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## Hygromechanical response of a panel painting in a church: monitoring and computer modeling.

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### Abstract

Wooden panel paintings are commonly displayed in traditional churches, where they play to some degree a religious function in addition to their cultural value. They are subject to uncontrolled microclimatic variations that include weekly heating periods. The actual amount of these variations, as well as the consequence on the panel deformations, are insufficiently known. Such information is particularly required when a painted panel needs to be transported, either to be displayed in a different place like a museum or to a workshop for restoration, in order to assess the risk resulting from the change of ambient conditions and make the appropriate decision for their preventive conservation.

The panel called “Le Couronnement d’Epines”, about 500 years old, is made of 3 horizontal boards assembled through a pair of vertical crossbars. It is on display in the choir of Saint Didier church, Avignon, south of France, and presents a satisfactory conservation state. Our study focused on the upper board.

In this paper we give details about the in-situ monitoring of the board deflection, together with results about surrounding environment over a 2 year period. We also introduce optical method based on 3D image correlation that we used for external shape measurements. The analysis of the shape, together with the observation of anatomical orientation of two wood samples, allowed estimating the board position in the stem. The deflection was simulated numerically using a 1D version of the code TransPore, which models the heat and mass transfer through the panel and the hygromechanical response of the wood.

The hygrothermal variations followed very slowly those of the external climate, and little perturbation resulted from the occasional heating. After adjustment of the permeability of the painted face, the observed deflection history was well predicted by the model, which could be used to predict the reaction of the panel to a different hygrothermal environment.

## Introduction

Wooden panel paintings are commonly displayed in traditional churches, where they play to some degree a religious function in addition to their cultural value. They are subject to uncontrolled microclimatic variations that include weekly heating periods. The actual amount of these variations, as well as the consequence on the panel deformations, are insufficiently known. Such information is particularly required when a painted panel needs to be transported, either to be displayed in a different place like a museum or to a workshop for restoration, in order to assess the risk resulting from the change of ambient conditions and make the appropriate decision for their preventive conservation.

This paper presents a case study for a painted panel located in a French church. Experimental procedures and numerical tools will be explained, as well general features of the hygromechanical response of painted panels.

## Geometry and material orientation:

This panel consists in 4 poplar planks, including one small piece in the lower part. Figure 1 shows the front and back faces of the panel; white dotted lines are added to make a clear distinction between the main boards (numbered 1, 2 and 3). The planks are assembled by two vertical cross beams with dovetail joint (see Figure 1b). The panel is floating in its frame; the frame is fixed to the wall through three angle brackets.

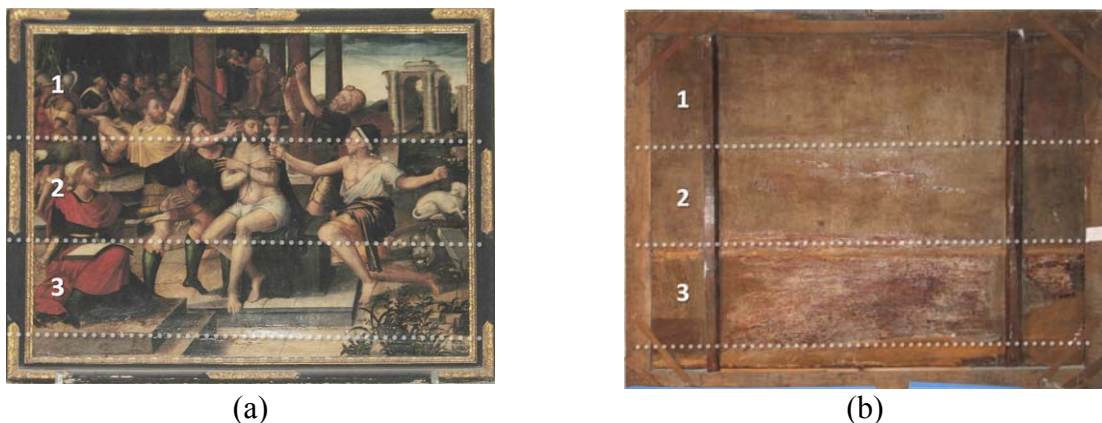


Figure 1 : “Couronnement d’épines”, anonymous, 1563, exhibited in the Saint Didier church (Avignon, France). Length: 143cm, Width: 178cm. Front (a) and back (b) faces of the panel with indication of boards position (white dotted lines).

