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EXPERIMENTAL AND NUMERICAL MECHANICAL STUDY OF A FRAMING TECHNIQUE FOR CUPPING CONTROL OF PAINTED PANELS COMBINING CROSSBARS AND SPRINGS

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Abstract

This communication deals with theoretical and experimental researches being carried out by the authors in order to model an actual wooden support, and its deformational behaviour, after a back frame has been applied by means of springs, in a Florentine restoration laboratory. Such a device is aimed to serve as a framing technique useful for conservation of one-sided painted boards of wooden artworks. The main outcome of such a research, still ongoing, is a calibrated mathematical and numerical model, which allows one to choose the most appropriate mechanical parameters for springs, according to expected environmental conditions, in order to achieve a balance between deformation control and stress control.

Keywords: finite elements; wood structures; hygromechanical coupling; conservation; cultural heritage

1. Introduction

A challenge for curators and restorers of panel paintings of cultural heritage is to perform restoration interventions which will contribute to the long time conservation in the best possible state. One of the main causes of damage is due to the environmental microclimatic variations, which may induce moisture changes, moisture gradients, transient and permanent deformations, stresses and damage to the pictural layers up to their decohesion from the wooden support. Wood science, specifically with the modelling of phenomena like shrinking/swelling, creep, relaxation, and mechano-sorptive effects, may help to analyze and calibrate restoration interventions, taking into account the individual painted panels and the conservation environment. The wooden supports of many Italian panel paintings, especially in Central and Southern Italy, during late-thirteenth, fourteenth and early-fifteenth century, were typically made with boards of Poplar (*Populus alba L.*) glued along their edges, to form a planking. Ground layers, paint layers and protective varnishes were applied on the support face. Frames and cross-beams were often applied on the rear face, having – among others – the function of controlling the deformations of the support due to the humidity changes. Connections between the boards and the cross-beams were of various types, including nails (clinched back into the wood to prevent their extraction), metal or wooden bridges or other devices allowing for some sliding, dovetailed joints (trapezoidal shape of the cross-beam cross-section, inserted in corresponding grooves made in the planking; sliding was not so easy, due to the large friction forces acting on the slanted edges). Although the above connections were conceived and executed to allow for some movements and to minimize damage, they could not cope with large environmental variations, taking place – just to make a few examples – when paintings were moved from original locations to museums where heating systems were installed, or when a large number of visitors severely modified the environment. Many interventions have been devised and performed in order to modify the mechanical characteristics of the connection between planking and cross-beams, and hence to reduce damage. Although based on good intentions, many of such interventions resulted in negative consequences. At present time, the soundest approach appears to try to solve the problems by controlling the environmental conditions rather than modifying the physical structure of the wooden support. However in several cases there is a need for redesign of the system of cross-beams; *e.g.* when it has been destroyed by previous interventions, or when serious accidents have severely damaged the support.

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In these cases a compromise needs to be reached: a stiff connection will prevent permanent deformations (caused by complex rheological phenomena in wood) and damages to paint layers (unable to follow the wood movements) but it may produce cracks and ruptures in case of large environmental variations; whereas a too yielding connection will be useless, being at all unable to control deformations.

An interesting new framing technique was developed at OPD (*Opificio delle Pietere Dure* – A state restoration laboratory located in Florence – Italy) consisting of a back-frame, connected to the rear of the panel with springs (fig. 1).

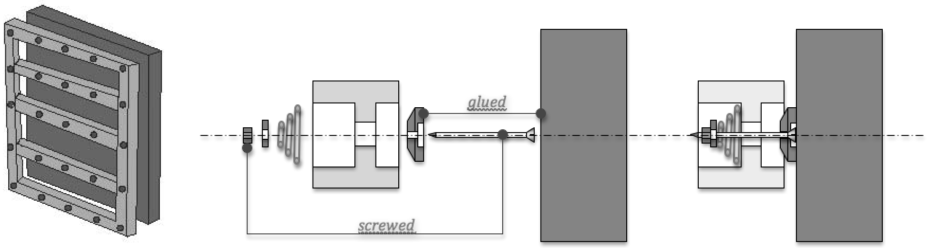


Fig. 1. Back-framing technique

The practical implementation of such a technique is quite satisfactory, and has now been adopted by several restoration laboratories; however one of the main problems, still unsolved, is the definition of the most desirable mechanical parameters of the springs, *i.e.* their stiffness and the pre-load to be used when installing them. Of course such parameters cannot be the same in any case, but need to be calibrated for each situation.

