On shape stability of panel paintings exposed to humidity variations – Part 2: Shape stability of sawn wood

S. Reijnen and A.J.M. Jorissen
Eindhoven University of Technology, the Netherlands

A panel painting is a painting made on a wooden panel. It is not well known, but a lot of famous paintings are actually panel paintings, such as The Mona Lisa by Leonardo Da Vinci, Assunta by Titian, Primavera by Botticelli and Samson and Delilah by Rubens. Artists had clear reasons to choose wood instead of canvas, one of the main reasons was availability and stability. Before an artist could start his painting he had to prepare the panel with several layers of gesso (mixture of glue, gypsum or sometimes ground chalk and water) ossein (lime made from bones) or other materials. After several layers and considerable sanding, the panel surface became perfectly smooth if properly done.

Part 2 discusses the effect of wood moisture changes on deformations. All kind of deformations like cup, twist, bow, etc. (see e.g. figure 8) can be simulated by numerical modelling when taking the wood properties in all directions and the change in properties due to moisture changes into account. Furthermore, for panel paintings, the effect on these deformations of added material like gesso and paint is discussed. The same drying conditions as similar to those considered for the example calculations discussed in part 1: a step from RH = 70% to RH = 30 % . Descriptions of similar studies can be found in literature, e.g. Omarsson *et al.* – related to the shape stability of sawn wood - and Jakiela *et al.* – related to painted panels. The purpose of the study described in this part 2 is study benchmarks and to extend the study discussed in part 1

1 The influence of changing wood moisture content on sawn wood

Sawn timber, when exposed to changing environmental conditions below the fibre saturation point shrinks or swells. The deformation of sawn timber exposed to changing environmental conditions can be a serious problem for museums and industry. For both museums and industry, it is important to investigate how the material properties, the internal structure and changing environmental conditions influence the shape deformation. More knowledge could lead to stable wooden products and economic benefits.

Shrinkage and swelling, deformations initiated by wood moisture content changes, are well understood. However, the simulation of the deformations of wooden products like boards due to these effects is problematic to carry out accurately without numerical analyses. For accurate deformation predictions it is necessary to consider not only the distinction between longitudinal, radial and tangential directions but also the orientation of the fibres (spiral grain and conical angle orientation).

The shape stability of sawn timber exposed to changing environmental conditions can be divided into four types of deformation: cup, twist, crook and bow, see figure 8. These deformations are simulated using ABAQUS finite element software. As described in paper ½ the moisture diffusion process, which is a mass transfer process, can be simulated by a heat transfer process. This is used in this part 2 as well. The material properties are taken from Kollmann and Cote (1968) for pine; missing values like spiral grain and conical angle orientation were taken from Blumer (2006) and Ormarsson, Dahlblom and Petersson (1997. In the analyses carried out for this paper variations in longitudinal moduli of elasticity and longitudinal moisture expansion coefficient are not considered. Taking these variations into account only refines the modelling, not the focus of the study described in this paper: numerically verifying the deformations initiated by changing wood moisture content. More information about varying material properties in longitudinal direction and from pith to bark can be found in Ormarsson *et al.* (1997).

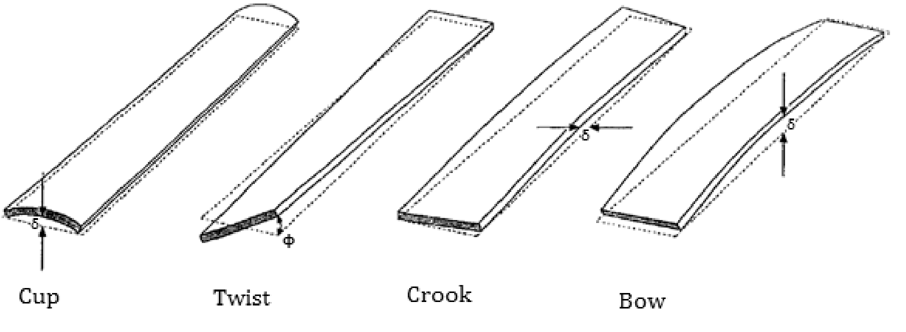

Figure 8. Different deformation types, Ormarsson et al. (1997)

2 Types of deformation

Sawn timber exposed to changing environmental conditions can show cup, twist, crook or bow deformation, see figure 8. The content of this paper focusses at in depth understanding, by investigating cup, twist and bow deformation as a function of moisture content and distribution. Before addressing this the typical deformations observed are explained in this section.

