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Learning from Objects: the use of advanced numerical methods to exploit a complete set of information from experimental data, for the Mona Lisa's Digital-Twin

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Abstract. The approach to wooden artefacts of historical importance, and panel paintings in particular, is a task that requires a multidisciplinary approach based on experimental observation of the artwork and advanced techniques to make these data actually useful for the knowledge and preservation of the object. This study illustrates how a series of scientific observations and instrumental analyses can be used to construct a numerical simulation that allows a deeper understanding of the physical structure and behaviour of the object itself, namely to construct a hygro-mechanical predictive model (a “Digital-Twin”) of Leonardo da Vinci's Mona Lisa panel. Based on specific request from the Louvre Museum, a group of experts with different and complementary skills cooperated and are still cooperating to construct a complete set of experimental observation and non-invasive tests; so, the integration of the collected data made the construction of the panel's Digital-Twin possible. This paper also specifically examines how the Digital-Twin can be used to compare two framing conditions of the panel; although the two experimental configurations are not inherently comparable, the comparison is made possible by the introduction of a technique of projection of the fields obtained as results of the two analyses, named the Projected Model Comparison (PMC), which has been developed specifically for this research.

Introduction

Since 2004, the wooden panel on which Leonardo da Vinci painted his “Mona Lisa” has been studied by an international research Team, and several experimental campaigns have been carried out to understand its mechanical, hygroscopic and shape characteristics and behaviour, to evaluate its present state of conservation, and provide related suggestions in order to optimize its conservation.

The artwork is painted on one face of a flat-sawn Poplar (*Populus alba* L.) panel, doubly curved (convexity towards the front face), and pressed against the rebate of the frame (in French *châssis-cadre*, an intermediate frame, see Fig. 2) by two crossbars screwed onto the frame itself. The *châssis-cadre*,



with the panel inside, is placed and fixed by metal brackets in a sculptured and gilded external frame, which significantly contributes to the stiffness of the system. An ancient crack runs through the wood from the upper edge of the panel down to the top of the Lady's forehead.