All three boards show a general cupping deformation, assumingly the result of many years of humidity variations. This visual assessment has been supported by optical measurement with stereo correlation technique; the deformed shape of the painted side is shown with amplification in Figure 2. The condition of boards 2 and 3 led us to study exclusively the mechanical state of board 1.

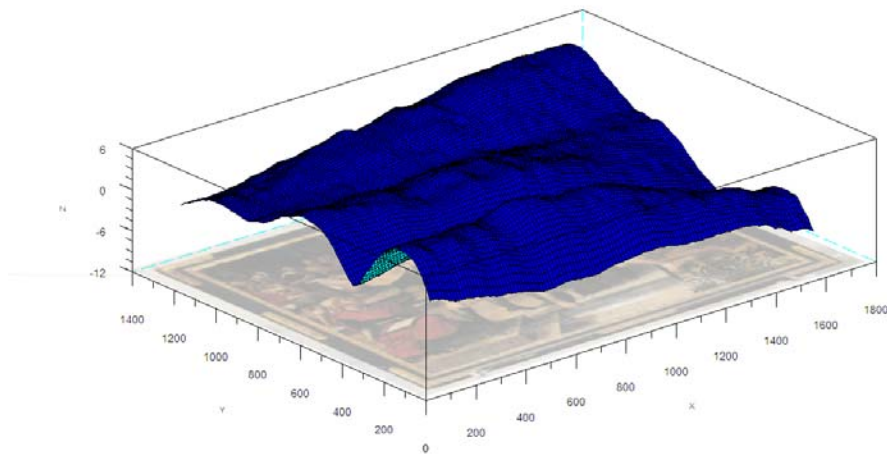


Figure 2 : general deformation of the panel measured by stereo-correlation (scales in mm).

Two micro samples have been cut from the back of the panel; their localization is schematically indicated in Figure 3. Anatomical images (Figure 3b,c) allowed to estimate the position of the corresponding cross section within the transverse plane (Figure 3d).

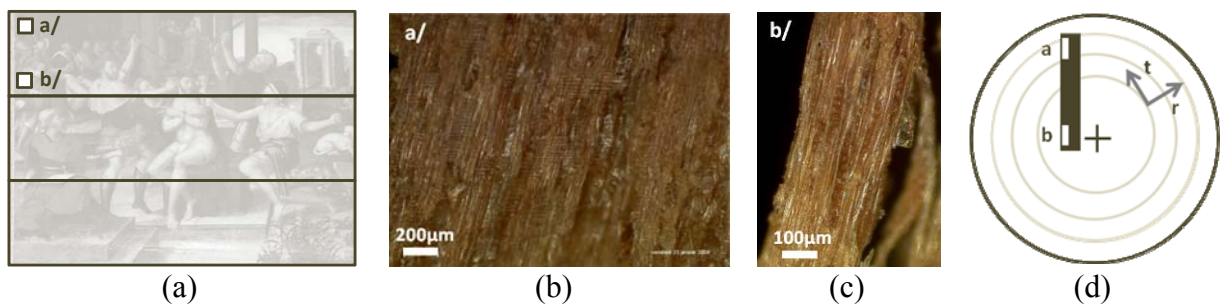


Figure 3: Possible orientation of the upper plank estimated from anatomical samples.

Optical measurements can also provide with valuable information on the material orientation. By plotting only the upper board (Figure 4), we note a general twist of the plank, which we assume to be due to the grain orientation relative to the length of the board. Plotting the maximum cupping along the length suggested a grain tilted by  $5^\circ$  to the horizontal.