The stability of sawn timber strongly depends upon the fibre direction, perpendicular to grain orientation (radial or tangential), growth ring orientation, spiral grain and conical angle orientation. It is essential to have detailed information on the original position of the sawn timber within the tree stem and the orientation of the fibres.
The conical angle (angle between pith and fibre direction) of a tree can be regarded as being constant from the bottom to the top of the tree. Because the diameter decreases from the bottom to the top of the tree, the conical angle is negative. The conical angle is generally regarded as being constant and in this paper set to -0.5°. Spiral grain, explained in paragraph 3.3 in relation to figure 11 is taken constant at 4°. In this paper, cup, twist and bow deformation will always be defined using displacement δ (cup and bow) and the angle φ (twist), see figure 8.

3 Input ABAQUS finite element models:

*3.1 **Geometry***

Numerical models for boards taken at different locations from the tree cross section, see figure 9, were developed. The first model is called Wood Board -1 (WB-1), second model is called Wood Board -2 (WB-2) and the third model is called Wood Board -3 (WB-3), see figure 9 and table 3. These three boards are chosen because of expected different reactions to wood moisture variations. The moisture release (drying) takes place at all sides of the cross section.

*3.2 **Thermal and hygroscopic boundary conditions***

The thermal and hygroscopic boundary conditions are described in part 1, 2.1.3.

3.3 *Mechanical boundary conditions*

Four centre nodes in the middle of the wood board's cross section have the following restraint displacement conditions: node 1 (U1, U2, U3), node 2 (U3), node 3 (U1, U3) and node 4 (U3), see figure 10. Due to this mechanical restraining the model is able to move free in each direction and rigid body movement cannot take place. As a consequence of restraining these nodes, very small stress concentration around these nodes developed which can be neglected and does not influence the outcome.

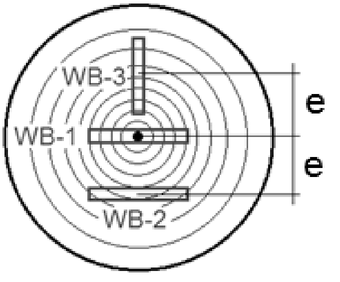

Figure 9. WB-1, WB-2 and WB-3 stem orientation

Table 3. Dimension of wood beards

	Spiral grain [degrees]	Conical angle [degrees]	Pith distance from centre [mm]	Thickness of wood board [mm]	Length of wood board [mm]	Width of wood board [mm]
WB-1	-4,0°	-0,5°	0	15	1000	200
WB-2	-0.0°	0°	-107.5	15	1000	200
WB-3	-0.0°	0°	107.5	15	1000	200

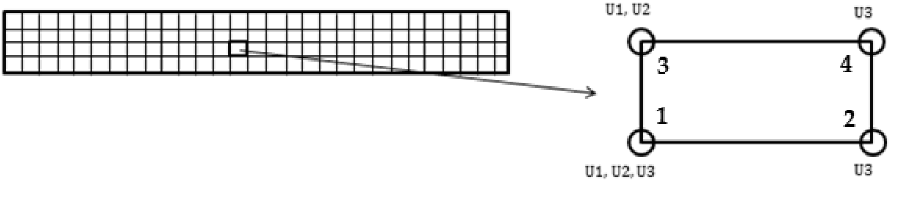

Figure 10. Mechanical boundary conditions, restraining of centre nodes

3.4 *Material properties*

For the numerical analyses for the three boards chosen, see figure 9, material properties are essential. The properties considered are discussed here.

The elastic material properties taken from Jakiela, Bratasz and Kozlowski (2008) presented in table 1 – see part 1 – differ from the properties given by Kolmann and Cote (1968), which are presented in tables 5 and 6. The differences between the moduli of elasticity in tangential direction seems to be 2.6% and in the radial direction 10.0%: relatively small.

