Compression set and cupping of painted wooden panels

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Abstract
Factors that need to be considered to explain the observed cupping pattern of panel paintings are reviewed. The anisotropic shrinkage and the action of the paint layer, both a reinforcement and a moisture barrier are the most obvious ones, but the progressive contraction of ancient wood is usually invoked. Although the aging process of wood could be responsible for some of it, several mechanical processes may lead to compression set: mechano-sorption, microbuckling, or even the recovery of locked-in growth strains.

1. Introduction

Wooden boards used to support historical paintings often exhibit cupping. The origin of this unwanted curvature is not completely elucidated, as sev-eral factors could be involved and the condition of conservation of the pan-els through the centuries is mostly unknown. According to information giv-en by conservators, panel paintings that were not heavily restrained through craddling or similar reinforcement, tend to cup toward the observ-er, meaning that the central part of the board moved frontward relative to the lateral parts (**Figure 1**).

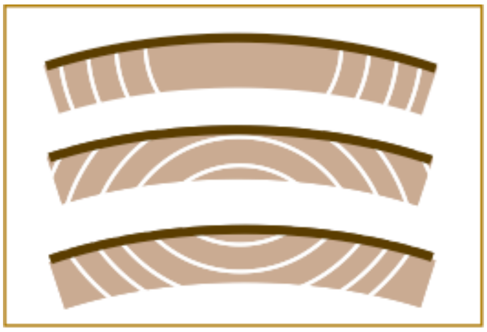

Figure 1: Why do most unrestrained painted panels cup the same way?

This paper aims at discussing various factors that need to be considered to explain this phenomenon, including the so-called "compression set", a per-manent contraction made evident, for instance, by the gap between an his-torical panel and its original frame.

2. Anisotropic moisture expansion

Among wood technologists the most well-known cause of board cupping is the anisotropy of moisture shrinkage ratios in the RT plane (**Figure 2**).

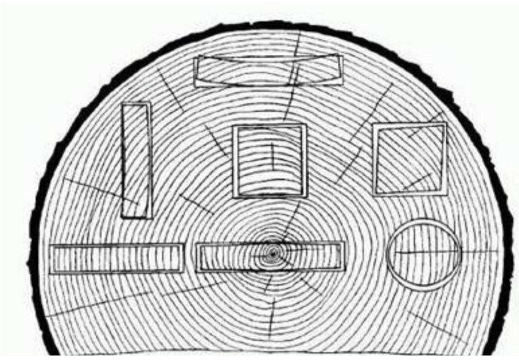

Figure 2: Deformation of wooden blocks resulting from T shrinkage exceeding R shrinkage.

There is a simple stress-free solution describing the deformation of an homogeneous wooden piece subjected to a slow humidity change that didn't induce any moisture gradient:

$$X(x,y) = (1 + \alpha_R).x - (\alpha_T - \alpha_R).\text{atan}(y/x).y \quad (1)$$
$$Y(x,y) = (1 + \alpha_R).y + (\alpha_T - \alpha_R).\text{atan}(y/x).x$$

where X, Y is the deformed position of a point initially at position x, y and α the moisture expansion having homogeneous polar coordinates centred on the pith (constant values of α_R and α_T, α_{RT} = 0…). This expression is only valid when the piece does not contain the pith. It can be verified that this solution fulfils all the conditions of a mechanical problem for the fields of stress (σ), strain (ε) and displacement (u):

- static equilibrium: $\sigma = 0 \Rightarrow \text{div}\,\sigma = 0$
- kinematic compatibility: $(\text{grad}\,u + \text{grad}^t u)/2 = \varepsilon$
- free boundary conditions
- hygro-elastic constitutive equations: $\varepsilon = \alpha \Rightarrow \sigma = C(\varepsilon - \alpha) = 0$

where C is the rigidity tensor.

