contact forces pressing them against each other, which in turn depend on the geometry of the dovetail, the tapering of the crossbeam, and the individual boards' and whole panel's tendency to cup.

1.4. How the Damage Occurred

As a result of changes in environmental humidity, the planking swells/shrinks mainly in the transverse anatomical direction of the boards. In contrast, this direction is anatomically longitudinal for the crossbeams, and hence shrinkage/swelling is negligible. If the dovetailed connections allow for mutual slippage between planking and crossbeams, dimensional changes in the planking are permitted; otherwise, the impeded deformation can lead to stress states (tensile and/or compressive) in the planking that can cause damage and cracks in the planking and paint layers.

The panel is exhibited in the Church of Santo Stefano dei Cavalieri in Pisa (Italy). Until the end of 2011, it was in a side aisle, anchored on the wall by means of several stiff bolts passing through the thickness of the boards. These rigid constraints limited the deformation of the panel, which would have benefited from being free to shrink and swell in response to the climatic fluctuations. Due to roof damage, the environment surrounding the panel was exposed to rainwater infiltrations and thus high humidity. As a result of the constraints preventing the natural swelling caused by high humidity, the panel developed a permanent "compression set" deformation. Later, when the humidity decreased, the shrinkage of the wood was again limited by the constraints, so internal tension stresses developed. These produced two cracks along the wood grain in two areas of weakness. One of the cracks developed along the joint between boards 5 and 6, where the glue line yielded. The other was triggered by an initiating ring shake on board 5, which partially yielded along a longitudinal tangential surface. The two cracks seriously damaged the planking and paint layers in the right (seen from the back) half of the panel's width and were at risk of propagating across its entire width.

2. The Monitoring Approach

This paper focuses on the experimental analysis, carried out through medium-term monitoring, of the actual slippage, if any, allowed by the dovetailed connection between the crossbeams and planking of the panel painting. If present, such slippage would allow the planking a certain, albeit limited, freedom to shrink/swell during changes in environmental humidity, thus avoiding the occurrence of dangerous stress states in the wood. As detailed below, knowledge of the existence and basic features of such slippage was important to orient the structural restoration work to be carried out.

2.1. The Possible Strategies for Structural Restoration

A restoration intervention was deemed necessary to recover the panel's integrity. However, the risk existed that too much friction between the panel and its dovetailed crossbeams (possibly incremented by the cupping tendency of the planks) or even a blockage due to other factors could act as a constraint and induce new cracks. To evaluate the risk, the hygroscopic deformations of the panel and the relative slippage between the panel and crossbeams needed to be accurately estimated. If the measurements showed that slippage between the crossbeams and boards had occurred, the reconnection of the two cracks could be recommended. If no slippage took place, it would be better to reconnect only one crack and let the other act as an "expansion joint". Before starting structural restoration, the following alternatives were therefore considered:

- If slippage between the planking and crossbeams was possible, structural restoration could be carried out by reconnecting the separate parts without fear that further damage might occur from the seasonal climatic variations of the church in which the painting hangs;
- If slippage could not take place, it would be better to avoid reconnecting the separate parts to minimise the risk of further fractures and damage to the paint layers.

2.2. The Outcomes Resulting from the Applied Monitoring Procedure

After having determined through the method described in this paper that slippage between the planking and crossbeams was possible, the structural restoration was carried out by "repairing" the damage (i.e., reconnecting the separated parts and restoring the paint layers).

After the completion of the restoration, its validity was verified by using the same measurement techniques to monitor the actual slippage over the course of a year, during which significant environmental climatic variations occurred.

2.3. Diagnosis by Monitoring: Objectives, Methods and Equipment

To determine whether slippage between the planking and crossbeams could take place in the actual historical panel painting under its actual exhibition conditions, which involved significant seasonal variations in environmental humidity, we developed an innovative method and related experimental procedures. This method was minimally invasive and relatively simple and inexpensive (except for the time invested by the researchers and restorers to implement it). Furthermore, it could be completed (at least in the first fundamental cognitive phase) in the time scheduled for the artwork's restoration. It can be summarised as follows.

(1) Appropriate electronic displacement transducers (here, named "deformometers"), connected to data loggers, were installed in carefully chosen "strategic" locations on the back face of the planking. They were designed to automatically detect and record the slippage of the planking with respect to the crossbeams and the width variations of the cracks whose possible repair was under discussion. The data loggers also recorded the thermo-hygrometric conditions of the microenvironment surrounding the artwork.
(2) The monitoring was conducted over a period which included at least one dry and one moist season. During the entire period of the restoration, including the pre- and post-restoration monitoring, the artwork was kept in an ancillary room in which the environmental microclimatic conditions were practically identical to those of the church.
(3) The deformometric and climatic monitoring data were analysed and correlated to highlight any slippage in particularly significant areas of the planking. These included the areas in which the fractures had occurred (which behaved like smaller, separate plankings) and the areas that remained connected (which better represented the planking in its entirety).

