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**Mona Lisa saved by the Griffith theory:
assessing the crack propagation risk in the wooden support of a panel painting**

*Joseph Gril¹, Elisabeth Ravaud², Luca Uzielli³, Jean-Christophe Dupré⁴, Patrick Perré⁵,
David Dureisseix¹, Olivier Arnould¹, Paolo Dionisi Vici³, Daniel Jaunard⁶, Patrick Mandron⁶*

¹Laboratoire de Mécanique et Génie Civil, University of Montpellier 2, France

²Centre de Recherche et Restauration des Musées de France, UMR 171, Paris, France

³Dipartimento di Scienze e Tecnologia Ambientali Forestali, University of Florence, Italy

⁴Laboratoire de Mécanique des Solides, University of Poitiers, France

⁵Laboratoire d'Etude et de Recherche sur le Matériau Bois, ENGREF, Nancy, France

⁶Conservation-restauration de supports bois en peintures de chevalet, 12 rue d'Enghein, Paris 10^{ème}, France

Abstract

A 2D finite elements model of the wooden support of Mona Lisa painting was developed to estimate the risk of propagation of the existing crack due to the restraining action of the frame, using observations on the wood structure and panel geometry and measurements of the forces exerted by the crossbars on the panel. A good agreement was obtained with shadow Moiré data of the displacement field. According to the simulations, the frame applies a small tearing and a slight opening of the crack lips; the calculated release energy rate is far below the critical values, suggesting practically no propagation risk, even accounting for the effect of hygrothermal fluctuations.

INTRODUCTION

Many cultural objects are made of –or contain– wooden panels painted on one side. They may be, for instance, paintings conserved in museums or in monuments, or parts of musical instruments. When properly handled to avoid biological degradation, wood exhibits long-lasting performances and can efficiently serve as a structural element and/or as the support of a painting. However, in the frequent case of panels painted on one face only, the asymmetry of humidity transfer has almost always resulted in curvatures, or, when these were restrained, by rupture of the wooden support [1, 2]. In all cases the deformations of the wooden support induced a more or less pronounced degradation of the pictural layer. Moreover, the checking pattern or “craquelures” visible in every painting, for instance, result for a large part from the fluctuating deformations of the support.

The present research project aims at improving our understanding of the hygromechanical behaviour of wooden paintings as much as developing experimental and numerical tools useful for restorers, curators and art historians. Although restoration practices are well-established, the decision regarding the treatment of a given painting is often difficult. Most panel paintings were built with cross-beams and frames, in order to strengthen them, keep them flat, and reduce the moisture-induced movements of the wooden support. Often, especially in the 19th century, framing and cross-beams were modified or substituted, according to various criteria; not always such interventions gave positive results. The generalisation of central heating in the second half of the 20th century, and more recently that of air-conditioning, increased dramatically the amount of stress supported by the wood, inducing sometimes severe cracking. Whether to modify the crossbars or to leave them as they are, is one of the dilemma frequently faced by a restorer- and the same can apply to any change applied to the framing of the panel [3]. These are questions where mechanical analysis can provide useful answers, combining experimental and numerical approaches, using recent knowledge of wood rheology and benefiting from advanced technology in data acquisition and simulation capacities.

Art historians, on the other hand, need to reconstitute the material history of their object of investigation. In the case of wooden panels, their present state mainly depends on the previous hygromechanical loading to which they were subjected in the past. This so-called “retro-engineering” is another situation where mechanical simulation can help, by testing the possibility of various scenarios. In a painting for instance, the shape of the panel, the cracks in the wood, or the checking patterns in the paint layer, could be interpreted mechanically.

A recent study on the wooden support of the world-famous painting of Mona Lisa, that will be detailed below, has initiated a cooperative research among French and Italian teams. Mona Lisa painting has been well preserved although it has been subjected to a few accidents during its 500 years of history. It is made of a single wood piece, inserted in a frame applying few constraints, and has been damaged by an ancient and seemingly well-stabilised crack. It can serve as a typical case for this category of wooden painting and, more essentially, as the starting point of a wider project concerning various types of wooden painted panels of cultural value. A series of studies started in 2004 are about to be published in a book meant for a large diffusion [4].

