Time to reach the equilibrium moisture content: laboratory tests on Poplar (*Populus alba* L.) mock-up panels.

Paola Mazzanti, Luca Uzielli

DISTAF, University of Florence, Italy

Abstract

At DISTAF laboratories many tests have been carried out on Poplar (*Populus alba* L.) mock-up panels to study their stress and deformational behaviour. The main aim of these tests is to improve the knowledge of their conservation and to work out mathematical models to explain the behaviour itself.

In addition to stress and deformation measurements, weight is monitored to determine the equilibrium moisture content (EMC is the acronym) time for each tested panel. These weight data are here collected and analyzed.

Although several computer softwares allow to simulate the moisture exchange of a wooden panel, time to reach EMC, etc., the experimental data reported in this paper might be of some use to Conservators and to Researchers, since they provide indications about the actual behaviour of true physical panels.

Tests on the following panels, featuring various shapes and dimensions, are here reported:

- large panels made of “new” wood, not waterproofed;
- large panels made of “new” wood, waterproofed on the edges and on one face;
- small panels made of old and “new” wood, waterproofed on the edges and on one face;
- mock up “Medusa” shield (replica of the laminated shield on which Caravaggio painted his well-known “Medusa”), not waterproofed.

The panels have been kept in a climatic chamber at DISTAF, where the environmental conditions cyclically vary, in order to reproduce the following climates:

-dry climate: 42% RH and 30°C;

-humid climate: 85% RH and 30°C.

The adsorption, or desorption, process is monitored by periodic weighings. This paper reports the analysis of the weight data, the evaluation of the time to reach EMC, and the elaboration of the fitting curves for each of the tested panels.

1. INTRODUCTION

It is well known that when the temperature and the relative humidity of the air change, wood changes its shape and dimensions while reaching its new EMC (Equilibrium Moisture Content)..

The wooden cultural heritage objects shows the same behaviour, and as a consequence they may change shape and dimensions, or stress situation, which sometimes may lead to permanent damages.

An obvious question is: how long does it take before the new EMC is reached? Minutes, hours or days?

Giving some practical answers to the above questions is the main aim of this paper, trying to give some basic and practical informations related to mock-up panels, which may provide indications about the panel paintings behaviour.

The process is strongly influenced by many factors such as:

- the initial and final climatic conditions;
- the wood species;
- the dimensions of the panel;
- the structural features of the panel;
- the symmetry or asymmetry of the hygroscopic exchanges;

and some of these cases are discussed above.

2. MATERIALS AND METHODS

All the tested mock panels were part of other tests, some of them still ongoing; however, just the weight-versus-time data are reported here. They are made of Poplar wood (*Populus alba* L.), this choice is supported by Marette [3], who reports that during the Renaissance period in Tuscany (Italy) this species was the most utilized to manufacture the supports of the painted panels, in around 90% of cases.

The boards, chosen to manufacture the mock panels, usually originate from new wood. That helps in reducing the possible variables involved in physical and mechanical processes. Indeed, while ancient wood has a memory effect due to its history (e.g. permanent deformations due to creep or mechano-sorptive behaviour), the new wood obviously hasn't. Exceptions are specimens V and T, which are obtained by cutting an ancient Poplar shelf (dated back to the beginning of the XIX century). The wood presents some anomalies (e.g. knots or slope of grain) and among them the main one is a biotic (insect) attack, probably anobiids, no longer active. Monitoring these two specimens gives qualitative information and quantitative data useful to compare them to new wood ones.
The chosen panels have different shapes and dimensions, in order to represent various situations:

- large panels:
    · specimen A: 600 x 40 x 765 mm (LxRxT), made by gluing two boards which dimensions are 600 x 383 x 40 mm and 600 x 382 x 40 mm [2],
    · specimen B: 600 x 40 x 765 mm (LxRxT), made by gluing two boards which dimensions are 600 x 40 x 424 mm and 600 x 40 x 341 mm [2],
    · specimen C: 700 x 50 x 415 mm (LxRxT),
    · specimen D: 630 x 56 x 40 mm (LxRxT);
- small panels:
    · specimen N: 305,5 x 30 x 282 mm (LxRxT),
    · specimen V: 300x30x300 mm (LxRxT) made by gluing two boards (unfortunately the dimensions of each board are unknown),
    · specimen T: 304 x13 x 48 mm (LxRxT);
- shield mock up panel: made of two layers of lamellae 7 mm thick, that are glued to each other, the radius of curvature is 403 mm long [6].