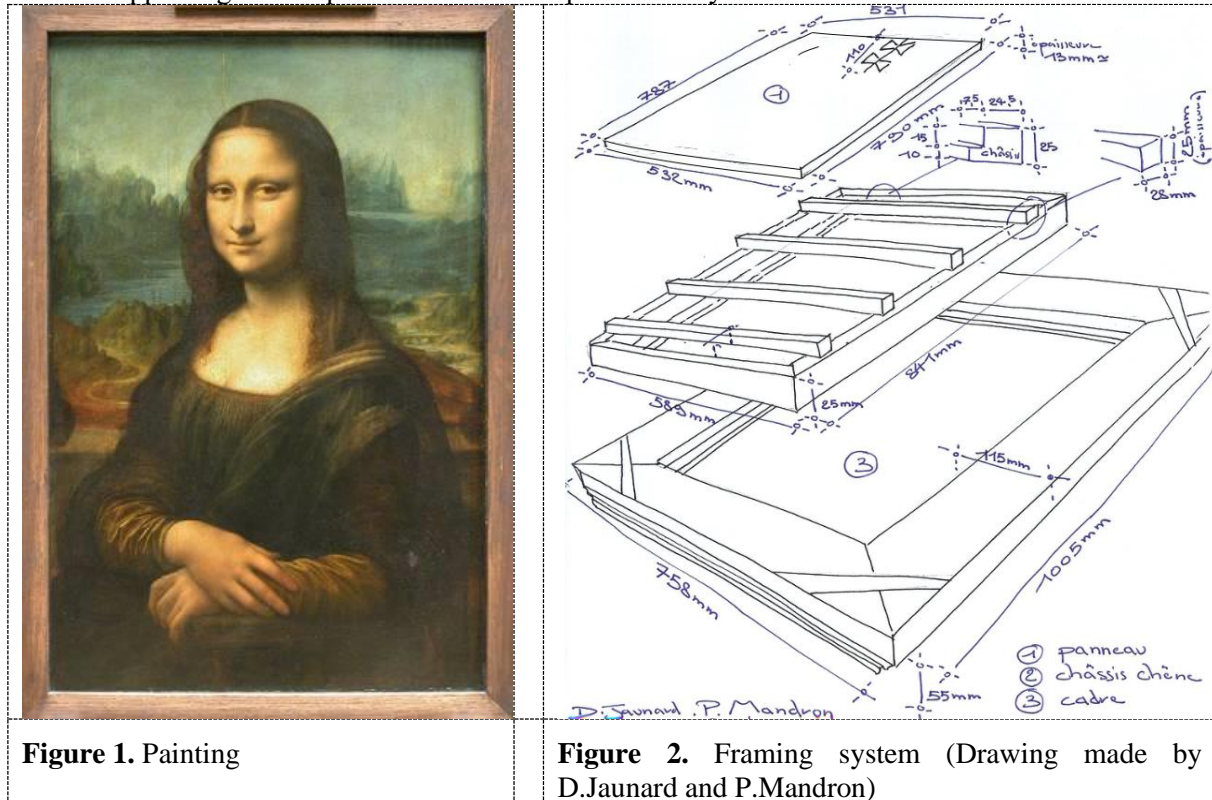


Figure 1. Painting

Figure 2. Framing system (Drawing made by D.Jaunard and P.Mandron)

The team, formed by specialists in wood science and technology (LMGC of Montpellier and DAGRI of University of Florence) and in optical measurements (PPrime Institute, University of Poitiers), closely interacted with the curators, the scientists from C2RMF and with the restorers taking care of the artwork, and approached the work according to the following four main tightly intertwining topics:

- studying the artwork by direct observation and measurements (once a year, during the few hours when it is removed from its climate-controlled exhibition case, for the routine inspection of its conservation conditions, or for the execution of exceptional measurements);
- analysing the propagation risk of the fracture [1];
- monitoring the behaviour of the panel during its permanence in the exhibition case, by special ad-hoc equipment, conceived and implemented specifically for this task [2];
- developing and calibrating a numerical model (a so called "Digital-Twin"), capable of reproducing accurately the original artwork's reactions to simulated external stresses (hygroscopic and mechanical) that might (actually or potentially) affect it.

The observations methods include:

- (i) scientific and technological analysis of the wooden panel, including wood anatomy, macrostructure and physical and mechanical properties;
- (ii) optical measurements of its shape [3];
- (iii) continuous monitoring of the forces acting on the panel and of its deformations;
- (iv) detection and description of contact areas between the panel and the *châssis-cadre* using pressure-sensitive film.

In the course of fifteen years, the team's knowledge about the panel has progressively increased along with measurement and modelling techniques; based on the collected data, numerical models of the wooden panel have been developed to accurately simulate its hygro-mechanical behaviour and its constraints.

The aspect that the authors want to emphasize in the present paper is that numerical modelling tools are also being used in order to enrich experimental investigations, thus allowing to reach deeper information levels.

1. The Digital-Twin and its meaning

The general problem that arises in the modelling of a panel painting is the need to correctly understand its hygro-mechanical characteristics and structure and based on that give information to the conservators, always keeping the artwork undamaged; which makes mandatory the use of non-invasive technologies for their characterization. At the same time, the uniqueness of the artworks (inter alia due to the variability of wood, the interaction between the elements composing the system, the conservation history including restoration works executed in the past), makes it difficult to apply literature parameters in the definition of a predictive numerical model. In any case, understanding the stresses and strains acting on the actual art piece is of great interest for its conservation and for the study of potentially dangerous conditions. For these reasons the systematic series of non-invasive experimental observations made on the Mona Lisa panel aimed towards, and made it possible, to develop a numerical model totally calibrated on the artwork itself.

The model was calibrated by means of the following non-destructive measurements [4]:

- the shape of the panel was derived from optical surveys and reconstructed in a numerical three-dimensional model;
- the boundary conditions, i.e. contact zones and pressures between the panel and the framing components surrounding it, have been detected using *ad hoc* developed techniques, and then have been transferred within the three-dimensional model;
- through visual anatomical observations and results from X-ray investigations, the local principal directions of the wood at each point of the panel have been reconstructed, and this made it possible to construct a model consistent with the anatomy and the stiffness of the actual wooden board;
- from the load cells readings, it was possible, through an optimization process, to calculate the actual stiffness characteristics of the wooden panel (including the contribution of the preparation and pictorial layers).