The initial monitoring was initiated approximately six months before the restoration work. During the restoration, the monitoring was interrupted for one month and the instruments temporarily removed from the areas around the cracks to be repaired, so as not to impede the work. After the end of the restoration the instruments were installed again, and the monitoring was re-started to check the effects of the structural changes which had been made. This further study phase, made possible by an unexpected delay in the panel's relocation, lasted for over a year and made it possible to check the panel's behaviour during a year's worth of climatic variations and hence verify the correctness of the choices made for the structural restoration.

3. The Monitoring Methods and Equipment

The monitoring equipment was installed on the back face of the panel (Figure 3) using a reversible glueing technique. It was composed of 12 dilatometers (Ds) to record the slippage between the crossbeams and selected points on the boards, and 6 deformometric kits (DKs) [14] to record small local deformations or distortions of the boards or the cracks in selected areas of the boards.

The climatic parameters (T and RH) were also recorded by stand-alone climatic data loggers. To check that no significant climatic vertical gradient existed, one climatic logger was placed near the base of the panel and a second near the top, almost 4 m above the other logger. All the potentiometric displacement transducers forming Ds and DKs were connected to multi-channel stand-alone data loggers, which were configured to simultaneously take a reading every 15 min.

Data loggers: Hobo U12-013 (temperature, RH, two external channels), U12-006 (4 external channels), Onset Computer Corporation (Bourne, MA, USA). The resolution of each was 0.6 mV and the precision was ±2 mV.

Linear displacement transducers SLS095/0030/1.2 K/R/50, Penny & Giles Controls Ltd. (Newport, UK).