Table 4. Coefficients of hygro-expansion, Kolmann et al. (1968)

Unities	Coefficients of hygro expansion
α_L $[m/m\%]$	3.0e-05
α_T $[m/m\%]$	3.6e-03
α_R $[m/m\%]$	1.9e-03

Table 5. Moduli of elasticity, Kolmann et al. (1968)

Unities	Modulus of elasticity
E_L [MPa]	13553
E_T [MPa]	616
E_R [MPa]	1232

Table 6. Shear moduli, Kolmann et al. (1968)

Unities	Shear modulus
G_{LT} [MPa]	836
G_{LR} [MPa]	788
G_{TR} [MPa]	79

Table 7. Poisson's ratio, Kolmann et al. (1968)

Unities	Poisson's ratio
ν_{LT} [–]	0.4
ν_{LR} [–]	0.4
ν_{TR} [–]	0.4

Since also presents the elastic properties in grain direction, the values presented by Kolmann *et al.* are taken into the analyses.
The moisture diffusion coefficients presented in table 2 – see part 1 - by Jakiela *et al*. differ much more from the values given by Kolmann *et al*.. The values presented by Jakiela *et al*. are considered in the analyses.

4 Shape stability

Part 1 describes the response of a limewood cylinder with a thickness of 130 mm. It takes the cylinder – see part 1 – 40 hours to get into full equilibrium with the new situation (wood moister content = 6%). The boards considered here are just 15 mm thick – table 3. Consequently, the time needed for reaching full equilibrium is much shorter; it turns out to be about 45 hours. Due to the changing moisture content from 14% to 6% for a drying period of 45 hours twist for specimen WB-1 and cup and bow for specimen WB-2, see figure 9, were numerically simulated.

*4.1 **Twist deformation***

Twist deformation under drying conditions is mainly the result of the spiral grain orientation, see figure 11 and 12. Without a spiral grain orientation, WB -1 would be stable and consequently twist deformation would not occur. The strong relation between twist deformation and spiral grain orientation is a consequence of the wood board being much stiffer in the longitudinal direction, compared to the radial and tangential directions. Because the properties in the spiral grain direction equals the direction of the longitudinal material properties, placing the spiral grain under an angle of -4.0° results in a relatively large diagonal stiffness and, as a consequence, under drying conditions twist deformation of the wood board will occur. Although the model used by Ormarsson *et al*. (1997) is dimensionally quite different, the result shown in figure 11 and 12, are in agreement with the result found by Ormarsson.
The wooden boards studied by Ormarsson were 3.0 m long, 100 x 10 mm in cross section and exposed to a sudden change in

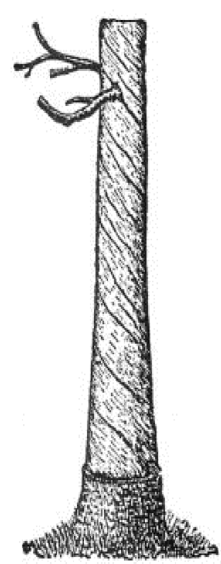

Figure 11. Spiral grain (Kollmann 1968)

relative humidity (RH) from 27% to 10.75%. After 1 day of drying, Ormarsson calculated a twist deformation of 2.5 degrees.

Figure 13 shows a strong twist gradient in the early stage of the drying process, as a consequence of progressive drying, this twist rate decreases until equilibrium is reached. This strong twist rate in the early stage is a consequence of the average moisture content decreasing very quickly in the first few hours, see figure 5. This strong twist rate in the early stage of the process was also found by Ormarsson.