In-depth studies are available in the literature that examine the fundamental aspects of the above methods [5,6,7,8].

The present paper focuses on the study of contact areas in various configurations, necessary for the correct modelling of the panel, and on analytical techniques to compare the results of two numerical analyses representing two different mechanical conditions.

2. Materials and Methods

2.1. Experimental campaigns on contact areas

Two experimental campaigns were conducted to investigate the areas of contact between the panel and the *châssis-cadre*. In the first one (performed in 2012) the panel was directly in contact with the wood of the *châssis-cadre* [9]. In the second one (performed in 2016), the effects of the interposition of a closed cell polymer foam (Plastazote©) between the wood of the panel and the *châssis-cadre* were investigated [data still unpublished].

In order to identify and evaluate the contact zones, in both cases a pressure sensitive film (LLLW Ultra Super Low Pressure, two-sheet film, Fujifilm Prescale®) was used to perform some totally non-invasive tests: strips of the film were placed on the rebate surface of the *châssis-cadre*, and the panel was carefully inserted and pressed during the prescribed short time (few seconds), reproducing the actual assembly situation, and then disassembled. Red patches appear on the film at the contact areas, and the level of pressure is indicated by the density of the colour (Figure 3).

The restraining forces are applied by the crossbeams on the back the panel, near its four corners, in order to partially contain its tendency to cup; four miniature load cells continuously measure these forces, and the data are fed into a continuous recording system [2]: this arrangement makes it possible to have available both the contact profiles and the four forces balancing the contact forces, in other words to have under control the whole system of the boundary conditions and the forces acting on the panel.