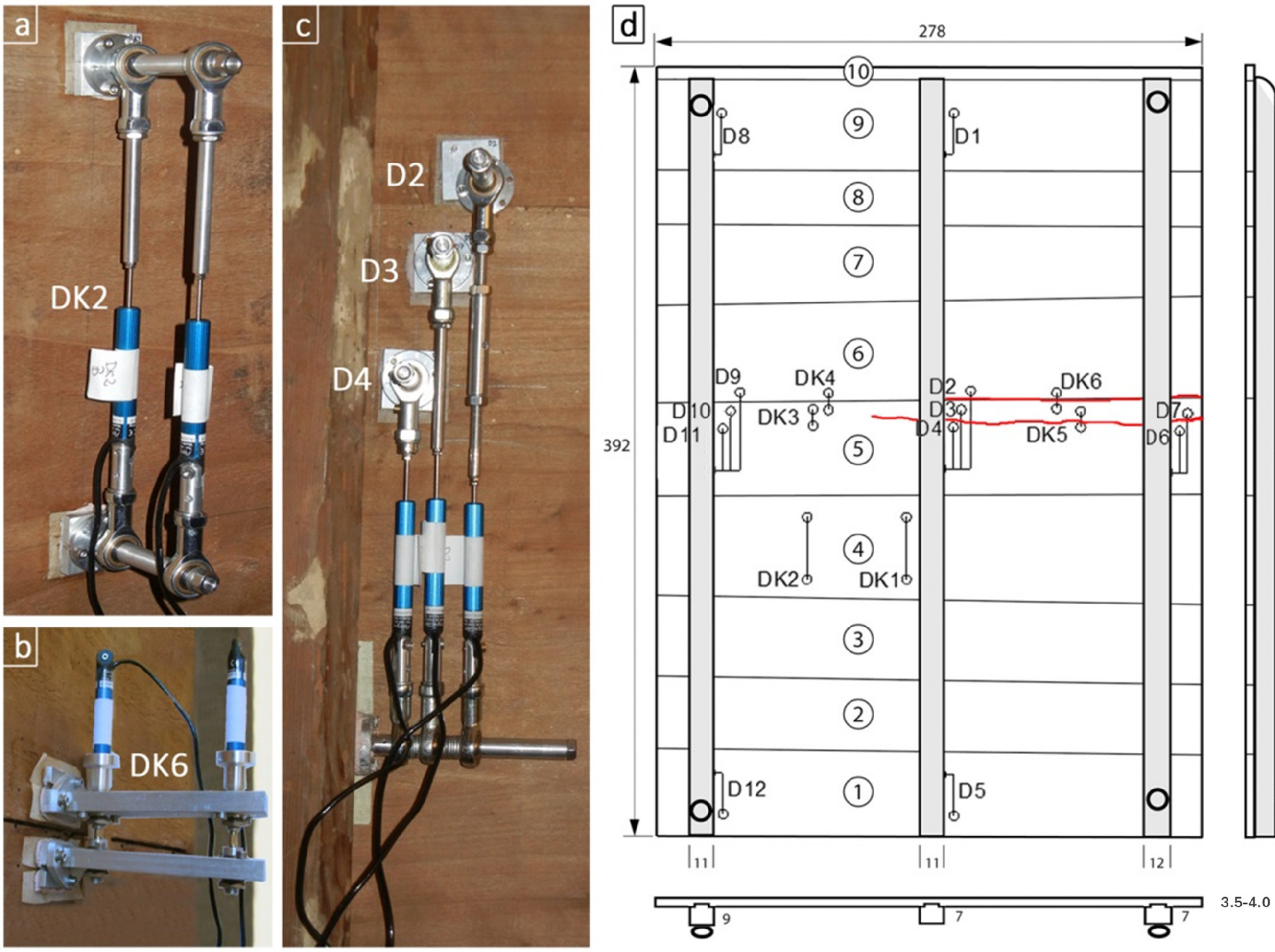

Figure 3. The monitoring equipment installed on the back face of the panel. (**a**) A "long" deformometric kit (DK2), installed on board 4; (**b**) a "short" DK (DK6), installed across a crack (the broken glue line); (**c**) three dilatometers (D2, D3, D4), installed with their lower ends at the same level on the central crossbeam, and their upper ends on three locations on the back face of the panel; (**d**) the structure of the panel and the arrangement of the monitoring equipment, with the red lines representing the two cracks (above, the broken glue line; below, the opened ring shake).

Potentiometric displacement transducers were chosen mainly because of their low cost and low power consumption, which allow for the assemblage of self-supporting systems with very long battery lives.

Each D had a resolution of 0.0007 mm and a precision of 0.002 mm. The Ds were calibrated in the laboratories before being applied to the panel painting.

Frequency of data acquisition: 15 min.

Monitoring started six months before the restoration, was interrupted for one month to remove the instruments and allow the restorers to repair the cracks, and continued for a further 12 months after the restoration.

3.1. The Equipment for Monitoring the Relative Slippage between the Panel and Crossbeams

The Ds were displacement transducers. They were placed so that their longitudinal axes were parallel to those of the crossbeams, and their ends were anchored through articulated ball joints, one on the panel and the other on the nearby crossbeam. Some Ds were installed individually and others together with one end fixed at a common point (Figure 3c). The variations in the length of the crossbeams along their axes could be ignored because the shrinkage/swelling and mechanical strain in the longitudinal direction are extremely small. Therefore, the displacement recorded by each of such transducers represented the slippage (along the crossbeam's axis) between the two points, one on the board and the other one on the crossbeam; each crossbeam constituted a common reference for all the Ds having one end connected to it. However, it was unnecessary to establish a common reference for the three crossbeams.

One or more Ds were anchored on the panel in selected locations (Figure 3) considered the most significant for this research:

- On the central crossbeam: (D1), (D2,D3,D4), (D5).
- On right-hand crossbeam: (D6,D7).
- On the left-hand crossbeam: (D8), (D9,D10,D11), (D12).

Also, six DKs were installed on the back face of the panel, as shown in Figure 3. Each DK can measure between its two bases two kinds of deformation, which typically are (i) the change in distance between the two centres and (ii) the change in the angle between the surfaces on which they are fixed. Therefore, they were installed as follows:

- DK1 and DK2 were installed along the width of board number 4 (non-cracked), one (DK1) near the central crossbeam, and the other (DK2) halfway between the central and left-hand crossbeams (that is, 50 cm from each crossbeam). These locations were chosen to verify whether a difference in cupping could be perceived between cross-sections of the board located at different distances from the crossbeams.
- DK3 and DK5 were installed across the opened ring shake and DK4 and DK6 across the open joint in the middle of the right-hand half of the panel to monitor the variation in the cracks' widths, as well as in the middle of their unbroken prolongations on the left-hand part of the panel to quantify the width variation, if any, of the cracks before the restoration and observe any deformations occurring in the same locations after the cracks were repaired.

3.2. The Measurements Taken on the Panel in Selected Areas and along Selected Lines

The analysis (see further) of the variations in the sizes of the cracks and various parts of the panel led to the identification of three large areas of the panel which were deforming almost independently of each other (Figure 4):

- Area 1: the entire height of the left half of the panel (from the left edge to the central crossbeam).
- Area 2: the upper right-hand portion of the panel (from the central crossbeam to the right edge and from the top edge down to the ring shake).
- Area 3: the lower right-hand portion of the panel (from the central crossbeam to the right edge, from the ring shake down to the bottom edge).

Also, three lines were defined (Figure 4), along which the data provided by the deformometers could be used to compute the slippage between the planking and crossbeams, the shrinkage/swelling of the planking, and some width variations of the cracks:

- Line 1: adjacent to the left crossbeam, along the entire height of the panel (D8 to D12).
- Line 2: adjacent to the central crossbeam, from the top edge down to the ring shake (D1 to D3).
- Line 3: adjacent to the central crossbeam, from the ring shake down to the bottom edge (D4 to D5).

The width variations of the cracks were computed at several locations:

- At the centre crossbeam, based on the differences between the D2 and D3 and D4 readings.
- Midway between the central and the right-hand crossbeams, directly from the DK5 and DK6 outputs.
- At the right crossbeam, based on the differences between the D6 and D7 readings.