The mechanical analysis was started in 2004 to answer two questions raised by curators of the Louvre museum: (i) evaluation of degradation risk, especially in relation with the existing crack; (ii) optimisation of conservation conditions, regarding both the humidity regulation and the design of the frame. In this paper, we will summarize the approach chosen to address these questions, concentrating on (i). The work done so far is very preliminary, and can be improved and developed further to a large extent. However, the conclusions reached so far are reasonably convincing.

THE NUMERICAL MODEL

Available data

The approach chosen was based on the development of a mechanical model, nourished and validated by experimental data. These data, obtained manually during observation sessions or automatically during intermediate periods, concerned the wood structure, the panel geometry, the hygromechanical actions and the reactions of the crossbars on the panel.

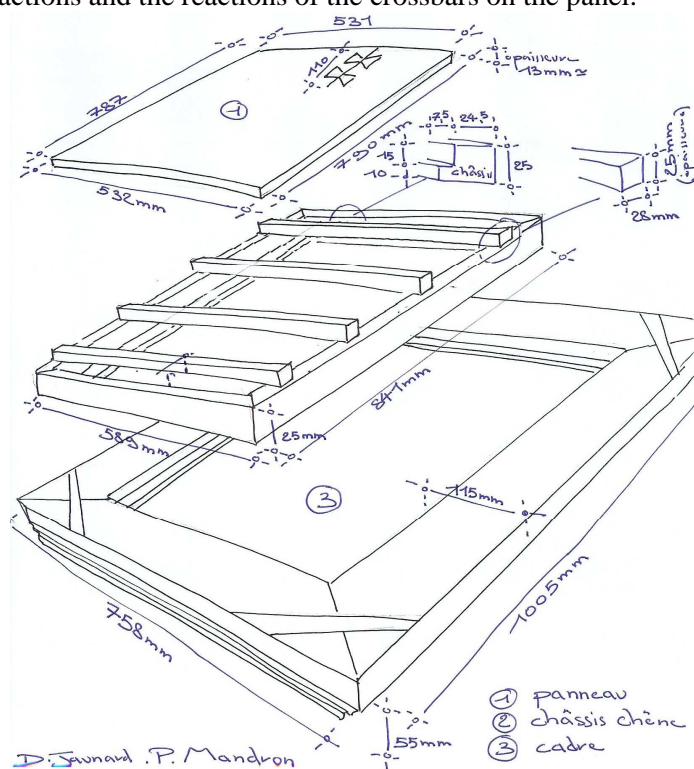
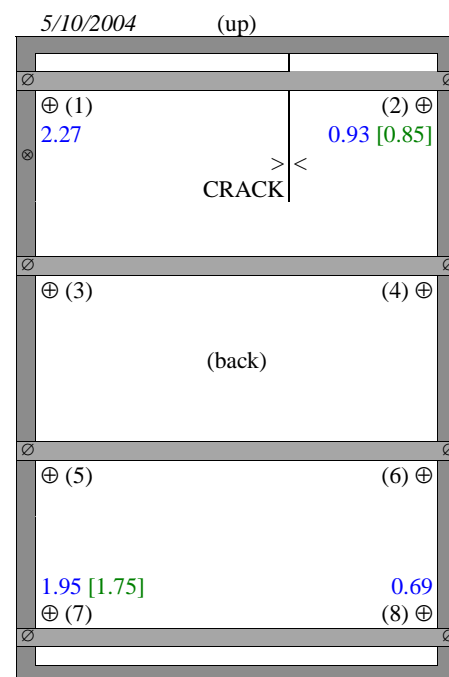


Fig. 1 A schematic drawing of the system elements: panel, frame, and external frame



⊕ Points of force measurement
 ∅ Screw for crossbar fixation on the frame
 in blue: crossbar lifted at measuring point
 [in green]: crossbar also lifted at opposite point
 Fig. 2 Position and value of the reactions by of the crossbars on the panel