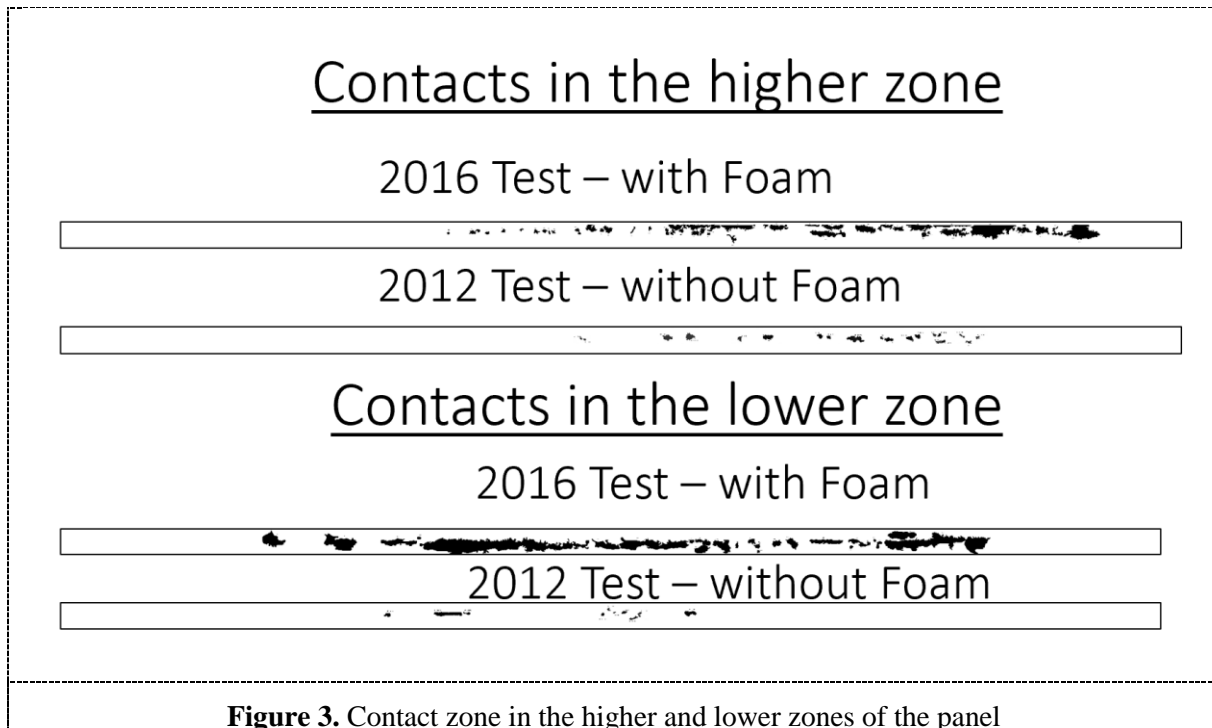


Figure 3. Contact zone in the higher and lower zones of the panel

Figure 3 shows the difference between the contact areas in the two configurations, with and without Plastazote: since the total forces measured by the load cells are of the same order of magnitude, whereas the contact areas are quite larger in the 2016 tests (with Plastazote), it is evident that the contact pressures must have a very different intensity in the two cases. Unfortunately this difference does not result from the figures shown, both because these are in black and white, and because two different types of films have been used, with different sensitivities.

2.1. Numerical modeling

The interpretation of the above results made it necessary to create an *ad hoc* FEM model, since it was not possible to evaluate the stresses and strains resulting from the two constraint configurations from the mere observation of the patterns of stains. An elastic orthotropic model was therefore developed, respecting the constraints represented by the contact areas identified by the tests and the forces measured at the points on the back where the load cells are located. This model is only an approximation as far as viscoelastic behaviour is concerned, but it is efficient in representing (“photographing”) the mechanical situations of the panel in both specific cases of the test by applying the experimentally detected conditions.

The shape of the panel was determined by optical methods by the PPrime Institute and based on these measurements a three-dimensional model was built within the open source ecosystem Salome-Meca.

The two obtained solid models, one for each test, of the panel were enriched with the contact areas detected during the Prescale campaigns, by partitioning the surface of the geometry concerned.

The two different models were subsequently meshed with a Netgen algorithm, always within Salome-Meca, as shown in Figures 4-5, with mesh refinement in the zones of the contacts and of the crack.

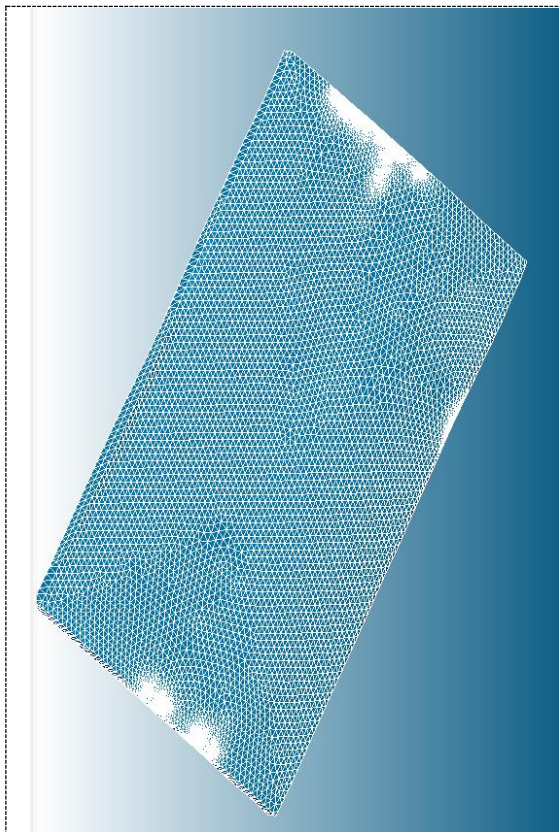


Figure 4. Tetrahedral mesh of the contact configuration of the 2012 campaign (Model A)