In the analyses reported here, the data obtained from D2 and D3 were taken into consideration as they provided the variations in the widths of the open joint and the ring shake in the same location (i.e., midway between the central and the right-hand crossbeams).

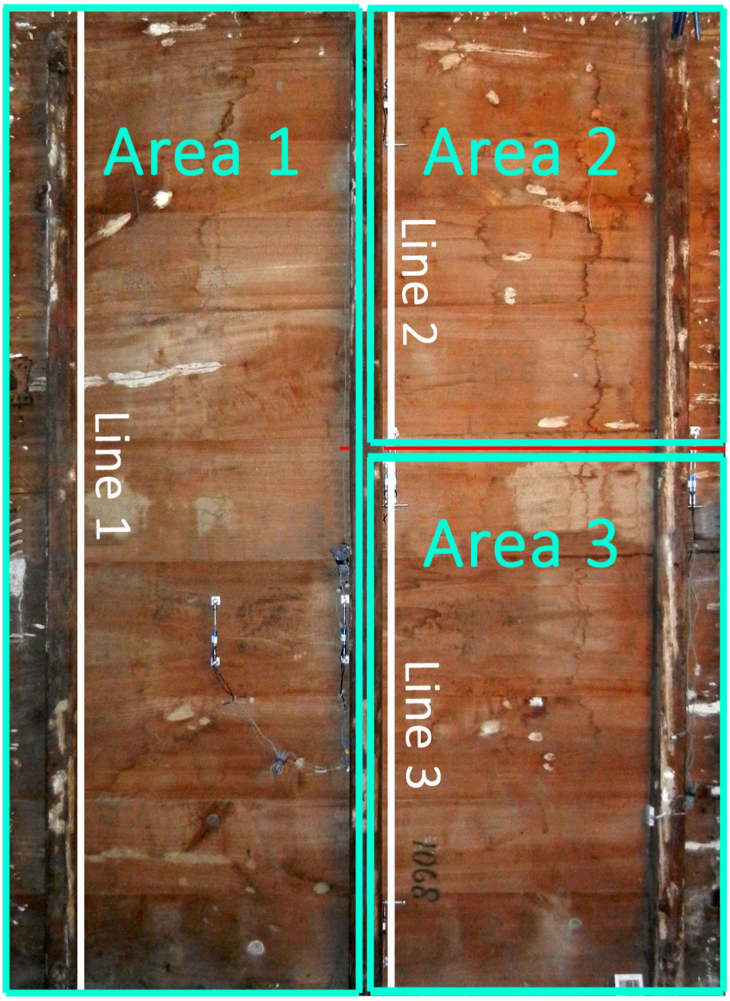

Figure 4. The three main areas and three main lines, before restoration. Note: Figure 4 is intended to show the three main areas of the panel painting rather than the location of the instrumentation. However, DK1 and DK2 (Area 1) and D2, D3, D4, D6 and D7 (across Areas 2 and 3) are visible, while DK5 and DK6 were not yet mounted when the picture was taken.

4. The Results

To provide the information needed to support the restoration decisions, the width variations of the cracks and the slippage between the crossbeams and selected points of the planking were collected and analysed in connection with the climatic variations (Figure 5) and organised in graphs showing parameters of interest versus time. This analysis showed that some slippage was occurring and, by identifying the existence and locations of some of the "no-slippage" zones, allowed reasonable assumptions to be made in favour of repairing both cracks, thus returning the panel to its original structural unity. After restoration, the monitoring was continued, making it possible to verify the validity of the choices which had been made based on the results from the initial monitoring.

4.1. The Panel's Deformational Behaviour before the Restoration

The data were processed by plotting against time the shrinkage/swelling perpendicular to the grain of the planking and the width variations of the cracks. Figure 6 also shows the air temperature and the relative humidity (RH) evolution in the vicinity of the panel. The monitoring lasted for about six months, from May to November, which made it possible to highlight the transitions between wet and dry periods.

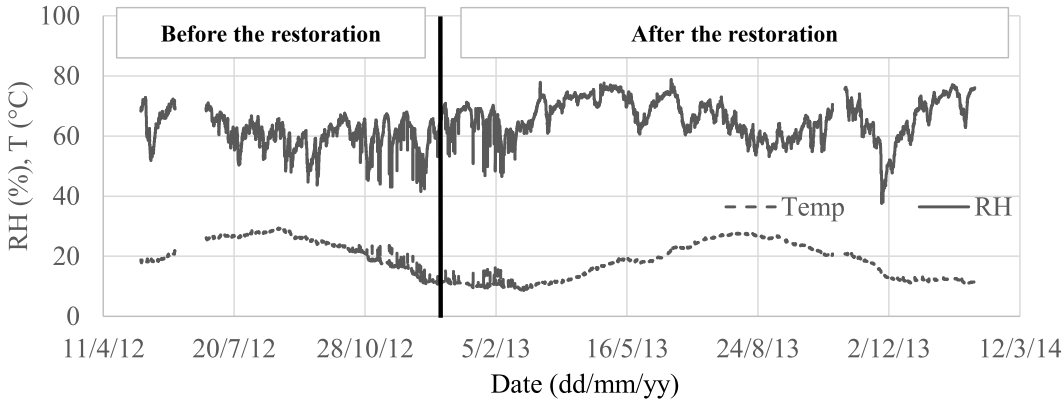

Figure 5. The graph shows the climatic conditions the panel painting underwent before and after the restoration. Note. Due to the unforeseen exhaustion of some batteries, data are missing for approximately the month of June.