Figure 0: the specimens

In addition to the wooden species and the shape, another factor needs to be considered, that is the asymmetry of moisture exchange due to the waterproofing induced by the painted face. That is why some mock up panels are coated on one face (more precisely, as the ancient techniques recommended for painting, the face towards the pith is covered). Actually the chosen materials -i. e. aluminium sheet or latex- ensure a complete waterproofing, while the ancient paint layers allow a partial moisture exchange due to the physical characteristic of the varnish and the presence of the micro *craquelure* on the paint layers. Of course the chosen materials cannot truly replace the original conditions, but they are useful to guarantee the asymmetry of moisture exchange and, at the same time, reduce the variables to study. Finally the edges are coated in order to eliminate the edge-effect.
Below here the list of the coated specimens:

- specimen A: covered by rubber latex layers (Rewultex®);
- specimen B: covered by rubber latex layers (Rewultex®);

- specimen N: covered by an aluminium sheet;
- specimen V: covered by an aluminium sheet.

Table 1: List of specimens.

Specimen	Long. [mm]	Radial [mm]	Tang. [mm]	Initial weight [g]	Wood	Coating
A	600	40	765	7783,50	New	Yes, latex layer
B	600	40	765	7748,00	New	Yes, latex layer
C	700	50	415	5898,00	New	No
D	630	56	40	570,00	New	No
N	305,5	30	282	1026,06	New	Yes, aluminium sheet
V	300	30	300	1107,44	Ancient	Yes, aluminium sheet
T	304	13	48	87,41	Ancient	No
Shield mock-up	radius of curvature: 403 mm thickness: 14 mm			1416,29	New	No

The tests are carried out in a climatic chamber at DISTAF. A schedule cycle is set where the Relative Humidity of the air (RH) abruptly varies from 42% (dry climate) to 85% (humid climate) and vice versa, while the temperature (T) is set on a constant value (30° C). According to the aims of this paper only the desorption part of one cycle is analyzed (see Figure 1).

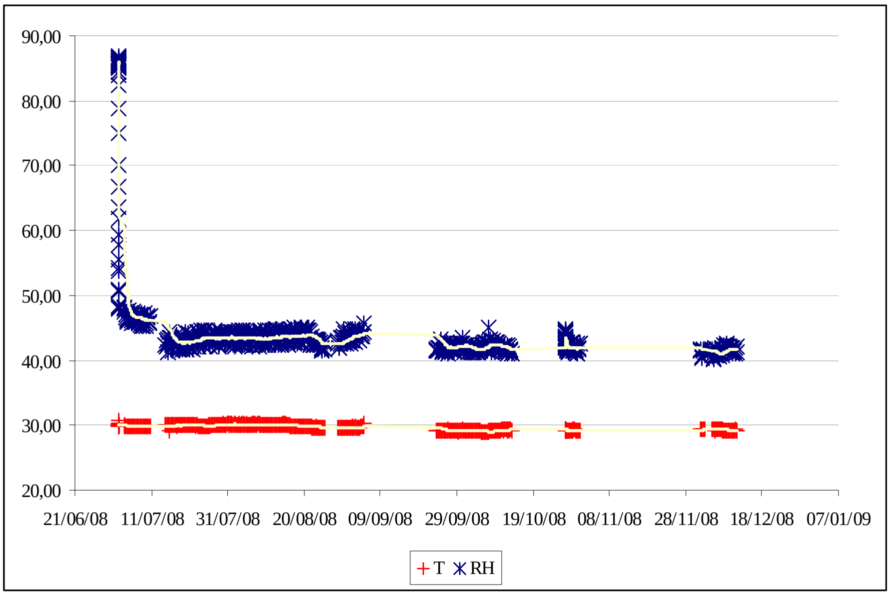

Figure 1: environmental condition set in climatic chamber.

The weight variations of the panels are monitored trough discrete weighings. Two different scales are used, depending on the panels: Sartorius QS16000B, full scale 16000 g and resolution 0,5 g, and Mettler PE1600, full scale 1600 g and resolution 0,01 g.

3. COLLECTED DATA

The collected data give information on the “equilibrium time”, which is the time needed by each specimen to reach the new equilibrium moisture content. The figures in the following pages (Figure 2-5) show the weight variations [%] of each specimen as a function of the time [days]. The weight variation is calculated as the percentage of desorbed water as to the initial weight.