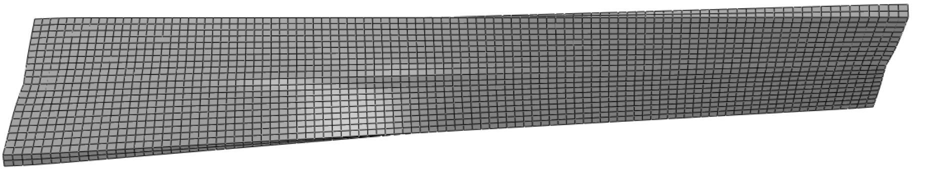

Figure 12. Twist deformation WB-1

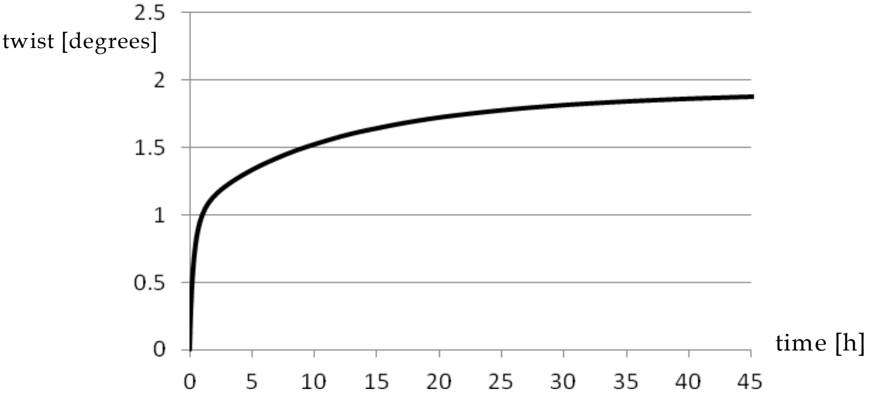

Figure 13. Twist deformation as a function of time in WB-1

*4.2 **Cup deformation***

Cup deformation is caused by the difference between radial and tangential shrinkage. Since shrinkage is larger in the tangential than in the radial direction, cup deformation develops, see figure 14. Also in the case of twist development, the cup rate is largest in the early stage of the drying process, see figure 15.

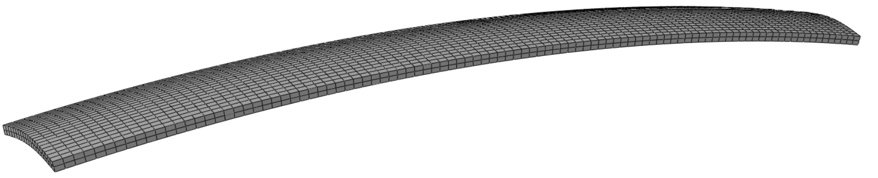

Figure 14. Cup and bow deformation, WB-2

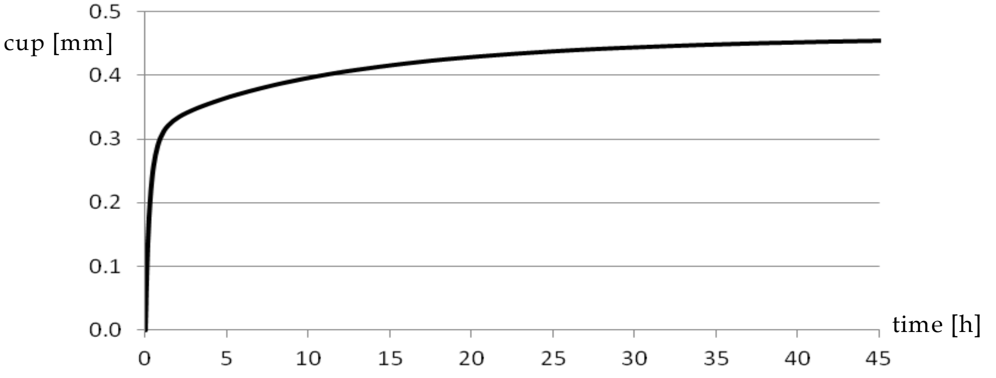

Figure 15. Cup deformation as a function of time in WB-2

4.3 *Bow deformation*

WB-1 does not show bow deformation because it is stable due to its growth ring orientation, see figure 9. This is opposite to WB -2 which shows significant bow deformation, see figure 16. The difference between WB-1 and WB-2 is clearly the orientation of the growth ring. It is known that the direction of cupping depends upon the orientation of the growth rings. If the growth rings point upwards, in case of drying the cupping direction will be downwards. In case of bow deformation, this is the opposite. The position of the pith, which is the centre of the growth rings, determines the direction of bowing. The bowing direction is always in pith direction, e.g. if the pith is located above the board, the bowing direction will also be in this direction. The reason for bowing is not clear. It cannot be the difference between radial and tangential shrinkage because of the orientation and because the wood boards are exposed to equal drying condition at each surface so, unequal drying of the top and bottom surfaces cannot be the reason for this behaviour. In the real world boards show bow deformation. However, the simulation presented here deserves more in depth study whether these simulations are suitable for describing this. For the model it is doubtful whether bowing is the result of material properties or a consequence of the local cylindrical coordinate system used. In the model, the fibres follow a conical angle orientation (due to the fact that a tree is not prismatic over its length) which might explain the simulation result as well (which shows bow deformation, see figure 16). See Reijnen (2012) for more information.