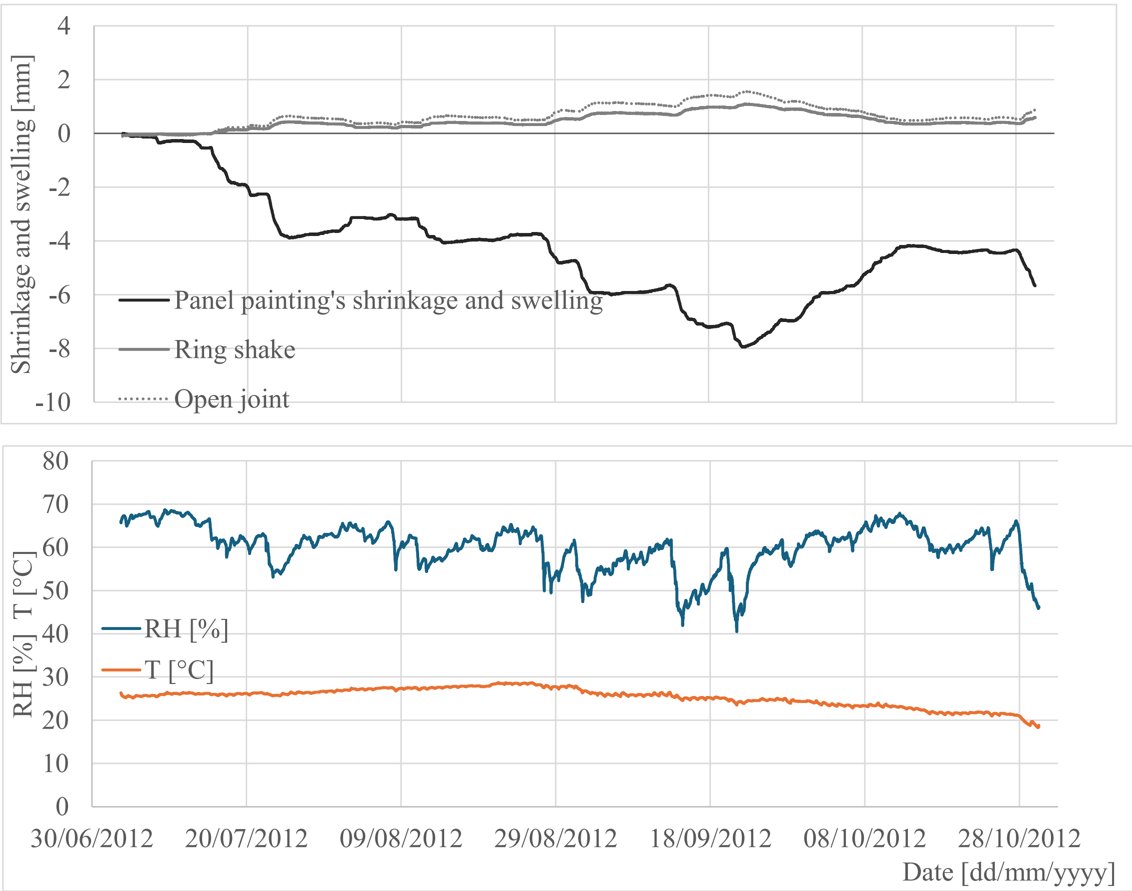

Figure 6. Before restoration: Width variation of the ring shake and open joint and vertical shrinkage/swelling of the whole panel along Line 1; the RH and T variation are also reported. Note. The accuracy of the swelling and shrinkage curves is ±0.002 mm, the accuracy of the temperature sensor is ±0.35 °C and the accuracy of the RH sensor is ±2.5%.

The graphs show that as the RH decreases, the wood shrinkage perpendicular to the grain makes the panel's height decrease and the width of the cracks increase and vice versa. The shrinkage was measured along Line 1, where the planking is whole (i.e., not divided by the cracks) and therefore represents the shrinkage of the entire panel. In Figure 6, we can see that the whole panel shrinks considerably due to the decrease in RH. However, the widths of the broken glue line and the ring shake increase due to the decreasing RH.

This is explained by the fact that the right part of the panel is divided into two parts: Areas 2 and 3 (see Figure 4). As they are no longer connected to each other, Areas 2 and 3 will shrink independently. However, they are still connected with the left part of the panel and hence cannot further approach each other, so both the open joint and ring shake widths will increase.

