EXPERIMENTAL ANALYSIS AND NUMERICAL SIMULATION OF THE HYGRO-MECHANICAL BEHAVIOUR OF HISTORICAL WOODEN OBJECTS

A STSM report of Daniel Konopka

1. Purpose of the STSM

Within our collaboration in a project of modelling and characterisation of the structural behaviour of wooden cultural heritage under hygro-mechanical loading, we, amongst others, try to develop material models for the typical applied materials in historic instruments, like pianofortes and other cultural wooden structures, like cupboards. These materials are different wood types, coatings and historical glutin-based adhesives, like bone glue or skin glue. The goal of the Institute for Building Materials (IfB) at ETH Zürich, our project partner and host institution of this STSM, is to investigate these materials under different climate conditions to develop models for the mechanical and hygrical material behaviour. The characterisations shall be the base for the numerical analysis of the historical objects with regard to short-term and long-term behaviour of the composite of different wood types and natural glues under mechanical and hygrical loading. In addition to the in [1, 2] explained analysis of short term behaviour of historic pianofortes under coupled hygro-mechanical loading, the long-term behaviour – creeping of the wooden structures [3] and adhesive joints [4] – and natural variation of the properties [5] and the influence of aging [6] shall be considered.

The general aim of the Short-Term Scientific Mission was, first, to learn about experimental procedures applied for the qualitative and quantitative description of the hygro-mechanical behaviour of wood and adhesives. The knowledge of the origin of experimental data is of essential importance for the numerical characterisation of the material behaviour in my future work.

In this scope, one main experiment was carried out while a multitude of other tests were investigated in parallel.

2. Description of the work and main results

2.1. Investigation of the strains and deformations of a veneered glue laminated wood panel with natural inhomogeneities under hygrical loading by 3D Video Image Correlation

The aim of this experiment is to find out the influence of the basic structural material with regard to its inhomogeneities, like differences in the fibre angles of the boards and branches or resin pockets, on the deformation of the surface of the on top glued veneer layer. The questions, we would like to answer are, first: how do the composite of a veneered wooden panel reacts under change of relative humidity and, second: how does these inhomogeneities influence the deformations and stresses in the veneer layer.

The background for this experimental set-up is a typical damage of historical veneered wooden objects where the veneer buckles or cracks.

2.1.1. Geometry and Preparation of the specimen

Two panels with the following geometry were investigated. The specimens have three wooden layers (see Figure 1). The basic middle layer is composed of four boards of spruce (picea abies) with a cross section perpendicular to the grain of 20 x 50 mm and a length of 100 mm. The boards have different fibre angles φ_i and are connected with a nowadays usual 1C PUR adhesive to a panel with a base of 100 x 200 mm . This adhesive is applied instead of natural bone glue because of the high initial relative humidity where it is bonded and its faster hardening. In the panel 1 is a big knot in board 2 (see Figure 2). The two largest surfaces are coated with a 0.7 mm spruce veneer layer with fibres in longitudinal direction y of the panel. The veneer is glued with a historical bone glue of “Kremer Pigmente” [7]. This adhesive is a typical adhesive applied in old wooden instruments and furniture. The adhesive has a large influence on the stiffness of the joint and on the water vapour transport, which influence the mechanical properties of the wood and the adhesive.

The panels for the samples are prepared under the initial climate conditions of the experiment with relative humidity of RH = 0.95 and a temperature of T = 20 °C. The selected and sawn wood is stored in the climate chamber until it is in equilibrium moisture content with the surrounding air, first. Second, the boards are bond with the 1C PUR to one panel. Subsequent to the hardening the spruce veneer is bonded with bone glue and is hardening again.

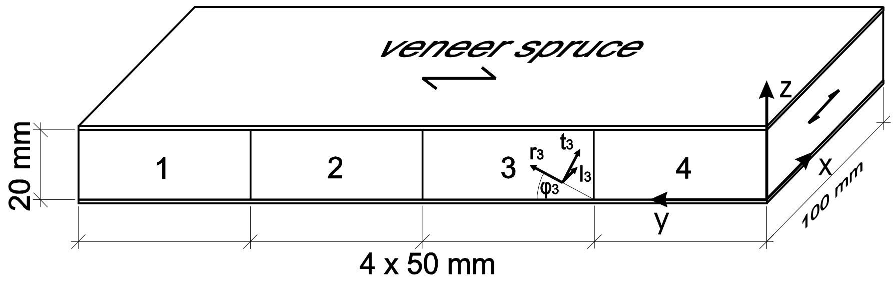

Figure 1: Geometry of the specimen.

Figure 2: The four boards of panel 1 with the knots.

In preparation for the 3D digital image correlation (DIC) the surface has to be speckled, i.e. it is covered with black dots (Speckles) on a bright ground in an irregular pattern [8, 9].