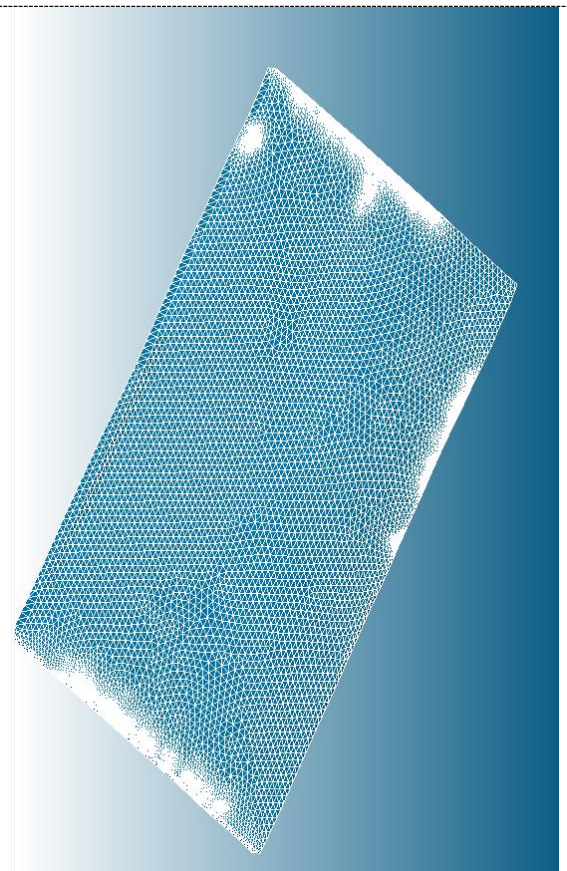


Figure 5. Tetrahedral mesh of the contact configuration of the 2016 campaign (Model B)

Two numerical models have therefore been created:

- Model A, based on the 2012 Prescale campaign consisting of a second order tetrahedral mesh of 368125 volume elements;
- Model B, based on the 2016 Prescale campaign consisting of a second order tetrahedral mesh of 430833 volume elements.

The FEM solution has been realized with the open source solver, code_aster [10], developed by EDF, for both cases in orthotropic linear elasticity with the mechanical characteristics of the wood, derived from [11], and the pressure data derived from the Prescale tests.

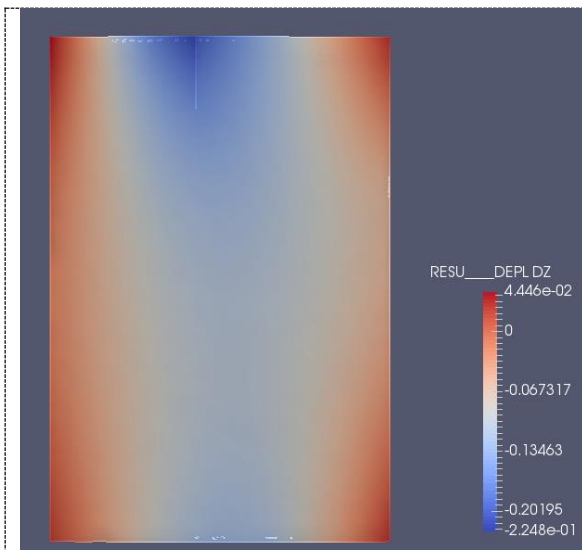


Figure 6. Model A: results in terms of displacements in the direction perpendicular to the panel [mm]

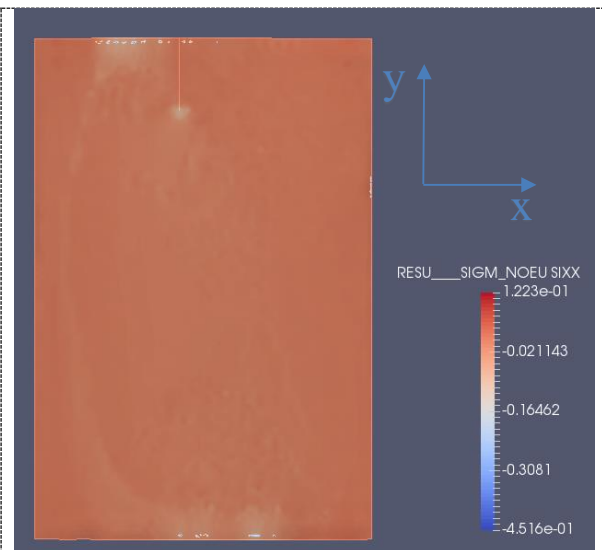


Figure 7. Model A: results in terms of stresses perpendicular to the grain in the plane of the panel (horizontal direction or x direction) at the level of the preparation layers [MPa]