Significant variations in the width of both the open joint and the ring shake were recorded between Areas 2 and 3. In contrast, no crack evidence nor significant deformations were observed in Area 1 along the potential prolongation of the two cracks; this area deformed as a single structural unit. The RH decreased from about 70% to about 45% in four months, causing the panel to shrink by about 8 mm and the cracks to widen by about 2.7 mm (1.6 mm for the open joint and 1.1 mm for the ring shake).

4.2. Identification of Actual Slippages, Hypotheses about Zero-Slippage Zones and Recommendations about the Structural Restoration of the Panel

Along Line 1 (representing the left side of Area 1), D8 and D12 showed slippages in opposite directions to each other, such that the upper and lower extremes became closer to each other. Additionally, D9, D10 and D11 (located about halfway) showed very small slippages, in agreement with D8. Similar slippages were found along Line 2 between D1 and D2 for Area 2 and along Line 3 between D4 and D5 for Area 3. For reasons relating to space, the relevant time-dependent graphs are not shown.

The combination of these slippages, evidently caused by the shrinkage/swelling of the planking, indicates that for each of the three areas, the sliding must have been zero at some intermediate position between the two extremes. Such positions were named "zero-slippage zones", and their most plausible locations were determined with the approximate geometric construction shown in Figure 6. Again, for reasons of space, such locations are shown together for all three areas before and after restoration. The determination of the zero-slippage zone was more reliable for Area 1 as information was available for an intermediate position.

It was evident that the available data were not sufficient in themselves to ensure that the locations of the zero-slippage zones were predominantly related to equilibrium between the friction forces (and thus to the geometry of each area), rather than to local blockages between planking and crossbeams, produced by very high friction or by other factors. However, following in-depth discussion with the restorers, it was considered that the hypothesis of equilibrium between the friction forces was the most plausible, and it was based on this hypothesis that the recommendations for structural restoration were formulated.

The assumptions about the zero-slippage zones not being produced by actual local blockages were crucial to deciding strategies for structural restoration. In summary, the appropriateness of a restoration intervention that would completely reconnect the cracks depended on whether such reconnection would result in a different slippage behaviour of the two areas and the appearance of a new common "zero-slippage zone". In other words, we had to determine whether or not the cracks were a necessary "release valve" to prevent unacceptable stresses resulting from the foreseeable hygroscopic movements of the panel. After the restoration, the panel showed consistent deformation even on the right side (where former Areas 2 and 3 were reconnected), behaving as a single structure with only one central "zero-slippage zone" (Figure 7). This confirmed the correctness of the hypothesis we formulated.

4.3. Slippage after the Restoration

Data were recorded for 12 months. Based on the examination of the "zero-slippage zones", it was concluded that repairing both cracks could be a safe intervention, although the success of the repair would have to be verified by subsequent monitoring. After the restoration, the right section of the panel showed consistent deformation, behaving as a single structure, with only one central "zero-slippage zone" Figure 7b).