2.1.2. Experimental set-up

In a climate chamber with a relative humidity of approximately RH = 0.50, the specimen was taken on a scale to measure the loss of weight and determine decreasing moisture content MC. It is in front of the two cameras taking photos in equal periods. The digital image correlation (DIC) or video image correlation (VIC) is a powerful tool to investigate deformations and strains of surfaces. With a software the deformation in the surface plane and perpendicular to the plane can be recorded to get the three dimensional deformation of the surface over time. The experiment is finished, when the difference of the last two weights is less than 0.1 per cent of the samples mass within 24 hours. It is assumed that the equilibrium moisture content is reached.

2.1.3. Results

First, we can detect large shrinkage deformations of the whole sample in z-direction. The specimen is warping. Because of the support on the plane y = 0 no displacement is present. In figure 3 the deformations in the area of interest normal to the surface are illustrated. One can see the buckles near the knots and between the boards.

Analysing the photos of DIC, we can observe strain concentrations in the area around the knot in board 2.

In a first numerical analysis of this experiment with the in-house FEM software, some simplifications were made because of missing hygrical and mechanical material properties of the knot and the bone. For all wooden parts, one constant mean fibre angle is assumed. Every part has its cartesian coordinate system for the material directions r, t, l (see Figure 1). It is well known, that the knots have different mechanical properties than the basic material. In the scope of the analysis, it is assumed to have the same properties like the basic material, but another fibre angle. The adhesives were not captured in the model. All joints are force-fitted and do not influence the moisture transport.

In Figure 3, the deformed structure is visualised. One can see similar behaviour like in the experiment. The specimen is warping and in the area of the knot are some peaks as well. In further research, the adhesive bond shall be regarded in terms of cohesive elements to capture its influence to the load bearing behaviour. With this it would be possible to model the delamination and the moisture dependent stiffness of the joint.

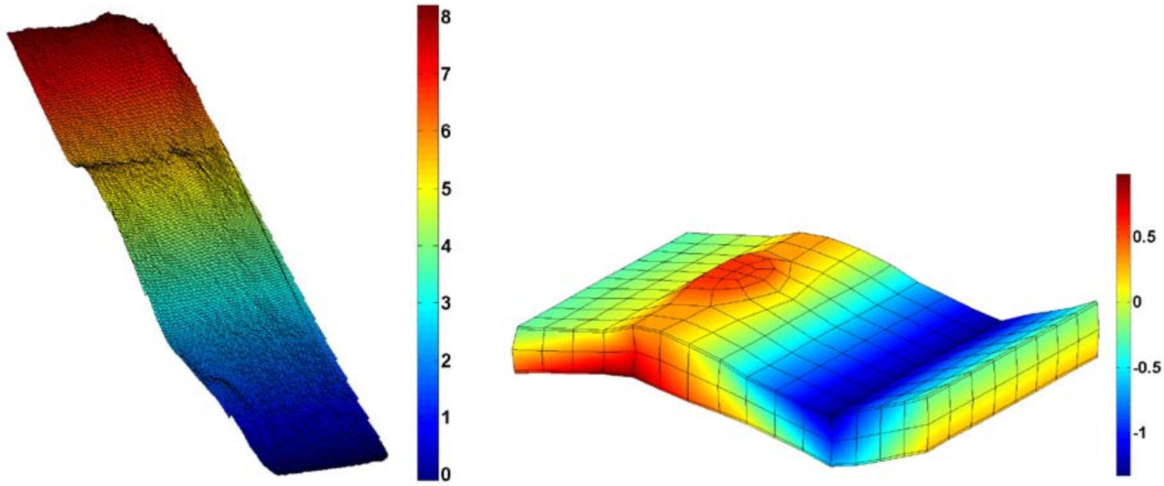

Figure 3: Deformation z [mm] in the AOI of the experimental sample (left) and the simulated board (right) perpendicular to the surface.

2.1.4. Discussion

The warping is a consequence of the different fibre angles of the boards. It is caused by the diverse shrinking behaviour in the material directions, which is characterised by the differential shrinkage values β with $\beta_r = 0.16$, $\beta_t = 0.34$ and $\beta_l = 0.08$ for spruce [e.g. 10]. Due to this anisotropic behaviour wood shrinks in tangential direction about two times faster as in radial direction. The boards with different fibre angles shrink in different directions and cause this warping.

In the experiment, the veneer layer has not cracked. Despite the large moisture change and large gradients of moisture content in the sample, the layer has not collapsed. This could be the influence of the weak adhesive layer in high humidity which allows more shearing between veneer and board. The analysis will be part of further research.

2.2. Further Experiments

In a laboratory with many scientists, it is necessary to coordinate experiments efficiently because of a limited number of devices. My aim was, to do as much experimental procedures as possible in the scope of testing material properties with respect to the running experiments in the laboratory. In parallel I got information to some running tests while maintaining their measurements.