Fig. 1 shows a schematic drawing of the whole structure. The wooden panel, supporting the paint layer, is made of a single piece of poplar wood of about 13 mm thick, with a rather straight grain. It was cut rather close to the pith (5 to 10cm), so that the ring orientation is flat-sawn in the central part, close to quarter-sawn on the sides. The natural cupping due to shrinkage anisotropy and asymmetric moisture exchanges on both faces is restrained by a frame made of a rectangular oak structure

reinforced by four maple crossbars. The frame is covered by an external (and visible) frame that does not act directly on the panel but provides an additional rigidity to the frame.

In this situation, due to the repeated humidity fluctuations and resulting compression set of the back of the panel, a double curvature toward the painted side is expected [1]. The early occurrence of a crack, about 10cm long running from the upper edge on the left (observed from the painting side), has modified this pattern, yielding a more complex shape with a maximum deflection of 11mm on the left of the panel. Detailed information on the panel structure, including an analysis of the ring and crack orientation based on X-ray and optical images will be found in [5]. In October 2004, during a session where the painting was removed from the showcase, the 3D shape of the panel was recorded using the shadow moiré method [6], with or without the frame removed. The precision of the measurement was sufficient to obtain deflection and curvature fields corresponding to the removal of the crossbars [7]. During the same day, the forces applied by the upper and lower crossbars were recorded (see Fig. 2), and an automatic reading of the central deflection was implemented. The temperature and relative humidity in the immediate vicinity of the panel has been also recorded systematically, both within and outside the showcase. At various stages, the panel was weighted. The precision was not sufficient to give any information on the sorption kinetics but provided an estimate of wood density of about 0.45 kg/cm^3 , a reasonable value for Poplar [8]. The recorded hygrothermal fluctuations were used as input for a hygromechanical simulation using a 1D or 2D version of Transpore software [9], giving predictions for the reaction of a panel portion in the two extreme situations of free or blocked curvature [10].

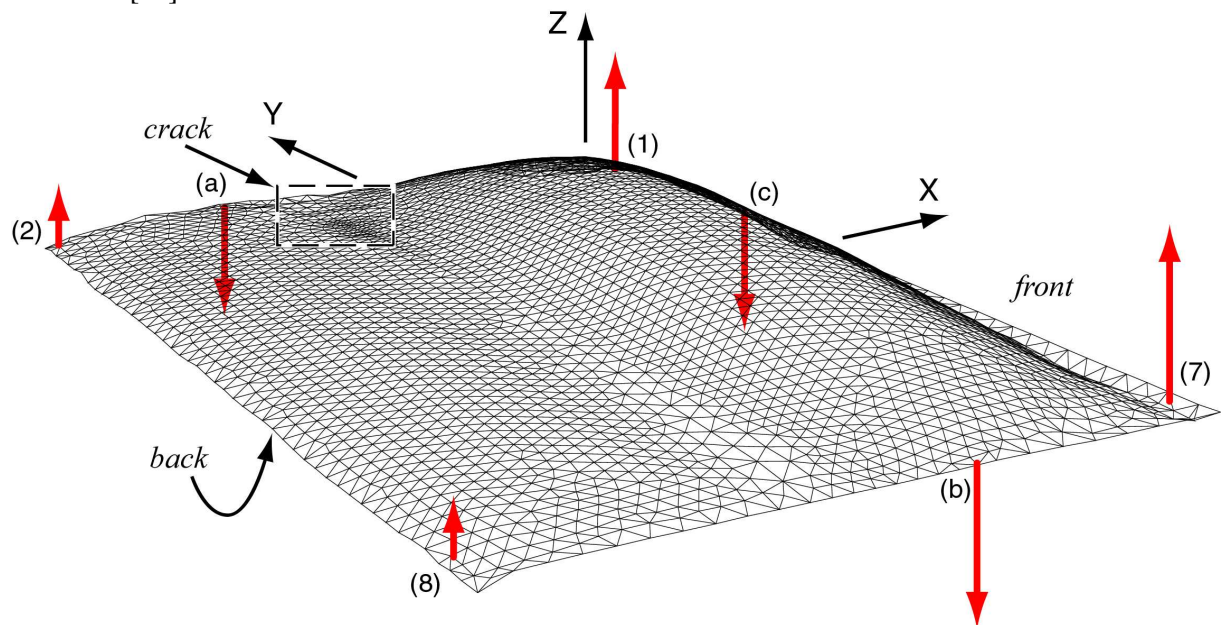


Fig. 3 Finite elements mesh of the panel and applied boundary conditions.