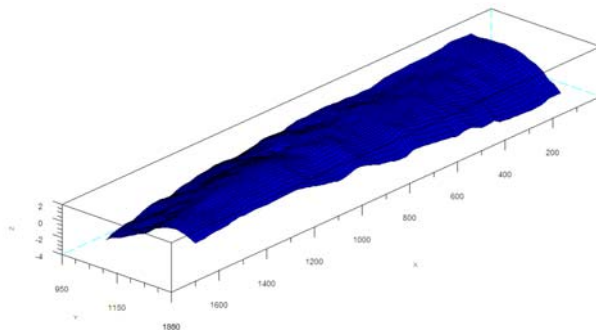


Figure 4 : shape of board n°1 (2006 dec 12th) by stereocorrelation

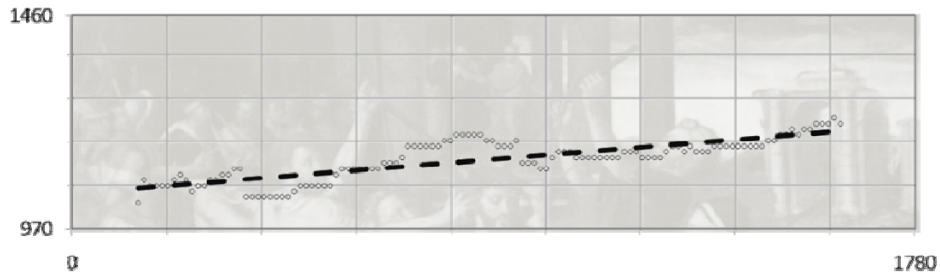


Figure 5: Fiber orientation deduced from deflection peaks across the board width, calculated from 3D image.

## General discussion about panel painting deformations.

From a mechanical point of view, deformations commonly observed by curators or restorers are of two types: wooden boards free to deform under climatic variations, and boards under constraint. Completely free deformation is rare: in certain cases, like in the present situation, we will neglect the influence of structural assemblies like cross-beams, or joints between two boards. This paper does not deal with the second type of mechanical problem: an example of panel painting with French “parquetage” is described in this conference [Baldit, *et al.*].

In the case of free deformation, panel paintings exhibit a permanent cupping oriented toward the paint layer, whatever the material orientation. When a board supposed to be initially flat deforms under wetting or drying, it will gain in transient stages either a negative or positive curvature (Figure 6) due to of reduced permeability on the painted side. When the contraction or the expansion of the back face of the panel is partly prevented by the other parts, it is subjected to tension set or compression set, respectively. However, the transverse behavior of wood is very different in tension and compression: while extensions are limited, leading easily to micro cracks, cellular buckling allows high levels of permanent compression. Consequently, in the long term the compression set always dominate over tension set, resulting in the permanent contraction of the back face of the panel.

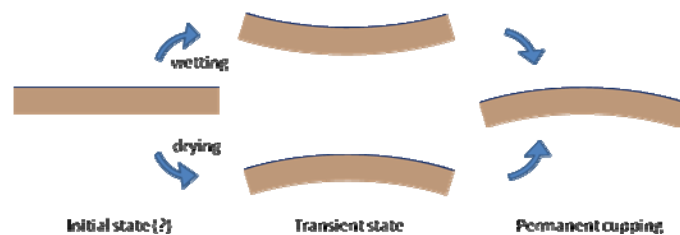


Figure 6 : description of permanent deformation on panel paintings.

For a 500 year panel painting, we assume that the permanent cupping has already occurred, but dimensional changes still occur under climatic variations. In this second stage, the material orientation becomes of great importance. We distinguish two different effects:

- Moisture gradient effect (described before as the effect of painted layer)
- Orientation effect (the equilibrium of orthotropic material under homogeneous moisture field in the plank).

The solution for a moisture gradient can be approximated through the use of computational models. The solution for the second effect is the analytic solution of:  $\text{div}(\sigma) = 0$  and  $\sigma = C \cdot \varepsilon$  with  $\varepsilon = \alpha \cdot h$  where  $\alpha$  is the shrinkage/swelling tensor and  $h$  the homogeneous moisture content field.











	Orientation effect	Gradient effect	Permanent state (flat represented)	Gradient effect	Orientation effect
	Dry period	Transient Drying		Transient Wetting	Wet period
Configuration 1					
Configuration 2					

Figure 7 : deformation of two different board types under a climatic variation.

Figure 7 shows the combined influence of painted layer and cross-section orientation of the board. In this diagram, we note that the two effects (gradient and orientation) are sometimes opposite and sometimes consistent. We will discuss later the different orders of magnitude of each effect. In the following part we describe the monitoring of our panel.

### **Apparatus for deformations monitoring.**

Optical measurements provide satisfactory information on the whole panel, but are also a time-consuming technique that cannot be used in situ for continuous measurements. Therefore we designed a device for in-situ monitoring of dimensional variations. This equipment provides continuous data on climatic-induced deformation of the panel. Our dedicated apparatus was set up behind the panel to measure the cupping of board number 1; the method could be extended to the other boards in further experimentations.

The global system consists in one apparatus for the cupping measurement and one data logger (the data logger used here is distributed by HOB0<sup>®</sup> firm). In this particular case, the data logger records both the cupping signal and the environmental conditions, temperature (T [°C] and air relative humidity (RH) [%]). All power supply needed for these three measurements are given by a 3V battery, so that a receptacle is not required. This should be considered a great advantage for panel monitoring, for instance in exhibition conditions.