3.1.Different geometry and different wood origin: specimens D and T

In Figure 2 the behaviour of specimens D and T is shown. They are two boards with different length (D is the double of T) and thickness (D is 4 time larger than T). Of course they have different values of surface and volume involved in the desorption process. Moreover specimen T is made by old wood, that was subjected to insects attack (probably anobiids), not active at the moment, that caused a decrease of wooden material. The presence of insect galleries increases the moisture exchange surface. In any case,, the interpretation of the test (see Figure 2) is clear: specimen D (because of its larger dimensions) needs much time to reach the new equilibrium moisture content, around 85 days as compared to the 60 days needed by specimen T.

3.2.Same geometry and different wood origin: specimens N and V

A comparison, useful for the study of painted panels, involves specimens N and V (see Figure 3). The two panels are alike, except for a light difference in weight (V is 81,38 g heavier than N) and the origin of the board (N is new wood, while V is ancient wood). Both panels are waterproofed, on one face and on edges, by aluminum sheet. The weight variation of specimen V is larger than specimen N, notwithstanding the damages caused by insects on the old wood. It could be due to the larger mass and higher density of the ancient specimen. By these conditions both the specimens need 90 days to reach the new equilibrium moisture content.

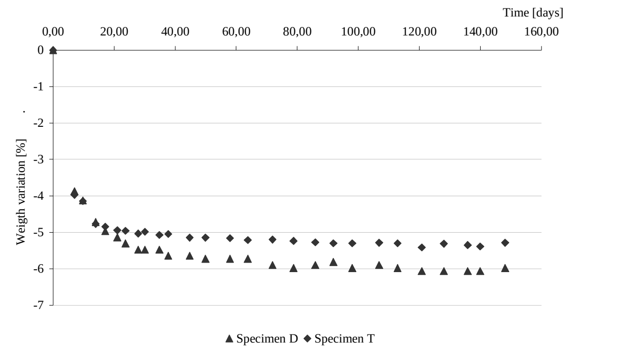

Figure 2: percentage weight variation of specimen T and D, their equilibrium times.

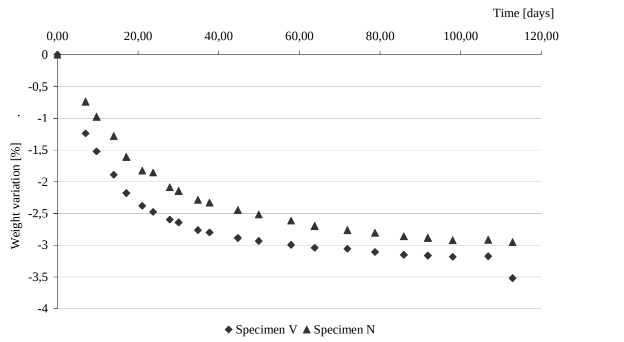

Figure 3: percentage weight variation of specimen N and V, their equilibrium times.

3.3.Replica of true painted panels: specimen A and shield mock up

Two particular specimens are the panel A and the shield mock up panel, both reproducing the structure of true ancient supports. Specimen A (see Figure 4) is a waterproofed board, which is 40 mm thick. Because of its dimensions and its coating layer, it could be considered as an example of the real behaviour of painted panels. The time to reach the new equilibrium state is really long, that is 150 days.

The last test here presented is the one involving the shield mock-up panel (see Figure 5). Because of its particular geometry and its uncommon structure, it is a unique case. It reacts strongly and fast to the RH variation, because of its high surface-to-volume ratio, and it reaches the new equilibrium state well in advance of the others, after only 45 days, because of its tiny thickness and the moisture exchange taking place on both faces.

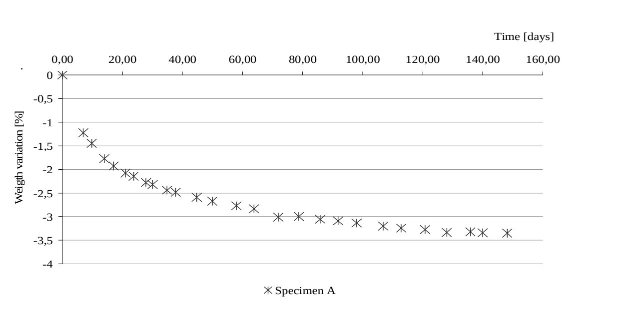

Figure 4: percentage weight variation of specimen A , its equilibrium time.