2.2.1. Creeping of adhesives under tensile load for different climate conditions

The experimental set-up is very simple. To check the influence of different loads on creep deformations, the thin layers of the investigated adhesives are clamped on a bar on top and loaded with weights of different percentages of the short-term strength. The deformations are recorded with a camera for six months or collapse and will be analysed by video image correlation. To prepare the samples, the glue has to be casted first and then after drying punched with a standard cutter for tensile specimen.

2.2.2. Diffusion of adhesives

The diffusion tests were made with Dry-Cup and Wet-Cup tests. The specimens are stored in the climate chamber with T = 20 °C and RH = 0.65. In the Dry-Cup silica-gel balls adsorb the humidity inside the cup. The relative humidity is very low and the moisture diffusion takes place from the climate chamber to the cup. The Wet-Cup is filled with water. Due to a humidity of approximately RH = 1.0 the water diffuses out of the cup into the climate chamber. The adhesive samples are fixed on top of the cup after measuring the weight of all parts of the apparatus. Furthermore, the mean diameter of the membrane is determined. Then, the experiment runs until the water uptake or water loss, which is measured by weighing the cups in periods, stagnates.

2.2.3. Dynamic MOE of wood by ultra sonic test

To determine the elastic properties of a material like moduli of elasticity (E_i), shear moduli (G_i) and Poisson's ratios (ν_i), it is possible to measure the time ultra sonic waves need to pass the specimen [11]. With different sized cubes, we get a relationship between the time and the passed distance and can derive the elastic characteristics from the regression. Three different sizes of cubes were prepared and have to be investigated in the different material directions. Each size is represented by several pieces, which is enough to fulfil the statistical requirements. The method is useful for the determination of E_i and G_i, but remains uncertain for Poisson's ratios ν_i [11].

In addition to the mentioned tests, I could have an overview of the following experiments:

- investigation of fracture energy (Mode I) of outside stored glue laminated beech wood,
- investigation of sorption behaviour of adhesives,
- investigation of shear strains and strengths of wood by Arcan-test and DIC [12],
- investigation of creeping of wood under compression for different mechanical and hygrical loadings.

3. Future collaboration and publications

Our project in the topic of modelling and characterisation of the structural behaviour of wooden cultural heritage under hygro-mechanical loading has just started and will be continued during the next three years. Therefore, we will work together in many different subjects in the scope of the project. Some common publications are planned as well, e.g. the results of the STSM experiment with the focus on the influence of inhomogeneities on the deformations as well as the material characteristics of historical adhesives and its numerical implementation in the scope of FEM.

I really appreciate the STSM and the possibility to get into contact with my research partners and their experimental work. In my point of view, it was a successful research exchange with a lot of experiences in a scientific, but also social and cultural manner. My thanks go to all employees of the Institute for Building Materials IfB at ETH Zürich and to the COST Action FP1302 which has enabled this fruitful mission.

4. References

[1] Saft, S. & Kaliske, M., Computational Approach towards Structural Investigations for the Restoration of Historical Keyboard Instruments, Journal of Cultural Heritage, 2012, 13S, S165-S174

[2] Saft, S. & Kaliske, M., Numerical simulation of the ductile failure of mechanically and moisture loaded wooden structures, Computers and Structures, 2011, 89, 2460–2470

[3] Ranz, T., Viskoelastisches Materialmodell für Holz -- Experimente, Modellierung und Simulation, Universität der Bundeswehr, München, 2008

[4] Konnerth, J. et al., Elastic Properties of Adhesive Polymers. II. Polymer Films and Bond Lines by Means of Nanoindentation, Journal of Applied Polymer Science, 2006, 102, 1234-1239

[5] Jenkel, C. et al., Modelling of uncertainties of timber structures due to growth inhomogeneities, Applications of Statistics and Probability in Civil Engineering, Taylor & Francis, London, 2011, 1353-1361

[6] Kránitz, K., Effect of natural aging on wood, ETH Zürich, 2013

[7] http://www.kremer-pigmente.com/media/files_public/Glues.pdf accessed 23 July 2014

[8] Caduff D.; Van Mier JGM., Analysis of compressive fracture of three different Concretes by means of 3D-digital image correlation and vacuum impregnation, Cement and Concrete Composites, 2010, 32, Pages 281-290

[9] Valla, A. et al., Comparison of two optical methods for contactless, full field and highly sensitive in-plane deformation measurements using the example of plywood, Wood Science and Technology, 2011, 45, 755-765

[10] Niemz, P., Physik des Holzes und der Holzwerkstoffe, DRW-Verlag, Leinfelden-Echterdingen, 1993

[11] Ozyhar, T., Moisture and Time-dependent Orthotropic Mechanical Characterization of Beech Wood, ETH Zürich, 2013

[12] José Xavier et al., Measurement of the shear properties of clear wood by the Arcan test, Holzforschung, 2009, 63, 217-225