2. Modelling the frame action

A numerical one-dimensional beam model, based on finite elements, is used to simulate the frame action on panel movements (fig. 1). The panel movements are predicted by the model, with the assumption that the front (painted) face is totally impervious to water vapour, which reflects an ideal situation, where protective varnish is still an efficient continuous layer. This situation will emphasize the transient deformations caused by the presence and the evolution in time of non-symmetric moisture gradients.

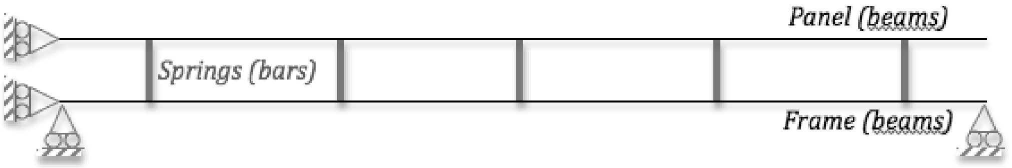


Fig. 2. Simple FE model of wooden panel with frame linked with springs

The model takes into consideration the unilateral contact conditions, the stiffness of springs and their pre-load. When the contact between frame and panel is active the contact force equals the initial pre-load. On the other case, the spring force is larger than the initial pre-load and tends to reactivate the contact. We assume here a linear relationship between the spring force and its compression (fig. 3).

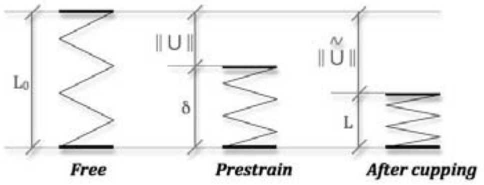


Fig. 3. Spring Force definition

$$F = (\|U\| + \delta - L).k \qquad (1)$$

$$v = (\delta - L) \qquad (2)$$

L_0 : free spring length / mm
δ : initial spring compression distance (prestrain) / mm
v : spring compression distance due to the panel cupping /mm
k : spring rigidity / $N.mm^{-1}$

The moisture distribution to the thickness is here assumed to be linear (fig. 4), though experimental results of Kollmann [4] can be used as an alternative. This assumption on the moisture variation in the thickness will lead to an overestimation of the deflection. A linear model for the swelling/shrinkage behaviour is selected.

$$\varepsilon_T = \alpha_T w\left(1-\frac{y}{h}\right) \tag{3}$$

$$\sigma_T = E_T \varepsilon_T \tag{4}$$

w : change in moisture content / %

ε_T and σ_T: strain field, and stress field / Pa

α_T : shrinkage parameter / %/%

h : board thickness / mm

E_T : transverse Young modulus of wood / Pa

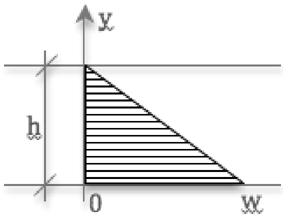


Fig. 4. Humidity gradient in the thickness

The torque Mz due to moisture content gradient in the thickness can be expressed as:

$$Mz = b\int_0^h \sigma_T\left(\frac{h}{2}-y\right)dy \tag{5}$$

$$Mz = \frac{1}{12} b h^2 E_T \alpha_T w \tag{6}$$

where b is the width of the wood piece.

The model is parameterized in order to be of practical use for curators (initial compression distance of springs, number of springs, panel dimension, wood mechanical characteristics of panel and frame…)

Note that, in this simplified model, the mechanical stiffness of the painting layer has not been taken into account. A crude homogenization estimation with two layers of different stiffness in bending leads to the following values: If the gesso is not damaged (no micro-cracks), with an elasticity modulus ten times higher than E_T, and with a thickness of 0.5 mm for 38 mm of wood thickness, the overall stiffness in bending is increased by 36 %. Taking into account this additional stiffness is not an issue, but renders the model more difficult to manage (with the requirement for a new constitutive parameter to be estimated).