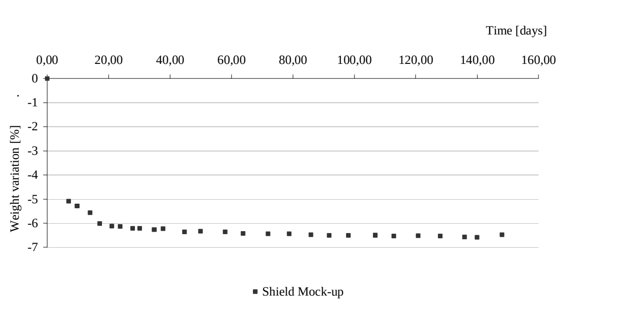

Figure 5: percentage weight variation of shield mock up panel, its equilibrium time.

4. DATA ANALISYS

4.1.Long term analisys

The time necessary for each mock up to reach the new EMC is related to the symmetry or asymmetry of moisture exchange and to the thickness of the panel, two factors involved in the calculation of the surface-to-volume ratio. Comparing the specimens with a symmetrical moisture exchange, it is clear that the shield mock up, the thinner one, needs only 45 days to reach its new EMC, but of course larger is the thickness, larger is the time. More precisely, both the mass and thickness contribute to lengthen the time nearly the triple for specimen C. The behaviour of the waterproofed specimens could be more interesting for applicative aims. These specimens - precisely A, B, N and V- have a similar surface-to-volume ratio, while the thickness and the mass are different. Comparing the small specimens (N and V) to the large ones (A and B), it is clear that the larger mass (in the proportion 7 to 1) and the larger thickness (in the proportion 4 to 3) slow down the desorption process by nearly 2 months.

Table 2: equilibrium time needed by each specimen.

Specimen	A	B	N	V	C	D	T	Shield
Equilibrium time [days]	150	150	90	90	120	85	60	45
Surface-to-Volume ratio [mm^{-1}]	0,02	0,02	0,03	0,03	0,05	0,09	0,20	0,17

4.2.Medium term analisys

At the beginning of the desorption cycle, the first weight data were measured after 7 days and the first comparison among the specimens is only possible starting from that time on. The shield mock-up panel is the most reactive, losing about 5% of its initial weight, that represents the 74,5% of the total desorbed water. Once again it depends on the symmetrical exchange of moisture and on the high surface-to-volume ratio. Comparing the waterproofed specimens (A, B, N and V) no great differences are evident during the first week. Their weight decreasing is included between 1,24% and 0,74% of their initial weights, representing a percentage between 25% to 38% of the total desorbed water.

Table 3: loss of weight at the 7th day for each specimen.

Specimen	Shield	T	D	C	V	A	B	N
Surface-to-Volume ratio [mm^{-1}]	0,17	0,20	0,09	0,05	0,03	0,02	0,02	0,03
Loss of weight, after 7 days [%]	-5,07	-3,97	-3,89	-2,26	-1,24	-1,22	-0,88	-0,74

4.3.Short term analisys

After collecting all the weight data, the following step is the elaboration of a fitting model necessary to interpolate the curve and reconstruct the trend of the first week. The elaboration is performed by Origin® 8, utilizing the formula (1):

$$y = a(1-e^{(-bx)})^{c} \quad (1)$$

The equation (1) is simple, because only 3 parameters are involved, and it interprets the physical phenomenon of desorption quite precisely. It is an exponential function that grows according to a decreasing rate. *X* is the independent variable, that is time, and *y* is the dependent variable, that is loss of weight. The parameters to fit are *a*, *b* and *c*. Parameter *a* is the curve asymptote and it shows the weight variation value once the new equilibrium moisture content is reached, while *b* and *c* strongly influence the slope of the curve. Table 4 contains the list of the parameter values obtained by the fitting process.

Table 4: the fitting parameter values for each specimen.

Specimen	A	D	Shield	N	V	T
a	-3,766	-5,979	-6,503	-2,956	-3,143	-5,297
b	0,0093	0,0466	0,0568	0,0383	0,0541	0,0529
c	0,351	0,335	0,224	0,889	0,779	0,217
R square	0,997	0,995	0,997	0,996	0,997	0,994

The fitting curves interpret well the experimental data (see Figures 6 - 9), and this is confirmed by the high values of R square (see Table 4).