Mechanical formulation

Using a part of this available information, a numerical model was developed [11]. The panel is represented as a parallelepiped 787mm high, 531mm wide and 13mm thick. The crack is placed at 211mm from the left edge (seen from the front), is 117mm long, and is perpendicular to the panel plane. Figure 3 shows a finite elements meshing of the panel considered as a thin plate. The initial deformation was introduced from the measured form derived by shadow Moiré on the panel back. The wood grain is assumed to be straight. To evaluate the orientation of the rings, we locate the pith at 50mm from the median axis of the back of the panel. The thinning in the area of the dovetail shaped braces, inserted to secure against a crack extension, has not been taken into account. The wood is assumed to be an elastic orthotropic solid with the following values for elastic constants of the wood: Young's moduli (GPa) $E_L = 10.06$, $E_R = 1.19$, $E_T = 0.58$; Poisson's ratio (%) $\nu_{LT} = 47.0$, $\nu_{LR} = 35.6$, $\nu_{RT} = 70.3$; shear moduli (GPa) $G_{TL} = 0.64$, $G_{RL} = 0.86$, $G_{RT} = 0.20$. In the numerical model, the

transverse anisotropy was taken into account approximately by introducing transverse isotropic behaviour dependent on the x position (see Fig. 3), calculated for the tangent plane.

On the back, the panel is subjected to forces from the upper and lower crossbars in the four zones labelled (1)–(2)–(7)–(8) in Fig. 2 and shown in Fig. 3 by the upward arrows. Reactions (a) and (b) from the frame occur toward the painted side, at the level of the upper and lower edges. Restorers have drawn attention to an additional contact point (c), located more precisely on the left side 235mm from the top. In the lack of direct observation, precise location of (a) and (b) is somewhat problematic, and happened to be a very sensitive parameter for the computation. We have provisionally taken their locations to be 365mm and 185mm from the left edge respectively. The fulfilment of the equilibrium conditions thus give us values for these three reactions at the contact points.

RESULTS AND DISCUSSION

Deformation of the panel induced by the frame

Figure 4c shows the displacement of every point in the mesh affected by the application of the forces indicated in figure 3. This simulation is compared to two shadow Moiré observations. To allow the comparison, all displacements are calculated from the mean plane passing through the top and bottom edges. A reasonable agreement is obtained, both qualitatively and quantitatively. This is all the more remarkable as no adjustment was made to the values of elastic constants. Differences remain, which may partly be explained by sensitivity to measuring conditions.