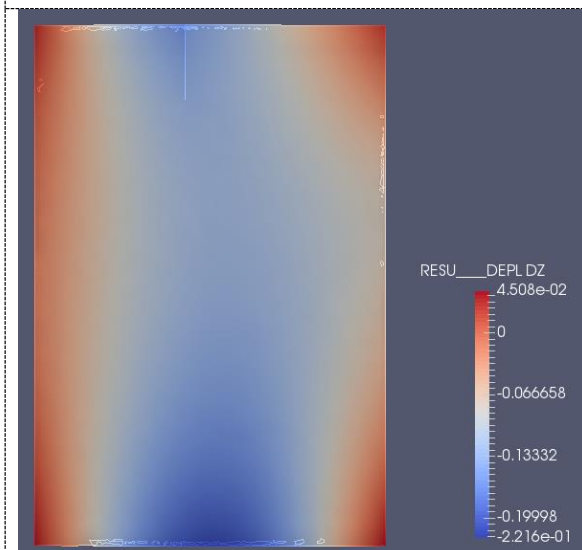


Figure 8. Model B: results in terms of displacements in the direction perpendicular to the panel [mm]

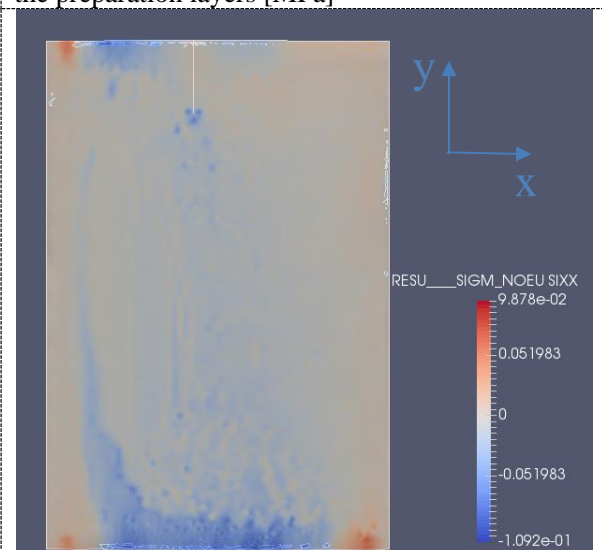


Figure 9. Model B: results in terms of stresses perpendicular to the grain in the plane of the panel (horizontal direction or x direction) at the level of the preparation layers [MPa]

3. Analysis of results and further processing

The analyses, whose results are shown in Figures 6-9, indicate that in both cases the stresses are in a safe range, considering the stresses in the wood are definitely smaller than the failure stresses reported in the literature (2.8÷5.14 MPa, bending) [12]; however, further investigations are necessary to understand the differences between the two solutions, i.e. to compare two results based on two different mechanical models.

These two models are not directly comparable because the sum of the reactions applied by the load cells in z direction (normal to the panel) for each model are different:

- Model A: Sum of reactions 51.92 N
- Model B: Sum of reactions 74.27 N

In order to clearly interpret the differences between the tensional states of the two configurations, a technique of projection of the fields obtained as results of the two analyses, here named the Projected Model Comparison (PMC), has been developed specifically for this research. Here follows a concise description of PMC.

After having normalized the two fields with reference to the constraint reactions listed above, a new mesh of comparison was created, and the numerical field of the model A was projected on such new mesh after normalization, while the model B was projected without manipulation (Figure 10).

The numerical technique used for the projection of a numeric field from the original mesh to the comparison mesh is based on the following steps for each node of the comparison mesh [13]:

1. We determine the element of the original mesh that contains the node of the comparison mesh.
2. We determine the position of the comparison node within the element identified in step 1, taking into account the fact that the meshes are non-linear, varying the jacobian of the geometric transformation on the element.
3. We use the shape functions of the element of the original mesh in the point of step 2 to determine the field value at the point determined in step 2.

