Studies on the Conservation of the *Mona Lisa*: numerical methods for future preservation.

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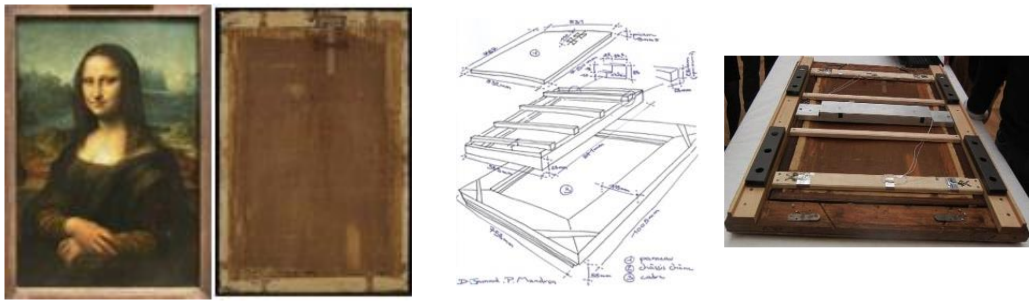
Background and objectives

Since 2004, the *Mona Lisa* painting by Leonardo da Vinci has been studied by an international research group of wood scientists and several experimental campaigns have been carried out to understand its characteristics and provide suggestions for its conservation. Based on the collected data, a numerical model of the wooden panel has been developed to simulate its mechanical interaction with the framing system. The main objective of this modelling work, described in this paper, is to extract as much information as possible from the experimental tests carried out, and thus reach a sufficient level of scientific knowledge of the mechanical properties of the panel to build a predictive model. The model can be used to predict the effect of modified boundary conditions and as a tool for preventive conservation.

The artwork is painted on one face of a flat-sawn poplar (*Populus alba* L.) (Fig.1a) panel doubly curved (longitudinally and transversally) towards the front face and pressed against the rebate of the auxiliary frame by the action of crossbars screwed on such frame (Fig.1b) ; the external frame contributes to the stiffness of the whole through metal brackets (Fig 1c). An ancient crack runs through the wood thickness from the left upper edge of the panel down to the Lady's forehead.



(a) (b) (c)

Fig. 1 : Mona Lisa panel painting (a) Painted face and back face; (b) Exploded view of the panel and its framing system (auxiliary frame with crossbars and gilded frame) until 2005; (c) Back face of the complete assembly in 2021, also showing some of the monitoring equipment

The observation methods, partly described in early reports (Mohen et al 2006, Gril et al 2015), include: (i) optical measurements of the shape (Brémand et al 2011); (ii) scientific and technological analysis of the wooden panel; (iii) continuous monitoring of the forces applied by the crossbars on the back of the panel, and of the deflections at mid-height with respect to an aluminium profile equipped with transducers (Fig. 1c); (iv) identification of contact areas between the front margins of the panel and the auxiliary frame's rebate using pressure-sensitive film (Goli et al. 2013).

Material and Methods

The multidisciplinary approach that characterized the entire project has also been adopted for the numerical modeling of the panel. The modeling has been developed to answer two concurrent parallel questions:

1. To obtain as much information as possible from the experimental tests, thus extracting from them a deeper level of knowledge.

2. To build a predictive model of the behavior of the panel, to better understand its tensional and deformation states.

In this logic we have, firstly, focused on the use of modeling to couple experimental results and numerical methods to calculate the stiffness characteristics of the panel in a totally non-invasive way. The knowledge of the stiffness of the panel is a parameter of extreme interest; in fact, once the stiffness is known we can understand the deformation and tensional behavior of the artwork and its state of conservation. Usually, to determine the stiffness of a wood sample, invasive and sometimes destructive tests are used; in the case of the *Mona Lisa*, an ad hoc protocol has been developed to ensure completely non-invasive and respectful tests. Specifically, extremely slight approaches of any individual load cell towards the panel made it possible to detect small increases in force in all the cells and displacements in the transducers placed at mid-height of the panel. These variations were processed by means of a FEM simulation of the panel which made it possible to compute the actual stiffness of the panel itself. For this method to be considered reliable, it is necessary that the simulation model matches very accurately the physical reality of the panel. To achieve this goal the following steps have been implemented:

1. The shape of the panel has been reconstructed based on optical measurements.

2. The contact areas and pressures between the panel and the auxiliary frame have been precisely detected.

3. Some specific aspects of the panel's structure (e.g. its cylindrical symmetry and the position and geometry of an ancient crack) have been identified by technological analysis.

Results and discussion

The stiffness characteristics of the panel's wood are shown below and compared with data from the literature.

Model	E_L[MPa]	E_R[MPa]	E_T[MPa]
Numerical	9.7	1.39	0.83
Literature (Guitard, 1987)	10.1	1.19	0.58

Our model, which at this point is a Digital Twin (DT) of the original panel, is strengthened by the real characteristics of the material and reacts to forces and stresses in a way similar to the original panel; it makes it possible to evaluate the internal stress states in the panel's wood, and to test new possible framing configurations, without exposing the original artwork to any risk.

The first application studied is the modeling of the stresses and deformations orthogonal to the grain: both are in a safe range for the artwork, in its present conservation conditions.

Subsequently thanks to DT the dynamics of the ancient crack and the probability of its propagation have been studied in the light of Griffith's theory. Confirming a previous study (Gril et al 2006), the possibility of propagation of the crack appears remote in the current conservation situation.

Another application concerns the possibility of inserting a polymer foam between the panel and the auxiliary frame. In addition to the fact that there would be a decrease in the risk of damage to the paint's crests, the application of DT has shown a decrease, although low, in the stresses at the crack's tip.

Last but not least, based on the DT a device conceived to maintain the forces acting on the panel into a safe range and integrated in the auxiliary frame's crossbeams, has been proposed.

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