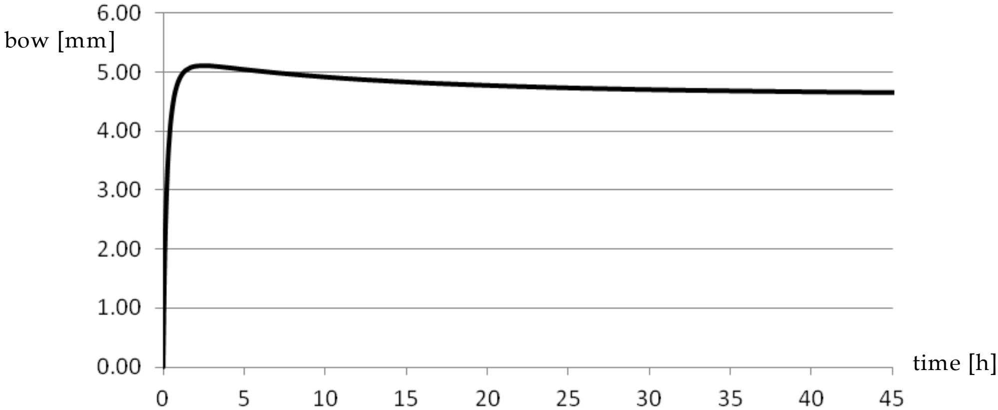

Figure 16. Bow deformation as a function of time in WB-2

5 Influence of gesso layer on shape stability

A panel painting is a painting made on a wooden panel. Examples are The Mona Lisa by Leonardo Da Vinci, Assunta by Titian, Primavera by Botticelli and Samson and Delilah by Rubens.. The main reasons artists choose wood instead of canvas was availability and stability, see Reijnen (2012).

This part of the paper discusses the influence of a gesso layer on the shape stability of wooden boards. The numerical models of WB-1 and WB-2 from the previous chapter are expanded with a gesso layer. The content of this paper is limited to the influence of a gesso layer on the twist stability and the influence of changing diffusivity on twist deformation in case of WB-1. Besides the wood properties, already discussed, the gesso properties are of influence on the board response. These are discussed more in detail in 5.1. More information regarding the influence of changing material properties of wood and gesso on shape stability can be found in Reijnen (2012). The board studied is shown in figure 17).

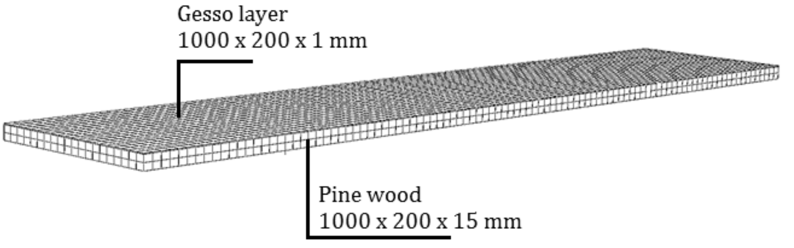

Figure 17. Board and Gesso layer dimensions

5.1 *Boundary conditions and material properties*

The influence of this gesso layer on twist stability will be discussed for the same drying and boundary conditions as presented previously in part 1. The material properties of gesso are adopted from The Getty institute and the Getty Museum (1995) from which the strain – RH graph shown in figure 18 and the so-called PVC – hygro expansion graph in figure 19 are taken.

Different artist have different recipes for making gesso. Sometimes inert materials as zinc and clay are incorporated. The ratio of inert materials to the binder (hide glue) has a great influence on the mechanical behaviour of gesso. This ratio of inert materials is called the PVC ratio (Pigment Volume Concentration). The higher the pigment volume ratio, the weaker, stiffer and less hygro-expansionally responsive the gesso becomes. Also, more glue means stronger, more elastic and more hygro-expansionally responsive the gesso becomes, see figure 18 and 19.

Figures 18 and 19 represent the behaviour of two different pigment volume ratio values on strain and hygro-expansional behaviour of gesso. Figure 19 shows that a pigment volume ratio of 58.3% has a higher effect on the hygro-expansion than a higher pigment volume ratio mixture, of which the curve of PVC = 81.6% is also in figure 19. Overall, it can be concluded that the pigment volume ratio affects the mechanical behaviour of gesso quite significantly. The mechanical behaviour of gesso is also affected by other aspects, such as light and ageing.

5.2 *Influence of the gesso layer thickness on moisture transport*

Figure 20 shows the wood moisture content in the centre of the board. It clearly shows that a thicker gesso layer slows down the process of moisture release. This is not surprising, because a thicker layer gives rise to a longer distance for the moisture to travel before reaching the surface.