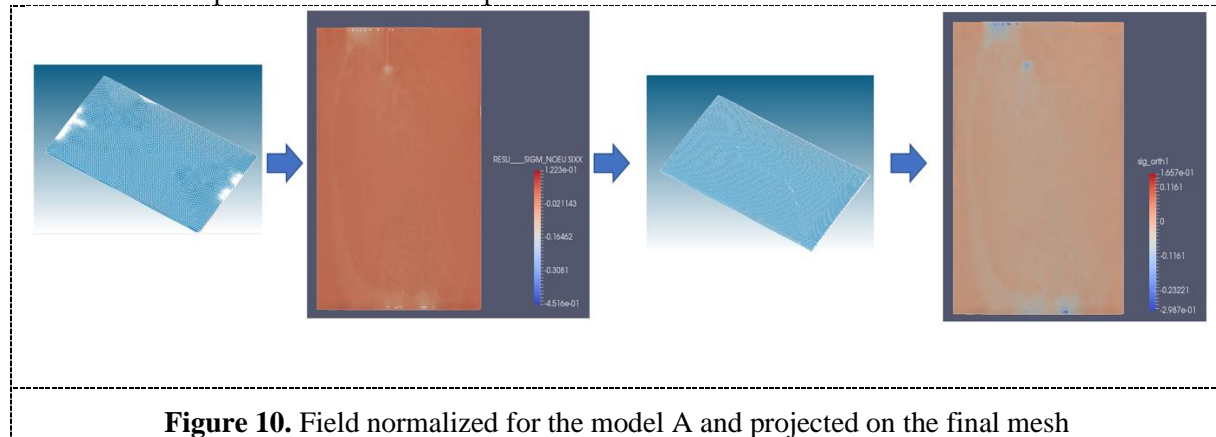
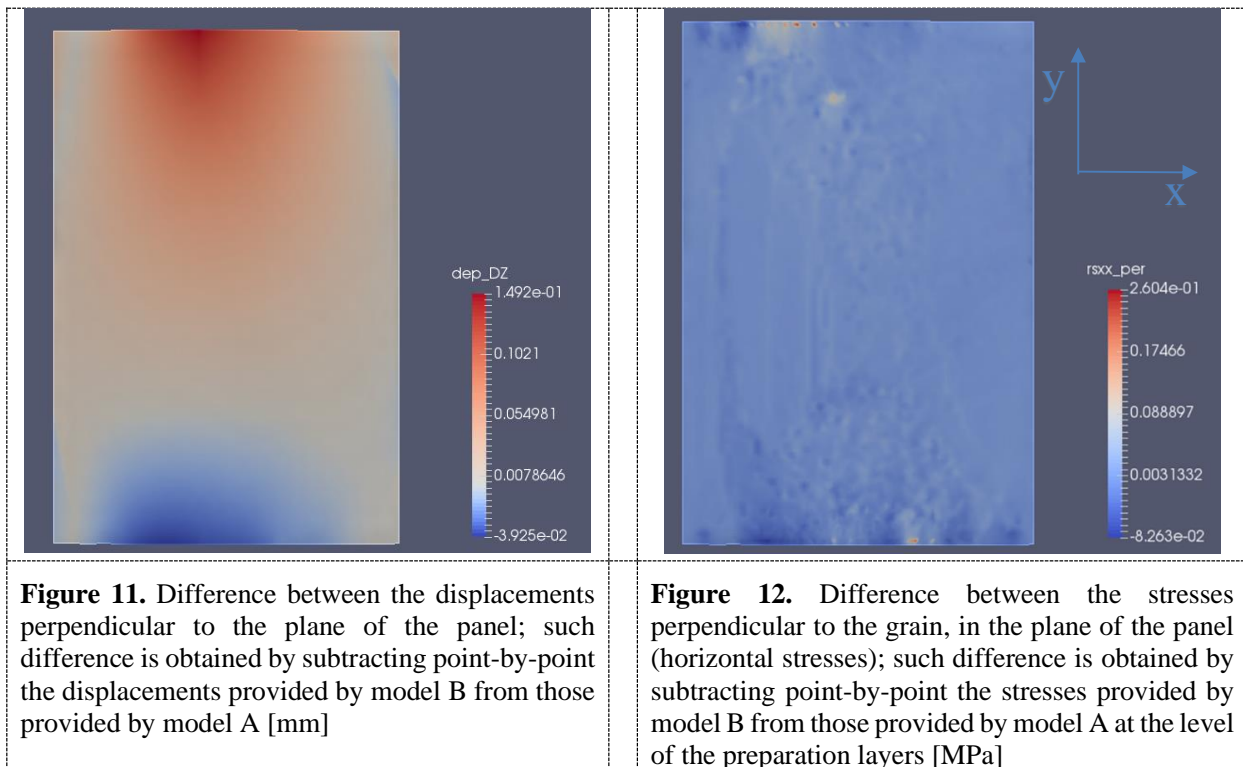