As mentioned before, we assumed that each plank of its panel is free to deform under climatic environment, i.e. the presence of the two cross-beams is not generating large constraints by limiting the cupping. This first assumption is not as restrictive as it could seem. Both in-situ observations and optical measurements showed that the board deformation is not disrupted in the proximity of the crossbars.

For in-situ monitoring, the complex three dimensions deformation of the board had to be simplified into a single variable; here we chose the bending deflection, proportional to the curvature. By measuring the distance variation between two sidelong points and a central third one (Figure 8), we obtain an image of the panel deformation.

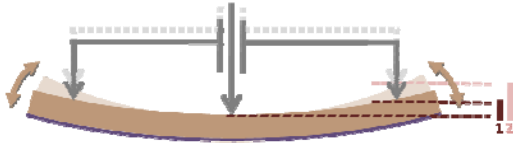


Figure 8 : Cupping deformation of a board cross section, and measurement apparatus with deflection at two different times.

Panel paintings are generally exhibited in very close position to the supporting wall. Such an apparatus is so designed to fit the reduced space behind the panel. In this case the back face of the panel is around 10 cm from the wall. In agreement with the restorers the apparatus was fixed on the two cross beams, thanks to a light tubular structure. Mechanically speaking, it was ensured that this fixation does not induce additional constraints.

**Measurement Results.**

Figure 9 shows the measurement of relative humidity in air (RH) and temperature (T) behind the panel, together with deflection of the board (in mm) over a two years period (07/05/03 to 09/09/15); the period between October and December 2008 is unfortunately missing. For a better view of the correlation between relative humidity variations and deflection, the deflection curve is plotted after multiplication by (-1). Correlation between relative humidity and deflection is evident, so as the smoothing effect of the diffusion in the wood plank. The temperature curve gives evidence of temporary heating during Sunday masses and other religious events.

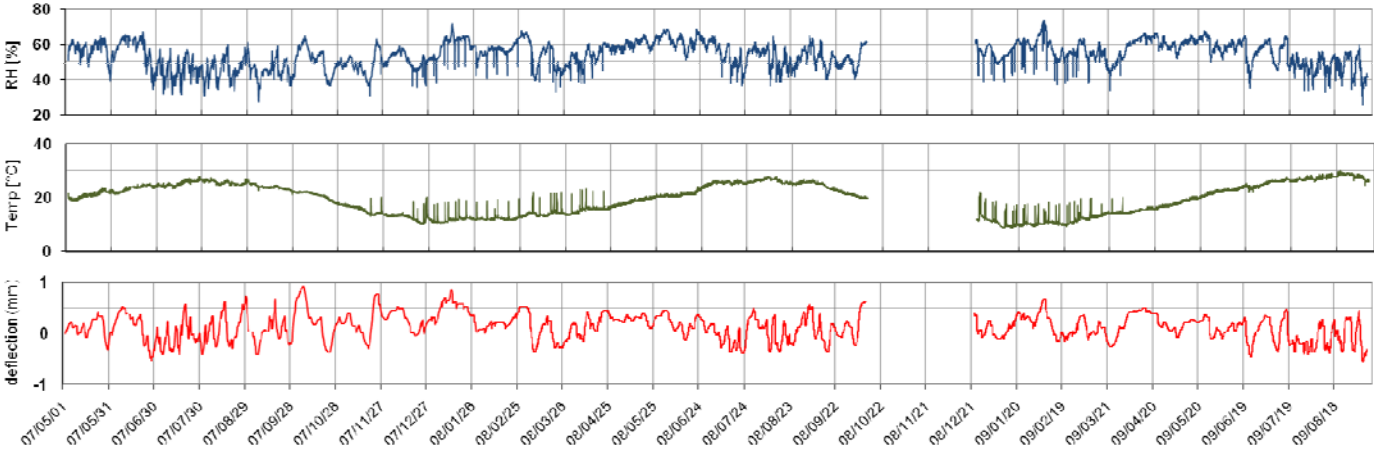


Figure 9 : Relative humidity and temperature behind the panel, and deflection of the upper board, over a 2 year period.