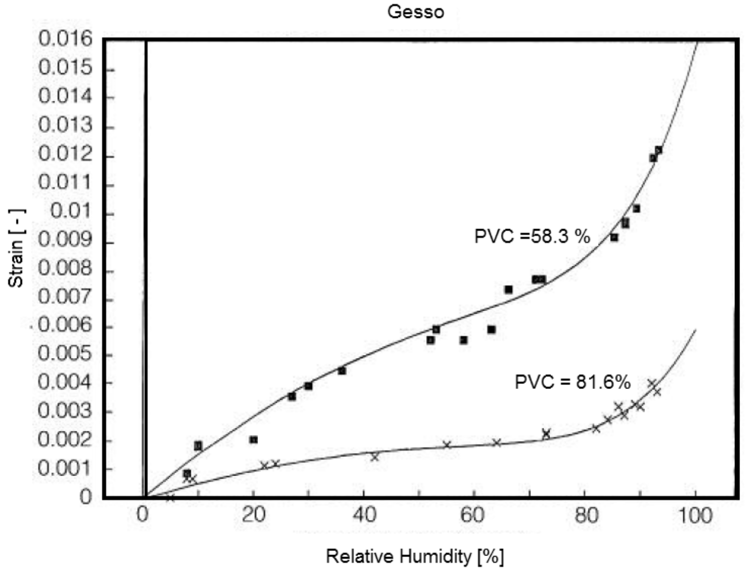

Figure 18. Influence of pigment volume ratio on strain (Getty Institute 1998)

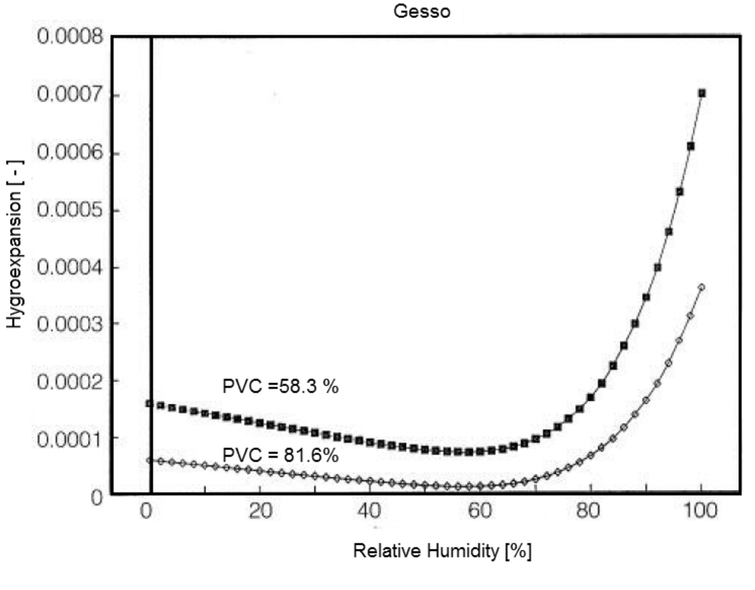

Figure 19. Influence of PVC on hygro-expansion (Getty Institute 1998)

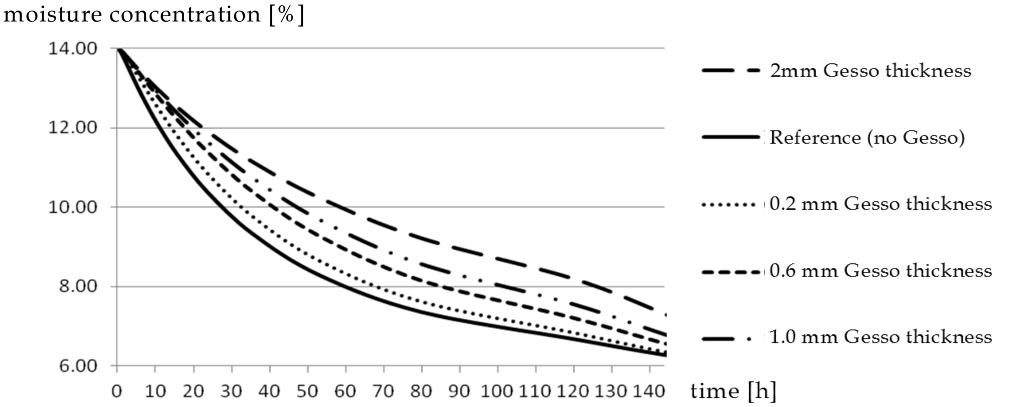

Figure 20. Influence of thickness of gesso layer on the wood moisture content in the board centre