Figure 10. Field normalized for the model A and projected on the final mesh

In summary, two meshes are generated, geometrically identical, containing the values of displacements perpendicular to the panel, and of stresses perpendicular to the grain in the plane of the panel, at the same nodes, one for each case, i.e. with and without Plastazote between the panel and the *châssis-cadre*. Another model was then created, for comparison, cross-checking the data fields of the previous models, creating a point-to-point function between the two states of the panel, i.e. with and without the foam. Here a simple function, valid in this case where displacements and bending deformed shape have everywhere the same direction, has been used point by point, extended to the entire 3d volume of the panel:

$$f(\text{point_to_point}) = |\text{value model A}| - |\text{value model B}|$$

This procedure makes it possible to highlight the differences between the two models, with respect to the displacements and stresses they provide.



In Figures 11 and 12 the red-coloured zones show where and how much the displacement/stress provided by model A (without Plastazote) is greater than the one provided by model B (with Plastazote); the reverse is true for blue-coloured zones. In particular, Figure 11 shows that (possibly due to the increase in the contact area) the presence of Plastazote leads to a decrease of the displacements (perpendicular to the plane of the panel) in the upper part of the panel, where the fissure is located; while the opposite behaviour (displacements increase) occurs in the lower part, where no fissures are present. Figure 12 in turn shows that due to the presence of Plastazote the stresses (perpendicular to the grain, in the plane of the panel in the wood situated in the contact zone with the preparation layers) tend to increase very slightly (one order of magnitude lower than the stresses of Figure 7, model A) throughout the whole panel, except in the following very restricted areas, identified by very small red spots, where instead the stresses decrease: (i) in the upper part of the panel, along the edge of the rebate of the *châssis-cadre*, where the contact pressures between *châssis-cadre* and panel are larger (see Figures 7 and 9) and where some very small aligned red spots appear; (ii) at the tip of the fissure, where one very small red spot appears; and (iii) on the edge of the lower rebate of the *châssis-cadre*, where one small red spot appears. As far as stresses are concerned, the above results suggest that the two configurations (i.e. without and with Plastazote) can be considered equivalent, except for the tip of the fissure, and for the small contact areas along the upper and lower rebates of the *châssis-cadre*, near which the *barbe* extends (*barbe* is the French term for the preparation and colour crest located along the contact angle between a no longer existing frame and the panel surface, formed when the work was painted [13]): here the presence of Plastazote produces a local decrease of the stresses in the wood. It should however be emphasized that these areas must be considered particularly significant for the integrity of both the panel and the pictorial layers.

4. Conclusions

The numerous and varied non-invasive experimental observations made on the Mona Lisa panel aimed towards, and made it possible, to develop the panel's Digital-Twin, i.e. a numerical model totally calibrated on the artwork itself.

Also, the Projected Model Comparison (PMC) was developed, which is a general method of comparison between the fields of two different FEM analyses, by generating 3d fields extended to the entire volume of the panel, and making it possible to combine, subtract, or generate complex functions to compare the numerical fields of the two different solutions. PMC made it possible to compare two framing conditions of the panel analysed by means of the Digital-Twin, although the two experimental configurations are not inherently comparable

This paper shows how the 3d comparison field is a point by point correlation between two different solutions, that can provide important information making it possible to compare different boundary conditions, mechanical properties, mechanical behaviour, loads (both mechanical and hygroscopic). With this method it was possible to evaluate how the possible insertion of a protective layer of polymer foam might reduce stresses in some significant areas of the panel, namely at the tip of the fissure and near the *barbe*. As far as the general state of stresses outside this area is concerned, there are no significant differences between the two configurations. The authors emphasize that the present work expresses only the evaluation of the stresses in the wooden panel and is not in itself capable of providing indication of the possible fragility of the work of art as a whole.

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