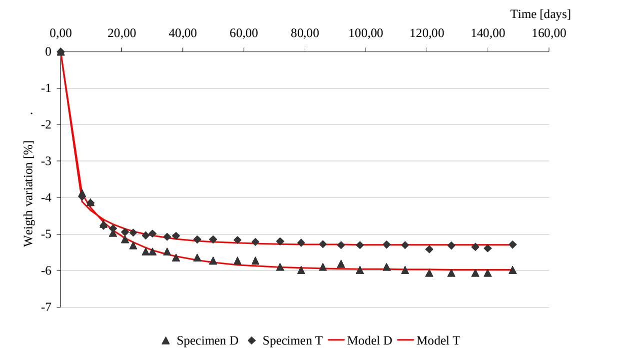

Figure 6: comparison between the experimental data and the fitting curve: specimen T and D.

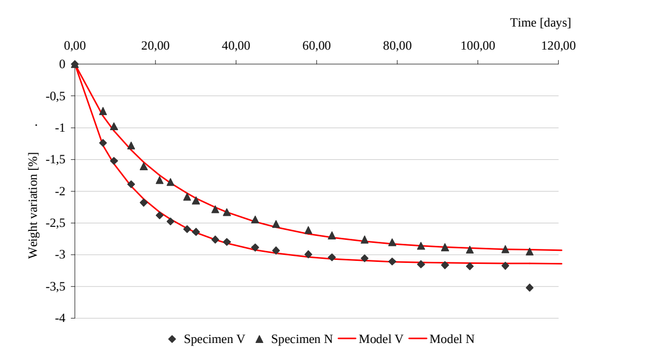

Figure 7: comparison between the experimental data and the fitting curve: specimen N and V.

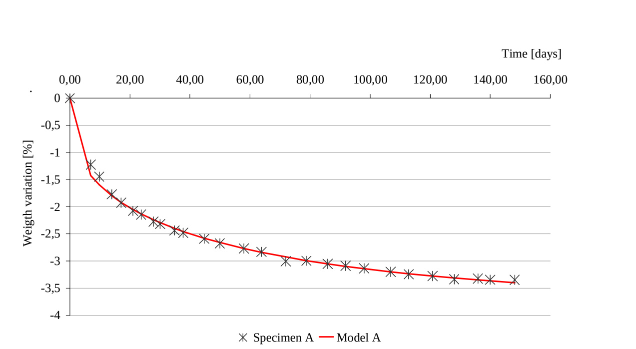

Figure 8: comparison between the experimental data and the fitting curve: specimen A.

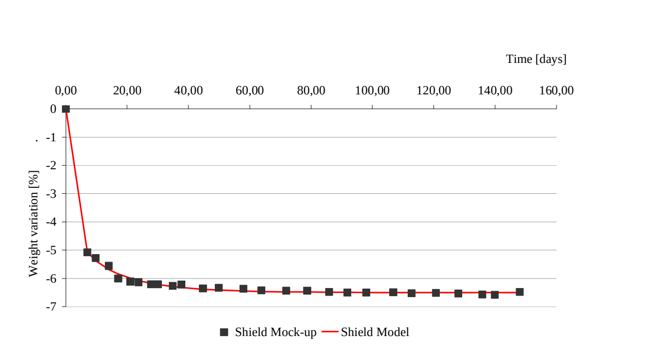

Figure 9: comparison between the experimental data and the fitting curve: shield mock up panel.

Thanks to the fitting good quality, the interpolation of the first missing days is possible so the focusing on the first one, in order to analyze the reaction of the specimens immediately after the environmental condition variation. It could be of some practical interest focusing on the effects of short time climatic variations on painted panels, to understand their behaviour when subjected to suddenly environmental variations. It is clear (see Figure 9) that the shield mock up panel changes very quickly its weight, after the first hour it loses 1,68% of its initial weight, corresponding to the 26% of the total desorbed water. Examining the waterproofed specimens, it is clear that their loss of weight is moderate. The higher value is 0,24% of the initial weight, that is nearly the 7% of the total desorbed water, and it is relative to specimen A. The loss of water of the others (B, N and V) is quite negligible, between 0,05% and 0,01% of the initial weight. It means that the loss of weight is between 1,5% and 0,3%. These values point out the high stability of the specimens during the first hour.

Table 4: loss of weight after the first hour for each specimen according to the fitting model.