The direction of the cupping depends on the sign of moisture change and ring orientation. We can reasonably assume that when a painter ordered a panel to a craftman, he expected the panel to be flat and air-dry before he applied the ground layer. A difference of humidity between the artist's time and nowadays is the most obvious explanation for the observed cupping. The central deflection d of a board of width 2L aligned parallel to y axis at distance h from the pith can be derived from (1):

$$d = -(\alpha_T - \alpha_R).L.\text{atan}(L/h) \quad (2)$$

the solution being only valid for h exceeding the half-thickness of the board. As an order of magnitude, a moisture content reduction of 5%, such as resulting from a drop of average RH from 75% to 50% at 20°C, for a poplar flatsawn board 40 cm wide cut 5 cm from the pith, would produce a deflection of 2 mm, independently of the panel thickness (**Figure 3**). The amount of this effect is compatible with the cupping of ancient panel paintings. However, if it was the only phenomenon involved, the cupping direction should depend on the ring orientation, contrarily to the fact illustrated in Figure 1.

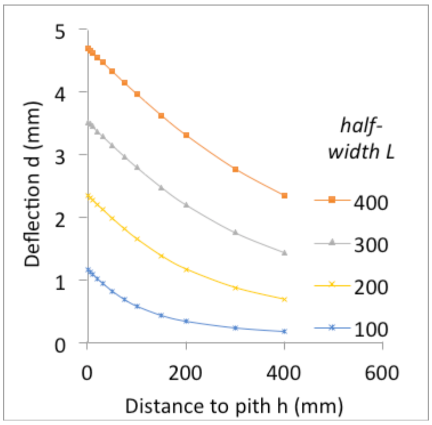

Figure 3: Central deflection (d) of a flat-sawn board dried from 70 to 50% RH, as a function of distance to pith (h) and half board width (L).

3. Asymmetry

The next cause of cupping for a panel is the asymmetry between both faces. It is either caused by different boundary conditions or by heterogeneous mechanical behaviour. Both factors occur in panels as soon as they are painted on a single face, since the paint layer reduces the speed of exchanges with the surrounding atmosphere, while contributing mechanically to the whole structure.

Figure 4 illustrates the cupping resulting from asymmetric moisture diffusion in the ideal case of a fully waterproof paint layer. The transient response is characterised by a peak at a time dependent mostly on the speed of water diffusion and panel thickness.

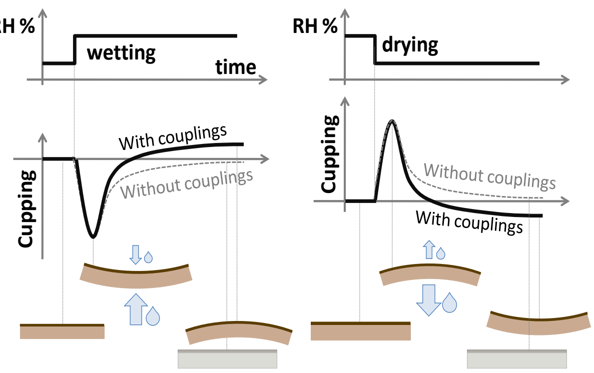

Figure 4: Transient and permanent effect of asymmetric boundary conditions.

If the material possessed a simple hygro-elastic behaviour, the panel would become flat again once the new equilibrium conditions are reached – or attain the state described in the previous section if the effect of ring curvature is taken into account. However, the hygro-mechanical behaviour of wood is characterised by a very significant coupling, called mechano-sorption. Due to mechano-sorptive coupling, permanent deformations are locked in wood as soon as it subjected to mechanical stress while the moisture content varies. This is one aspect of the "set" that will be discussed in the last section. As a result, a non-zero cupping is generated. In the long term, for a panel subjected to a complex hygrothermal history, both tension set and compression set will be generated in turn. Although they are likely to compensate each other, in some circumstances compression may occur at higher moisture contents than the tension and result in a dominance of the compression part (Hunt and Jeronimidis 2016).

The "paint layer" is a complex composite of various underground layers and paints, sometimes reinforced by canvas. Its physical and mechanical properties may change through the history of the artwork. In addition to its role as moisture barrier, it contributes mechanically to the curvature of the panel by having a different rigidity and moisture expansion than the wood of the panel. According to the findings of Aurand (2015) and Gauvin (2015) the elastic modulus of a few typical underground layers was 2 to 10 times higher than that of poplar in T direction. Thus even a thin paint layer may act as significant reinforcement of the wooden panel and prevent to some extent the deformation of the painted face. Moreovover, owing to the viscoleastic and mechanosorptive behaviour of wood, its effective rigidity under long term loading in a variable climate is considerably reduced so that the reinforcing action of the paint layer may even become dominant.