## Aim of the simulation: formulation of the problem.

For a practical, conservational point of view, it would be ideal to determine whether an ambient condition is “good or not” for a panel painting. On the other hand, wood mechanics allow predicting the reaction of a wood plank under given climatic conditions. For predicting the moisture content and the consequent deformation of the board, we used a computational code *Transpore* developed by P. Perré []. This code is based on heat and mass transfer formulation, and coupled with a 1D mechanical formulation. This allows predicting the cupping of a unidirectional board (radial or tangential direction along the thickness) with given boundary conditions (mainly relative humidity, temperature and convection coefficient on the two faces of the panel). Details on the formulation of *Transpore* can be found in Perre and Turner [1999] and Rémond [2004].

### Diffusion parameters.

Diffusion parameters for poplar were estimated from various experiments on spruce or poplar; some parameters are in consequence not fully representative of poplar. Formulation of diffusion in *Transpore* depends on many parameters: gaseous permeability, liquid permeability and diffusion coefficients with their dependence to temperature. It means that various experiments are needed for their determination. We only had at our disposal simple drying data on poplar samples, i.e. measurement of mass variation under climatic changes.

The reliability of the “spruce” parameters for describing poplar was verified by comparing the simulation with the diffusion data on poplar. The simulations were performed on four different thicknesses (5, 10, 15 and 20 mm) for radial and tangential orientation, as conditions in experiments. Results are reported in Figure 10. Regarding the thickness of our panel (20mm) and delays of sorption, we conclude that the diffusion parameters used in the following are fully acceptable.

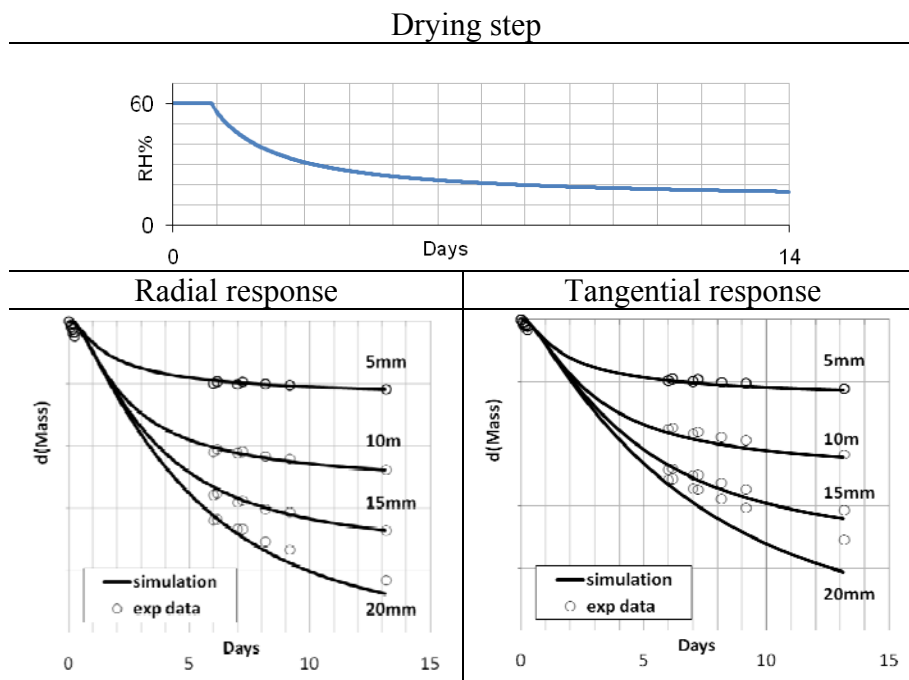


Figure 10: experimental diffusion data on poplar and simulations for radial and tangential thicknesses.



### ***Mechanical parameters.***

Until now *Transpore* has been used for short-term simulation: be it in drying applications (Rémond [2004]) or panel paintings ones (Allegretti, *et al.* [2003]), the experimental window was always shorter than one day. In our study we initiate parameter identification over a long term period (1 year for example); our final aim is to determine the precision of the prediction on another 1 year long period.

Some part of mechanical parameters is estimated from the literature. Indeed some others have to be estimated for our experiments: mainly parameters for time-dependant behavior in our experimental windows (1 year) which is not so common for identification.

The 1D rheological model used for the mechanical formulation is schematized in Figure 11. It consists in one swelling element, one elastic element, 4 viscoelastic bodies, and one mechanosorptive element. Viscoelastic and mechanosorptive parameters will be identified from the experimental data, over a 1 year period. Elastic and dilatation parameters in each orthotropic direction, as well as Poisson ratios, were estimated from the literature (Guitard [1987]).