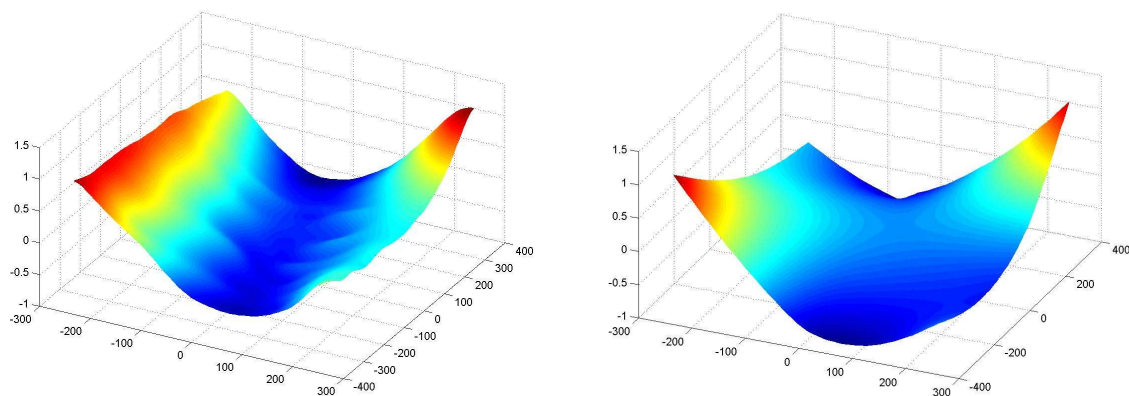


Fig. 4 Comparison between the simulated deflection induced by the frame (right) and that measured by shadow Moiré (left). The coordinates are given in mm, with the origin at the centre of the panel observed from the front (i.e., with the split upper left). The displacements are counted positively towards an observer of the painting.

To improve these results, it is possible to improve the evaluation of local panel rigidity, either by taking better account of thickness variations or grain orientation, or by adjusting the elastic constants. Even so, the most sensitive area in this simulation is probably the localization of the contacts on the edges.

The approach presented here assumes that the paint layer has only a negligible role in the panel rigidity, and therefore reacts passively to the strains imposed by the support. The strain generated by the action of the frame was evaluated at the level of the painted surface [11], showing an interesting correspondence with the cracking network in the paint layer [12]

Evaluation of the crack propagation risk

This problem will be approached within the framework of the Griffith theory, originally developed for glass [13]. Even if it is not applicable for wood, given its composite and viscoelastic nature, the theory may provide useful orders of magnitude. A small extension of the crack, under a constant loading, would induce a partial release of the elastic energy stored in the structure. According to Griffith, the crack cannot propagate if the elastic energy release rate G , ratio between energy decrease and crack surface increase, is lower than a certain critical value G_c .

The critical energy release rate G_c is in principle an intrinsic property of the material but depends on the cracking mode (mode I = opening; mode II = in-plane shear; mode III = antiplane shear or “tearing”). Moreover, with an anisotropic material like wood, it is essential to consider the crack plane and the direction in which it propagates. In the present case, the crack is located in a radial plane, and it is likely that any future propagation would occur in the grain direction. On the other hand, the present cracking mode is unknown, even though in the case of a thin panel mode III is the most expected.

The zoom in figure 5a suggests that the crack is indeed subject to mode III under the external loading, which is confirmed by the curves of displacement discontinuity in figure 5b. At the level of the upper edge, the calculation predicted a rise of about 0.15mm of the left of the crack compared to the right side. A small mode I opening was also found, of the order of 0.01mm, at the upper edge, resulting from the initially non-flat shape of the panel. We can therefore estimate the energy release rate G by calculating the effect of a small increase in the length of the crack. In our case a value of 8.7J/m^2 was obtained, which is very much lower, by almost two orders of magnitude, than the critical values normally encountered in wood. In other words, this simulation suggests that under normal conditions the crack will not propagate.