4. Aging

Thus any process inducing a deformation of the wooden panel transversally to the fibres is likely to induce a cupping. In case of a negative strain, a contraction, the cupping would indeed occur as shown in **Figure 1**.

A lower level of average humidity in the present storage conditions was evoked as a possible factor in the preceding section. Combined with the asymmetry imposed by the paint layer, it would indeed be able to explain the observed cupping of historical panels. To verify this interpretation, the direction and amount of cupping – and if possible its precise profile – should be recorded on a large number of panel paintings where the ring structure has been documented, so that the quantitative relation between cupping and estimated pith position can be checked. If the hypothesis holds true, the 3rd pattern in **Figure 1** should provoke the most cupping.

As an alternative to drier storage conditions, hygroscopic aging could be considered to explain a reduction of average moisture content. Yokoyama et al. (2009) observed a reduction by 2% of the equilibrium moisture content in given air-dry conditions, for hinoki wood used for Japanese temples 1500 years ago. Garcia Esteban et al. (2005) imposed 5 cycles between 90%RH at 50°C and oven dry state to several hardwood and softwood specimens, and obtained a significant reduction of equilibrium moisture content but at high RH only. In recent years, many attempts to reproduce the features of naturally aged wood through mild - typically, below 150°C - thermal or hygrothermal treatment have been made (Kránitz et al. 2016). However Obataya (2016) explained that the observed changes are partly reversible by exposure to high humidity. This suggest that some of the moisture reduction is due to structural changes, such as the formation of permanent hydrogen bonds (hornification), or to the dissolution of cell-wall components such as hemicelluloses: the former being potentially recoverable but not the latter. In any case, in the case of wood used in historical objects, a lower equilibrium moisture content can be expected, compared to recently processes wood. Although dimensions of ancient object cannot be directly compared to their original ones, we can reasonably expect that a lowering of the moisture content results in a contraction. This is at least the case with thermal treated wood, which has many common features with naturally aged wood.

5. Compression set

Wood is a highly compressible material, especially transversally to the fibre, as evidenced by "Cupido's arrow" (Inoue 1982). **Figure 5** shows two aspects of compression set illustrated by this artefact. The arrow's end has been softened in hot water to allow the wood to be considerably compressed without breaking the cell walls (**Figure 5**b). The compressed shape is fixed by drying the wood under restraint, inducing a considerable mechano-sorptive relaxation so that after release of the restraint the springback is very small. The remaining contraction could be named *viscoelastic compression set*. Most of it can be recovered by reconditioning the wood through boiling. **Figure 5**c shows, however, that the recovery is incomplete. Indeed, some damage and permanent folding has been induced in the cell walls.

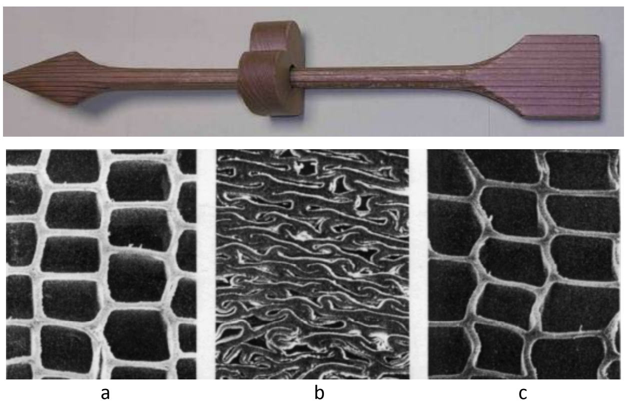

Figure 5: Cupido's arrow (up) and SEM images of the microstructure (down): (a) uncompressed wood; (b) heavily compressed; (c) after reconditioning (from Inoue 1982).

The permanent deformation resulting from such micro-buckling could be named *plastic compression set.* Transversally to the fibre, viscoelastic tension set can be obtained as well; but plastic tension set is unlikely to occur due to wood brittleness in transverse tension.

Figure 6 shows an experiment by Hoadley (1995) made to evidence the compression set in a board. The board on the right is free to expand, and returns to its initial shape after a full moisture cycle. When prevented from expanding the middle board undergoes a compression set clearly visible after returning to the initial moisture level. On the left the fully restrained board breaks in the final stage.