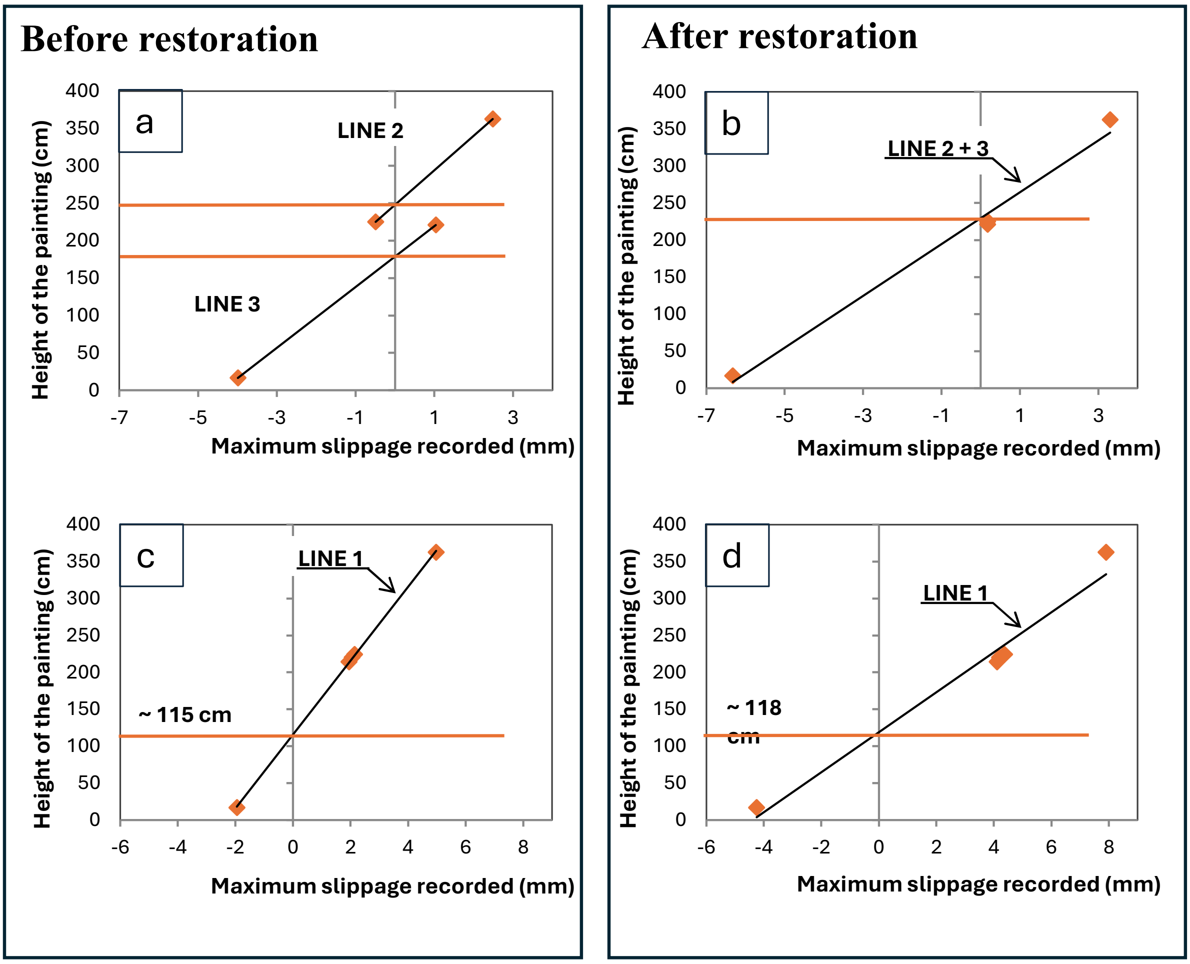

Figure 7. Approximate geometric construction to estimate the location of the "zero-slippage zones" on the central and left crossbeams, (**a**,**c**) before and (**b**,**d**) after the structural restoration.

Long-term monitoring after this restoration will be important to keep the behaviour of the panel under control. If the wooden support remains free to slip, its reactions after climatic variations should be similar to the deformations monitored previously. In contrast, reduced or no slippage would be a possible warning sign of unexpected constraints and would signal the need for closer exanimation to prevent otherwise unforeseeable consequences such as the opening of old or new cracks.

5. Conclusions

This paper describes the development and successful results of a methodological collaboration between wood scientists and panel painting restorers, which was initiated to make important decisions about the structural restoration of a large painted panel, the *Lapidazione di Santo Stefano* by Giorgio Vasari. It shows how important this kind of collaboration can be and how a technical analysis based on the monitoring of an artwork can significantly support planned restoration work. The innovative deformometric and slippage monitoring carried out by measuring and interpreting the relative slippage between the painting's planking and its dovetailed crossbeams proved to be a useful non-invasive instrument to orient the structural restoration of the panel.

The analysis of the data resulting from the long-term post-restoration monitoring, carried out over a year and a half, confirmed the diagnosis made through the analysis of the data collected before restoration over approximately six months: that the crossbeams were exerting a limited restraining effect on the panel and were not significantly preventing it from shrinking and swelling; therefore, a full structural restoration could be carried out without concern that the crossbeams could exert dangerous constraints on the panel—that is, subject it to significantly higher stresses than those that might have occurred before the restoration. In the context of preventive and forward-looking conservation, it might be desirable for such monitoring to be maintained indefinitely in such situations to verify the continuation across a wider range of environmental conditions of the desirable situation observed after the restoration and detect any new disturbances that might emerge.

Author Contributions: Conceptualisation, P.M., B.M. and L.U.; data curation, L.C.; formal analysis, P.M., B.M., G.G., L.R. and L.U.; investigation, P.M. and L.C.; methodology, L.U.; project administration, L.U.; supervision, L.U.; validation, P.M., B.M. and L.U.; visualisation, L.C.; writing—original draft, L.C. and L.U.; writing—review and editing, P.M., B.M., G.G., L.R. and L.U. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data available on request from the correspondening author.