5.3 *Influence of gesso layer on twist deformation*

Figure 21 shows the influence of a 1.0 mm thick gesso layer after a drying period of 24 hours on twist deformation. It looks like first negative twisting (clockwise) develops and after 4 hours of drying positive twisting (counter clockwise). This changing of twist direction is most unusual. Consequentially, figure 21 showing pure twist deformations, is most unlikely. Note that the lines of figure 21 only represent the angular rotation between the pith and the wood board edge as shown by figure 8. This means that negative rotation (clockwise) does not necessarily mean twist deformation; it could also represent cup deformation (as indicated in figure 21)

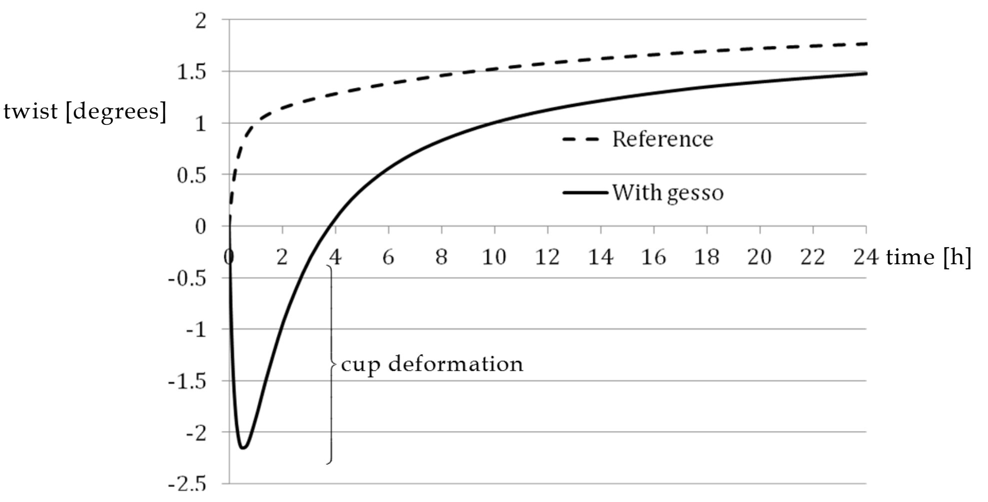

Figure 21. WB-1, influence of 1 mm of gesso on twist angle

Applying a 1.0 mm thick gesso layer on a sawn wood board seems to have a great influence on the shape stability. As a consequence of a gesso layer, unequal moisture transfer between the top and bottom surface develops. Applying a gesso layer on WB-1 results in combined cup and twist deformation. Because the gesso layer slows down the moisture transport in one direction under rapid drying conditions, the wood board develops a tendency to cup. After 2 hours and continuing drying, this short time cup behaviour slowly disappears and after 4 hours WB -1 slowly starts to develop twist deformation. Without a gesso layer WB-1 would not show any cup deformation at all, only twist deformation, see reference line in figure 21 The reference line shows a twist deformation of 1.7° after a drying period of 24 hours. The same wood board, with the gesso layer, shows a reduced twist deformation of 1.5° after a same drying period.

5.4 *Influence of changing the diffusivity of gesso on shape stability:*

Figure 22 shows the effect of a changing diffusivity of the gesso layer on twist deformation of WB1. Figure 22 shows that a high diffusivity, expressed by a higher value for the diffusion coefficient *D*, results in a faster twist development and that a lower diffusivity results in a slower twist development.