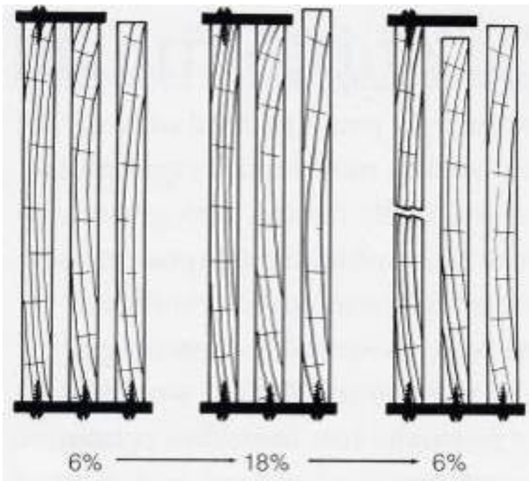

Figure 6: Evidence of compression set according to Hoadley (1995).

Mazzanti et al (2014) confirmed Hoadley's findings, except for the breaking of the fully restrained board that was never observed. The tangential stress and strain of free, partially restrained and fully restrained poplar specimens were measured. **Figure 7** shows the stress of the fully restrained specimen versus the opposite of the strain of the unrestrained specimen, this graph being the closest possible approximation of a stress-strain curve for the restrained specimen. The drop of compressive stress observed during the first wetting cycle (segment JL) can be attributed to some causes discussed above, such as mechano-sorptive relaxation or the occurrence of plastic micro-buckling in the cell walls. In any case, the order of magnitude of -1% for the residual strain is sufficient to explain the observed permanent cupping of panels that would undergo little contraction of their painted face.

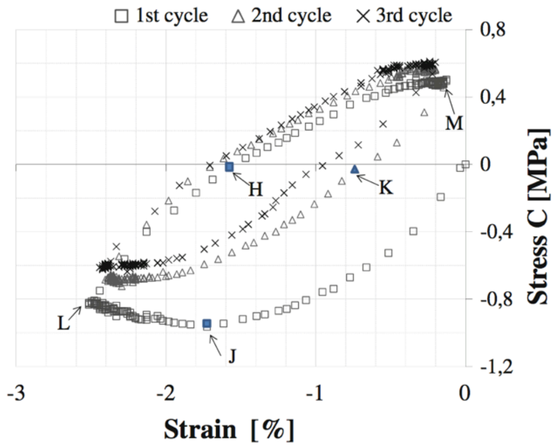

Figure 7: Stress of fully restrained specimen versus the unloaded strain of a specimen subjected to the same wetting-drying cycles (25°C, 30-80-30%RH): (square) 1st cycle, (triangle) 2nd cycle, (x) 3rd cycle. 0H: compression set; 0K dimensional loss for restrained or partially restrained specimens. J: stress peak, L: end of 1st adsorption; M: end of 1st cycle and start of 2nd (Mazzanti et al 2015)

Hunt and Jeronimidis (2016) studied the effect of compression set on the hygroscopic expansion of poplar wood. They induced the set either by preventing the swelling of specimens suddenly placed in wet condition, or by compressing them in dry state. In both case they were allowed sufficient time to recover in wet conditions. In R direction they obtained compression sets of 0.6% and a increase of the swelling rate of 20% and 9% for wet and dry compression, respectively. In T direction both the final set and the effect on swelling rates were small or not significant.

The *recovery of locked-in growth strain* should be also considered as one possible mechanism of irreversible strain. Wood formation at stem periphery is accompanied by prestressing. In T direction, the expansion of newly formed wood results in compression, progressively converted into tension with the deposition of newer wood. In R direction the small initial compression applied by the bark is rapidly converted into tension. Hunt and Mazzanti (2016) observed a shift of the relationship between dimensions and weight of specimens exposed during one year to the English outdoor climate, corresponding to a permanent strain of -0.07% and +0.12% in R and T directions, respectively. These values represent a fraction of the typical strain observed on green wood as a result of boiling, explained as the hygrothermal recovery of the viscoelastic strain locked in wood during the process of its formation. As this recovery is usually not fully expressed before drying, it is likely to occur slowly during the following centuries. In R direction at least, a contraction is expected, while in T both a contraction and an expansion can be expected.

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