3. Experimental device

In order to check and calibrate the finite element model, we designed a mock-up panel, reproducing the physical and geometrical characteristics of a real panel, which is part of a Florentine triptych presently being restored, and of the frame with springs purposely built by a restorer (fig. 5, 6).

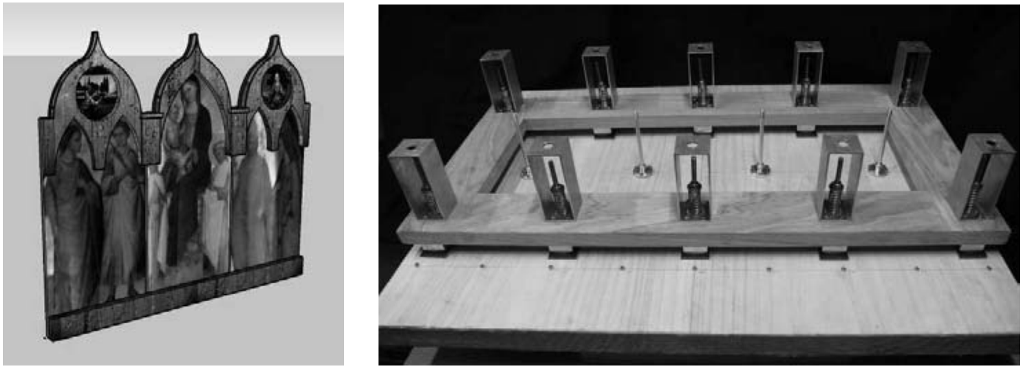
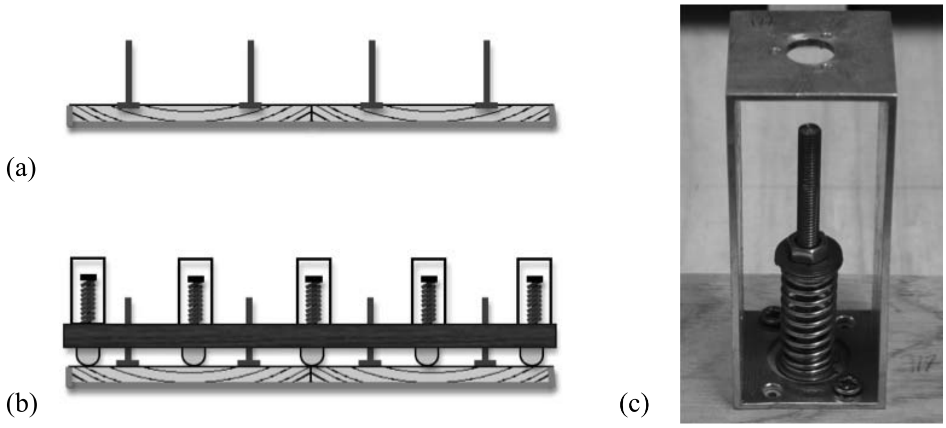

(a) (b)

Fig. 5. Florentine triptych (a) - Triptych mock-up with frame (b)

An identical mock-up panel without frame has been built as well, to provide a reference. The mock-up panels have been vapour-proofed with rubber latex on the front face (Rewultex®), simulating a protective varnish, as well as on the four lateral edges to eliminate edge effects.


(a)

(b)

(c)

Fig. 6. Reference mock-up without frame (a) – Mock-up framed (b) – Spring and displacement measuring reference (c)

22 displacement sensors can be also integrated for accurate monitoring in time of the deformations and forces in the springs, though up to the moment, the monitoring is performed manually. Moreover we measure the shrinkage/swelling at several points of both panels.

4. Results

4.1. Numerical results

The simulation concerns a panel initially at a stable humidity state which is dried by reducing the ambient humidity by 20 % (= 3 % of moisture content). The paramters used are detailed in Table 1.