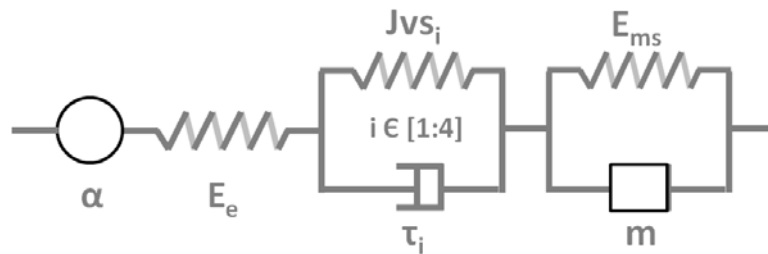


Figure 11 : rheological model with parameters

### ***Material orientation***

In order to avoid the use of the 2D version of *TransPore* that is much more time-consuming than the 1D version, the response of a board with complex material orientation along the cross-section was interpolated between a radial and tangential board behavior calculated by *Transpore*.

The orientation of the board was determined in accordance with the previous observations. According to Figure 7, we can predict the orientation of the rings with regards to the painted layer, i.e. our case corresponds to configuration 1 or 2. The observation of results in Figure 9 shows us that: transient moistening results in a transient diminution of the cupping (normal effect of the painted layer); wet period (3 months for example) results in global reduction of the cupping compared to a dry period. We conclude that the board of St Didier's panel is of configuration 2 (see Figure 9). Combining this with the anatomical observations and optical measurements, we get a global idea of the original plank position in the trunk for the simulations.

## **Results**

Here we present preliminary results of our simulations. Parameter identification is not complete but the next figures illustrate some points discussed before. Figure 12 shows results of radial and tangential simulations, with interpolation between the two curves according to the material orientation deduced in previous chapters. On Figure 13 we show preliminary results: parameters were estimated on first period from 07 May 1<sup>st</sup> to 07 February 1<sup>st</sup>; then we

attempted a prediction, i.e. a simulation with identical parameter set during another period from 2008 December to 2009 September. This first trial shows small discrepancy with experimental data: in near future we plan to improve the identification technique. In addition we aim at quantifying the prediction error, so we can obtain a reliable model able to determine conservation risks in any other climatic condition.

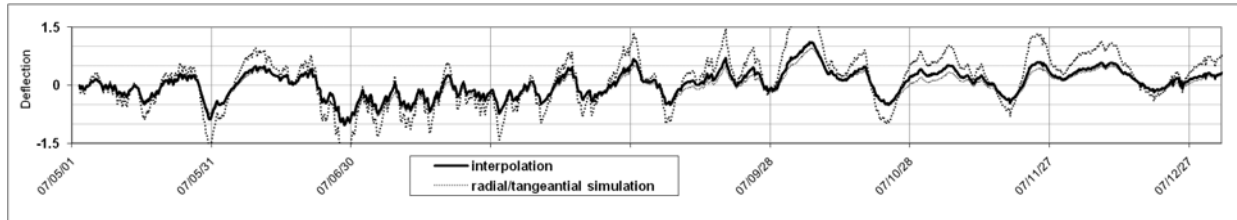


Figure 12 : interpolation between radial and tangential simulation

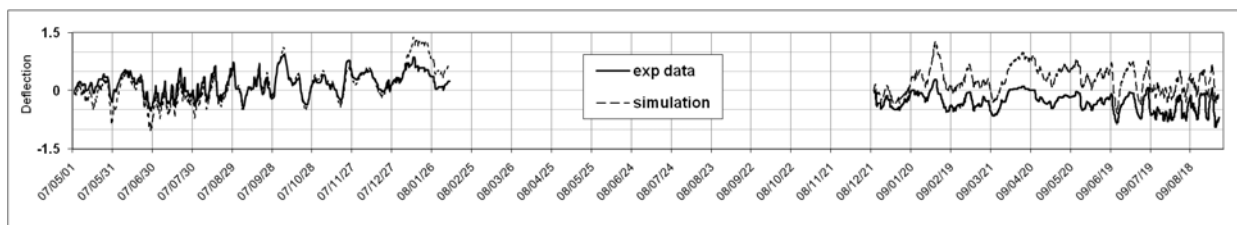


Figure 13: experimental data and simulation on calibration period (left) and prediction period (right)

## Conclusion

In this paper we presented an on-going study on panel painting conservation. We have presented the use of several techniques (anatomy, in-situ long-term monitoring, optical measurements, and computational modeling) in order to study the case of a poplar panel on display in St Didier's church in Avignon (France). In the near future, we will provide further results on parameters identification and simulation results.

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