Acknowledgments: The authors wish to thank Alba Maria Macripò (government officer—*BAPSAE di Pisa e Livorno*, head of restoration), who supported the work, appreciating the importance of cooperation between science and restoration; Nadia Presenti and Mario Verdelli (restorers—*Toscana Restauro Arte*, in charge of the restoration) for their enthusiastic cooperation, which went well beyond the call of duty, and their sincere interest in revealing the complex behaviour of the wooden panel; Monsignor Aldo Armani (rector of the Church of Santo Stefano dei Cavalieri) for his availability and willingness to make this research possible.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Buck, R.D. Some Applications of Mechanics to the Treatment of Panel Paintings. *Stud. Conserv.* **1961**, *6*, 156–162. [CrossRef]
2. Buck, R.D. Some Applications of Rheology to the Treatment of Panel Paintings. *Stud. Conserv.* **1972**, *17*, 1–11. [CrossRef]
3. Hoadley, B.R. Chemical and Physical Properties of Wood. In *The Structural Conservation of Panel Paintings*; Dardes, K., Rothe, A., Eds.; The Getty Conservation Institute: Los Angeles, CA, USA, 1998; pp. 2–20.
4. Riparbelli, L.; Mazzanti, P.; Manfriani, C.; Uzielli, L.; Castelli, C.; Gualdani, G.; Ricciardi, L.; Santacesaria, A.; Rossi, S.; Fioravanti, M. Hygromechanical Behaviour of Wooden Panel Paintings: Classification of Their Deformation Tendencies Based on Numerical Modelling and Experimental Results. *Herit. Sci.* **2023**, *11*, 25. [CrossRef]
5. Riparbelli, L.; Dionisi-Vici, P.; Mazzanti, P.; Brémand, F.; Dupré, J.C.; Fioravanti, M.; Goli, G.; Helfer, T.; Hesser, F.; Jullien, D.; et al. Coupling Numerical and Experimental Methods to Characterise the Mechanical Behaviour of the Mona Lisa: A Method to Enhance the Conservation of Panel Paintings. *J. Cult. Herit.* **2023**, *62*, 376–386. [CrossRef]
6. Riparbelli, L.; Mazzanti, P.; Helfer, T.; Manfriani, C.; Uzielli, U.; Castelli, C.; Santacesaria, A.; Ricciardi, L.; Rossi, S.; Gril, J.; et al. Exploring the Inner Hygro-Mechanical Behaviour of Historical Panel Paintings: A Novel Approach Using Digital Twins. *Herit. Sci.* **2024**, *12*, 27. [CrossRef]
7. Uzielli, L. *Historical Overview of Panel-Making Techniques in Central Italy*; Dardes, K., Rothe, A., Eds.; The Getty Conservation Institute: Los Angeles, CA, USA, 1998; pp. 110–135.
8. Dupre, J.C.; Jullien, D.; Uzielli, L.; Hesser, F.; Riparbelli, L.; Gauvin, C.; Mazzanti, P.; Gril, J.; Tournillon, G.; Amoroso, D.; et al. Experimental Study of the Hygromechanical Behaviour of a Historic Painting on Wooden Panel: Devices and Measurement Techniques. *J. Cult. Herit.* **2020**, *46*, 165–175. [CrossRef]
9. Uzielli, L.; Dionisi-Vici, P.; Mazzanti, P.; Riparbelli, L.; Goli, G.; Mandron, P.; Togni, M.; Gril, J. A Method to Assess the Hygro-Mechanical Behaviour of Original Panel Paintings, through In Situ Non-Invasive Continuous Monitoring, to Improve Their Conservation: A Long-Term Study on the Mona Lisa. *J. Cult. Herit.* **2022**, *58*, 146–155. [CrossRef]
10. Cocchi, L.; Marcon, B.; Goli, G.; Mazzanti, P.; Castelli, C.; Santacesaria, A.; Uzielli, L. Verifying the Operation of an Elastic Crossbar System Applied to a Panel Painting: The *Deposition from the Cross* by an Anonymous Artist from Abruzzo, Sixteenth Century. *Stud. Conserv.* **2016**, *62*, 150–161. [CrossRef]
11. Riparbelli, L.; Castelli, C.; Gualdani, G.; Ricciardi, L.; Santacesaria, A.; Uzielli, L.; Mazzanti, P. An Innovative Method for Dimensioning the Crossbeams of an Original Painted Panel, Based on Mechanical Testing, and on Numerically Modelling Its Distortion Tendency. In *The Future of Heritage Science and Technologies*; Furferi, R., Governi, L., Volpe, Y., Gherardini, F., Seymour, K., Eds.; Lecture Notes in Mechanical Engineering; Springer International Publishing: Cham, Switzerland, 2023; pp. 97–112, ISBN 978-3-031-17593-0.
12. Jullien, D.; Dupré, J.-C.; Gauvin, C.; Uzielli, L.; Hesser, F.; Riparbelli, L.; Mazzanti, P.; Gril, J.; Tournillon, G.; Amoroso, D.; et al. Hygromechanical Study of a 16th Century Painted Wooden Panel: In-Situ Experiments to Quantify the Mechanical Effect of the Frame and the Cradle. *J. Cult. Herit.* **2023**, *64*, 266–274. [CrossRef]

13. Macripò, A.M. La lapidazione di Santo Stefano" di Giorgio Vasari nella Chiesa dei Cavalieri a Pisa—Il restauro. *Crit. d'Arte* **2014**, *49–50*, 97–102.
14. Uzielli, L.; Cocchi, L.; Mazzanti, P.; Togni, M.; Julien, D.; Dionisi-Vici, P. The Deformometric Kit: A Method and an Apparatus for Monitoring the Deformation of Wooden Panels. *J. Cult. Herit.* **2012**, *13*, 94–101. [CrossRef]