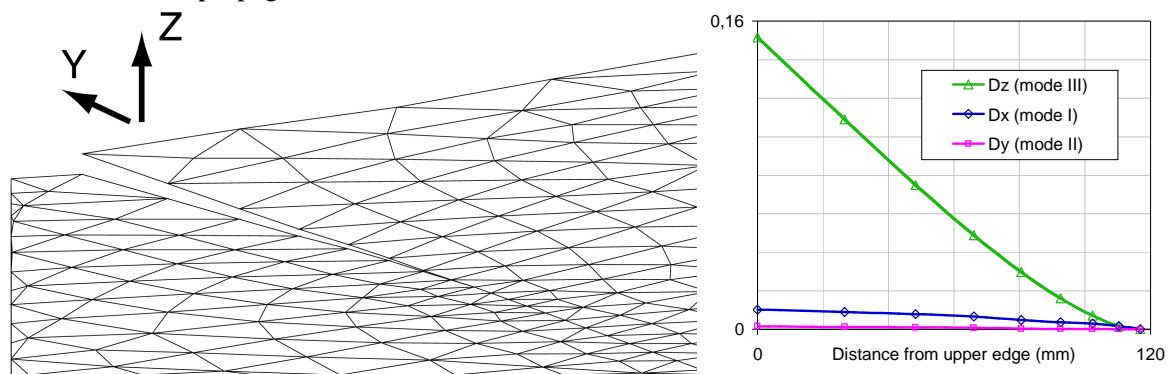


Fig. 5: Effect of the crossbars on the panel close to the crack lips. (a) Close-up view of the deformed mesh around the crack (left) and (b) displacement discontinuity along the crack lips (right)

The additional effects of hygrothermal variations

Hygrothermal variations induce variations of panel curvature by superposition of several phenomena. Heat and mass transfer, as well as viscoelastic and mechanosorptive behaviour should be taken into account in the model to evaluate correctly the panel behaviour. At this stage, we will use a simplified analysis to assess the order of magnitude of the fluctuations in the applied forces. According to simulations shown in [10], the torque per unit length (m) generated by a full restraint of the panel curvature may fluctuate, in extreme cases, within a range of $\pm 20\text{Nm/m}$. Considering that beyond a certain height h from the upper and lower edges the panel is entirely blocked by the corresponding crossbar on its width L , a force fluctuation ΔF applied to the extremities of each crossbar can be obtained as follows. Let us consider a beam cut in the transverse direction corresponding to the zone “blocked” by the crossbar, of width h , and length L equal to the width of the panel. Under the effect of the torque $m \times h$ acting on the entire beam, it would bend with a deflection $f_1 = (m \cdot h \cdot L^2) / (8 \cdot E \cdot I)$, where E is the elastic modulus of the wood in the axial direction of the beam and I its section second moment of area. On the other hand, a force ΔF applied on the two extremities of the beam, with a reaction at the centre, would produce, by three points bending, a deflection $f_2 = (\Delta F \cdot L^3) / (12 \cdot E \cdot I)$. Assuming $f_1 = f_2$, we obtain the force necessary to block the action of the torque generated in the beam: $\Delta F = 3 \cdot m \cdot h / (2 \cdot L)$. Taking $L = 0.5\text{m}$ and $h = 0.05 \sim 0.25\text{m}$, we obtain $\Delta F = 3 \sim 15\text{N}$, values to compare with the measurements of $7 \sim 23\text{N}$ obtained in October 2004.

Although too rough because it does not take into account the longitudinal forces, this approximation suggests nonetheless that variations in humidity may cause significant fluctuations in the forces applied by the crossbars, although they should not modify their order of magnitude. In terms of additional risk of crack propagation, there is probably no cause for concern, especially if in the future the level of fluctuations is greatly reduced.

However, it is essential to remain extremely careful, given the simplifying assumptions involved in this calculation. In particular, the analysis does not take into account local effects in the crack tip area. The role of the braces has also been entirely passed over. They prevent a wide crack opening, but at the same time the required thinning may have weakened the panel. The contribution to panel rigidity of the paint layer should also be considered. In any event, analysis will need to continue and be refined in order to take advantage of all the information available, and the greatest caution is required for the practical conclusions.

CONCLUSION AND PERSPECTIVES

The campaign of observations and experimentations initiated in October 2004 has filled some important gaps in our knowledge of the wooden support of Mona Lisa. The information collected has allowed us to obtain essential data on the panel structure and shape, its loading and its deformations in response to variations in temperature and humidity. In addition, devices have been put in place for the continuous recording of forces and camber, thereby permitting better monitoring of the picture. The information gathered will permit to take steps towards developing mechanical models both to accompany the monitoring and to improve our understanding of the panel history. While the crack appears to present no risk from the 2-D analysis, this needs to be confirmed by a 3-D analysis, which should include the viscoelastic and hygrothermal behaviour of the material. The predictive study, conducted after validation of the model, may lead to proposals for modifying the frame attached to the back. These should take into account data on the behaviour of the paint layer in relation to the support.

Acknowledgments

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