Specimen	Shield	T	D	C	A	B	V	N
Loss of weight after 1 hour [%]	-1,68	-1,41	-0,74	-0,31	-0,24	-0,05	-0,03	-0,01

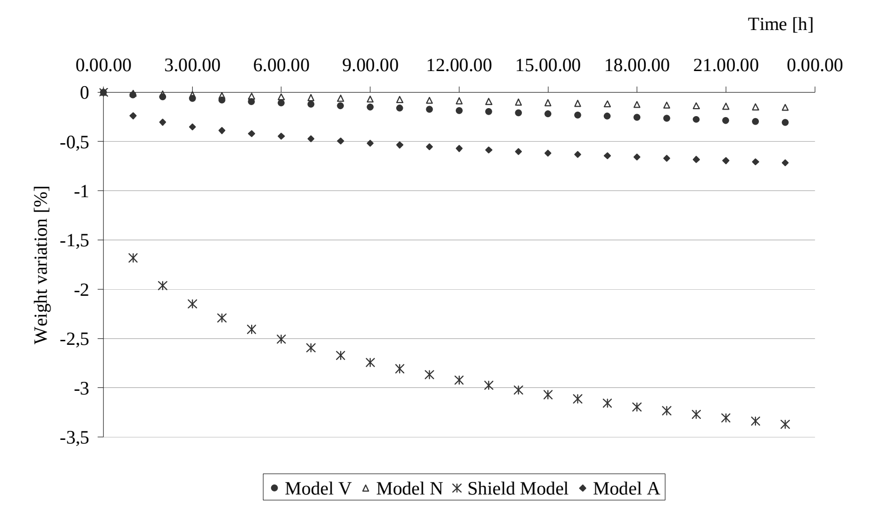

Figure 9: the weight variation of the tested specimens (A, N, V and the shield mock up) during the first 24 hours according to the fitting model.

5. CONCLUSIONS

The cases presented in this paper give some practical information on:
- the time necessary for the specimens to reach the new equilibrium moisture content;
- the weight variation immediately after the climatic condition variation.

Some applicative guidelines, if the environmental conditions vary (specifically the temperature is constant at 30°C, while the relative humidity of the air changes from 85% to 42%), are listed here below:

- thin panels with both exchange surfaces (high surface-to-volume ratio) are quite reactive. The shield mock up loses 1,68% of its initial weight during the first hour and reaches the new equilibrium moisture content after only 45 days;
- thick panels with only one exchange surface (low surface-to-volume ratio) are moderately reactive. The panels A, B, N and V lose less than 0,25% of their initial weight during the first hour and reach the new equilibrium moisture content in a period of time between 90 and 150 days;
- specimen N (new wood) and V (ancient wood) show the same behaviour;
- for panels with similar coating and thickness (similar surface-to-volume ratio) the mass is the significant factor. The different mass and thickness values of specimen A and N produce a lengthening of the time necessary to reach the new equilibrium moisture content from 3 to 5 months.

References

1. D. Vici P., Mazzanti P., Uzielli L.; (2006), Mechanical response of wooden boards subjected to humidity step variations: climatic chambers measurements and fitted mathematical models; Journal of Cultural Heritage, 7: 37-48.
2. Marcon B., Dureissex D., Dionisi Vici P., Gril J., Uzielli L.; (2008), Experimental and numerical mechanical study of a framing technique for cupping control of painted panels combining crossbars and springs; COST IE0601 Wood in Culture Heritage, Braga (PT).
3. Marette J., (1962), Connaissance des primitifs par l'étude du bois, A. & J. Picard & C., Paris.
4. Mazzanti P.; (2001), Comportamento meccanico e deformativo di due simulacri di dipinti su tavola aventi diversa simmetria igroscopica soggetti a variazioni igrometriche ambientali *(Mechanical and deformational behaviour of two painted panel structural replica with different hygroscopic symmetry subjected to cyclic RH variations)*; Degree Thesis, Firenze.

5. Uzielli L., (1995), Historical overview of panel-making techniques in central Italy, Proceedings "`The structural conservation of panel paintings"', Getty Museum, Los Angeles.
6. Uzielli L., Cardinali E., D.Vici P., Fioravanti M., Salvioli N.; (2008), Structure, mock up model and environment-induced deformations of Italian laminated wood parade shields from the 16th century; COST IE0601 Wood in Culture Heritage, Braga (PT).