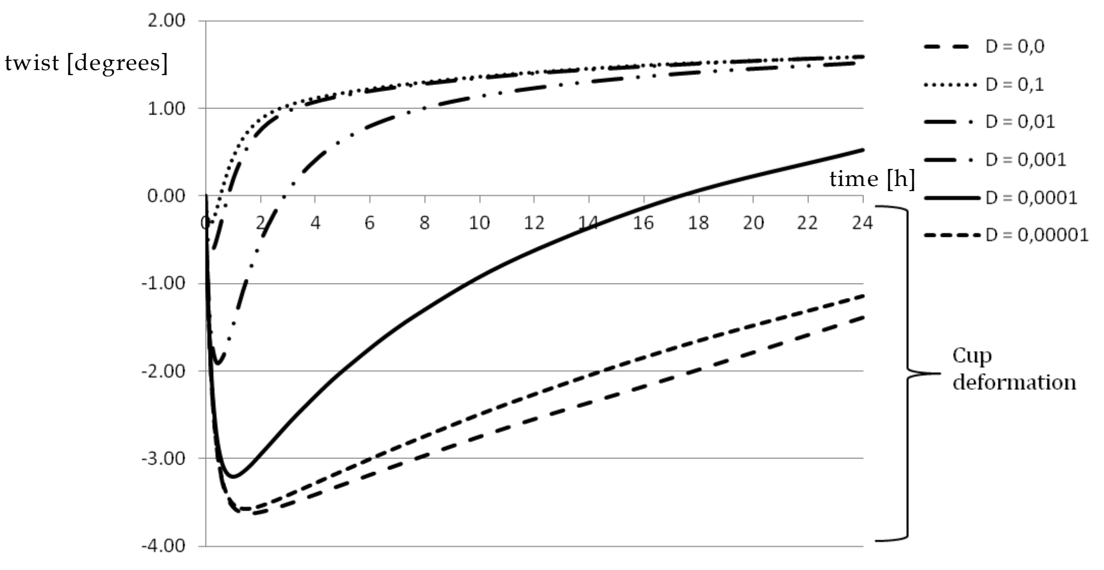

Figure 22. WB-1, influence of diffusivity of the gesso layer on twist deformation (twist angle)

Note that the lines of figure 22 only represent the angular rotation between pith and wood board edge as shown in figure 8. This means that a negative rotation does not necessarily mean twist deformation; it could also represent cup deformation. Further research has shown that this is indeed the case, see Reijnen (2012). Because the gesso layer slows down, the moisture transport in one direction under rapid drying conditions, the wood board develops a tendency to cup. Depending on the diffusion coefficient, after 30 minutes to 2 hours, as a result of continuing drying, this short time cup behaviour slowly disappears and twist deformation starts to develop.

6 Summary and conclusion

When sawn timber is exposed to moisture variation it most probably results in cup, twist, crook or bow deformations (or combinations of these deformations). The so-called shape stability of sawn timber depends upon the original orientation within the stem. To be able to simulate the deformations due to wood moisture changes properly, it is essential to have detailed information about the position of the sawn timber within the tree stem and the orientation of the fibres. It has been proven that cupping is the result of different radial and tangential properties. Twisting is mainly the result of the spiral grain orientation.
Applying a 1.0 mm gesso layer seems to influences the shape stability considerably. Moisture transport through a gesso layer depends upon the diffusivity and the thickness of the gesso layer. As a result of the thickness and diffusivity of such a gesso layer, completely new combinations of deformations occur, compared to the same wood board without a gesso layer.
When these deformations are constraint, stresses, of which tension stresses perpendicular to the grain may result in cracks, develop. Detailed information about the influence of different structural orientations can lead to a more precise and direct method of solving the deformation problem for different types of deformation. These results can also contribute to the development of a constitutive model able to predict deformation due to changing environmental conditions more precisely.
(Single sided) Coating layers like gesso seems to have great influence on the deformation behaviour of sawn wood when exposed to changing environmental conditions. Coating layers like gesso can lead to unexpected types of deformation. This knowledge can be used to develop a more permanent solution of conservation for individual panel paintings with different coatings.

Literature

Blumer S. (2006) *Moisture Induced Stresses and Deformations in Parquet Floors- An experimental and Numerical Study*, Lund University, Division of Structural mechanics (diploma thesis), Lund, Sweden.

Dardes K.,Rothe A. editors (1998) The Structural Conservation of Panel Paintings, proceedings of a *symposium at the J. Paul Getty Museum April 1995*, The Getty Conservation Institute, Los Angeles, USA.

Jakiela S., Bratasz L., Kozlowski R. (2008) Numerical modelling of moisture movement and related stress field in lime wood subjected to changing climate conditions, *Wood Science Technology*, 42,21-37

Kollmann F., Cote W. (1968) *Principles of Wood science and Technology*: 1 Solid Wood. Institute fur Holzforschung und Holztechnik , Munchen, Germany / College of Forestry, Syracuse, New York.

Ormarsson S., Dahlblom O., Petersson H. (1997) *A numerical study of the shape stability of sawn timber subjected to moisture variations*, Lund Institute of Technology.

Reijnen S. (2012) *Moisture transport and shape stability of wood exposed to humidity variations – A numerical study*. Eindhoven University of Technology, Department of Building and Architecture (master diploma thesis), Eindhoven, the Netherlands.

The Getty institute and the Getty Museum (1995), Structural Conservation of Panel Paintings, proceeding of a *symposium at the J. Paul Getty Museum April 1995*, Part 6: History and Conservation, Scientific Research, see Dardes and Rothe (editors) (1998)