Table 1- FE model characteristics

Panel (poplar)	Frame (oak)	Springs
Thickness “h” = 38 mm	Thickness = 22 mm	Number of springs = 5
Width = 768 mm	Width = 768 mm	$k = 2.4\ N.mm^{-1}$
Height “b” = 600 mm	Equivalent Height = 160 mm	Pre-load = 24 N
Weight = 8 363 g	Weight = 3 602 g	$\Delta w = -3\ \%$
$E_T = 576$ MPa	$E_T = 1027$ MPa	
$\alpha_T = 30\ \% / \%$		

The model response of such loading is showed in fig. 7:

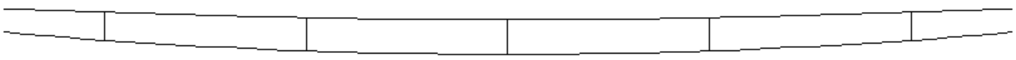


Fig. 7. Numerical solution for the drying of the panel

The maximum obtained deflection is about 16.7 mm. The maximum tension in springs is located at the middle of the panel with a value of 66 N. If the frame does not exist (frame with $E_T \approx 0$ or $k \approx 0$) the deflection is about 17.46 mm. It proves the effectiveness of the frame that has reduced the deflection by 5 %. To check the model results, we can compare with the analytical solution for the deflection (maximum value, obtained at the middle of the structure) with the following equation:

$$f = \frac{L^2.\Delta\varepsilon}{8.h} = \frac{L^2.\alpha.w}{8.h} \tag{7}$$

The analytical solution for such conditions is a deflection of 17.55 mm which is very close to the numerical result. The table 2 gives any results of the model in different conditions.

Table 2- Numerical results for various springs configuration: deflection in mm

v / mm	k / N.mm-1				
	≈ 0	**2.4**	**10**	**24**	**240**
5	***17.461***	*16.853*	*16.152*	*15.987*	*15.987*
10	“	*16.693*	*15.987*	*15.987*	*15.987*
15	“	*16.532*	*15.987*	*15.987*	*15.987*
20	“	*16.372*	*15.987*	*15.987*	*15.987*

We can notice that the frame/spring device is not very effective here. The frame structure is not so rigid and the selected springs have a low rigidy. This tends to consider the frame structure underestimation because with such apparatus we obtain a maximum reduction of the deflection by 2 mm.

4.2. Experimental results

For the experimental test we choose to stabilize the panels at the relative humidity of 65 % and at the temperature of 25 °C during one month to get a constant weight. The panels are then placed in another climatic chamber (45 % of relative humidity, 35 °C). To measure the curvature, a device using a differential length measurement ($l_2 - l_1$) is depicted on Fig. 8.

Up to now, the measurements are hand-made, so the curvature of the panels is not estimated very well. An error of $\Delta l_1 = \Delta l_2 = 5/100$ mm causes an error on the curvature of $\Delta R/R \approx 100$ % for the present device, this is why the experimental study is not yet presented here.

We have therefore planned to make an automatic measuring of every distance to increase the data precision. The error on the curvature determination is reduced to less than 10 % when using sensors with an accuracy of 1/100 mm.

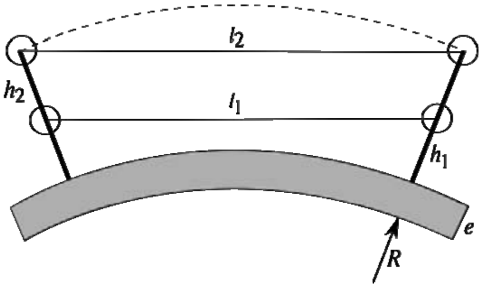


Fig. 8. Sketch of the experimental device to measure curvature of the panel

5. Conclusion

Regarding to the numerical results, we can assume that the frame has to be more rigid to be efficient. Up to now, the maximum effect (with stiff springs and a consequent pre-load) is a reduction of 12 % of the deflection. With an even more rigid frame, we expect to obtain a higher influence.

On one hand this affirmation has to be tempered by the fact that the model has not yet been checked against experimental results.

On the other hand we still have to discus the proposed changes with curators and conservators because a too rigid frame/spring system could damage the panel. A study of forces and stresses in the panel has to be carried out to get more relevant answers.

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