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Measuring stress levels of archaeological samples from the Oseberg ship under fluctuating relative humidity – preliminary results

Paolo Dionisi-Vici,*[1] Susan Braovac,[2] David Hauer,[2] Maria Malherbes Jensen[2]

[1]via Giuseppe Verdi 7, 54100 Massa, Italy paolo.dionisivici@gmail.com
[2]Museum of Cultural History, UiO PB 6762 St. Olavs plass, 0130 Oslo, Norway

Abstract
Long-term effects of climate fluctuations are very important to consider regarding preservation of archaeological wooden artifacts. Since 2009, a hygromechanical monitoring has been carried out on the Oseberg ship in the Viking Ship Museum (VSH) in Oslo. The monitoring has showed a measurable warping response of the oak planks to the uncontrolled relative humidity fluctuations in the museum.

However, one of the missing pieces of information for an improved understanding of the hygro-mechanical behavior of the ship is the measurement of the stress levels potentially absorbed by the restrained planks during relative humidity (RH) fluctuations.

Here, a methodology aiming to contribute to this analysis is proposed and the first results of the tests are presented. Measurements were carried out in a climate chamber, simulating the average extremes in RH commonly measured at VSH (30% and 75% RH).

The experimental results will allow us to determine realistic climatic set points for the plans of a new museum complex.

Keywords: hygromechanical stress, mechano-sorption, Oseberg ship, long-term monitoring, sustainable climate

Introduction
The Viking Ship Museum (VSH) houses the finds from the burial mounds of the Tune Ship, Gokstad Ship, Oseberg Ship and Borre, excavated in the late nineteenth and early twentieth centuries. In addition to the ships, these collections also consist of numerous grave goods, mostly made of wood.

The building that houses the collection was built in three different stages between 1926 and 1956 and was designed in a cross shape, one wing for each ship and a fourth wing containing the smaller objects. The ships and some smaller objects are exhibited in an open environment, while the smaller finds are displayed in climatized showcases.

During the last century, the ships have been exposed to an uncontrolled environment which follows seasonal changes in temperature (T) and relative humidity (RH). The relative humidity rises above 70% in summer and below 30 % in the winter, with a maximum daily variation of about 15%.

Early in the 2000s, plans for moving the collections to a new location raised questions about the exhibition climate for the objects on open display and whether the uncontrolled environment was appropriate to secure their long-term preservation. Was there a need to install a climate control system to reduce the seasonal fluctuations? And what was to be considered an appropriate exhibition climate?

To answer these questions, investigations started in 2009 to examine the behavior of wood to the ambient fluctuations in relative humidity. The aim of the project was to measure the response (strain) of the wood in the Oseberg ship, as it existed in its restrained construction.

Summary of previous results – in situ strain measurements on the Oseberg ship
Deformation measurements reported in a previous paper, where the climatic data and the testing methodology are described, (Dionisi-Vici *et al.* 2013) have shown that the maximum strains for (reference) unrestrained fresh oak and Oseberg ship oak samples were significantly higher (0.843% and 0.599%, respectively) than the one measured in the boards of the Oseberg ship restrained by rivets (average of two measurements, 0.258% strain). As the restrained boards are prevented from relieving applied stresses through deformation, the absorbed stresses must be dissipated within the board in another way. If

the level of stress exceeds the strength of the material, it may result in crack formation.

Thus, these investigations were initiated to determine whether the stresses absorbed by the restrained boards of the Oseberg ship are of a magnitude that can cause damage. This paper describes preliminary results, with a focus on a description of the set-up used to measure stress in the samples. Samples were cycling between a high relative humidity (RH), 75% and a low RH, 30%, which approximates the average seasonal range measured in the museum.

Material and methods

Material

Two samples are involved in this new chapter of the monitoring project: one from the Oseberg ship, cut from the lower part of the reconstructed ship in the early 1990s for dendrochronological dating (*Oseberg*) and one of recent oak (*fresh oak*). Both samples are of nearly radially cut oak heartwood Figure 1).

Figure 1: Orientation of the growth rings in the samples used. Fresh oak (left) and Oseberg oak (right)

The *Oseberg* sample measures 8.9 cm x 4.4 cm x 3.2 cm (length x width x thickness), with the grain direction along the short side (width). The density of this piece was calculated to be 0.54 g/cm^3. Other samples previously taken from this same board had average strength of 23 MPa (ca 19% of fresh oak) and average modulus of elasticity of 2783 MPa (ca 23% of fresh oak) (Hørte *et al.* 2006; Hoffmann, Schwab and Bonde 2002: Sund 2006).

The Oseberg wood was previously treated with linseed oil and creosote. Examination of cross-sections of samples from the ship showed that the surface coatings penetrated the wood minimally across the grain, up to about 3 mm. The surface treatment may cause delay of – but in no way hinders – the sample response to changes in RH.

The second sample is of recently cut, seasoned oak measuring 9.1 cm x 4.8 cm x 3.5 cm (length x width x thickness), with a density of 0.76 g/cm^3. It is named *fresh oak* in the study. It has not been surface-treated.

For both samples, the radial face corresponds to the dimensions given above for length x width, the tangential face corresponds to width x thickness, and the transverse face corresponds to length x thickness.

Measurement methodology

The system compares the tangential and radial forces induced on similarly-sized samples obtained from sound oak and archaeological oak. Measurement of forces in the longitudinal direction is neglected, since we can reasonably consider it to have much lower magnitudes than those measured in the radial and tangential directions.

The ‘load’ in these experiments is relative humidity. RH is cycled at high (75%) and low (30%) levels in a climate chamber held at 20˚C, approximating the average seasonal RH range measured in the museum.

The measurement system

Each sample (*Oseberg* and *fresh oak*) in the setup, which we have named the Stress Monitoring Kit (SMK), is mounted to two force sensors, which are set up perpendicularly one another (in the radial and tangential directions).

One end of each sensor is mounted onto a rod end bearing – which avoids torque. The rod-end bearing is then attached to a c-mount which is directly screwed into the sample. The other end of each sensor is mounted to a low-friction ball-bearing carriage-and-rail system. This rail allows the sensor to slide, which avoids non-axial loading situations (Figure 2). The carriage-and-rail is fastened to a steel frame.

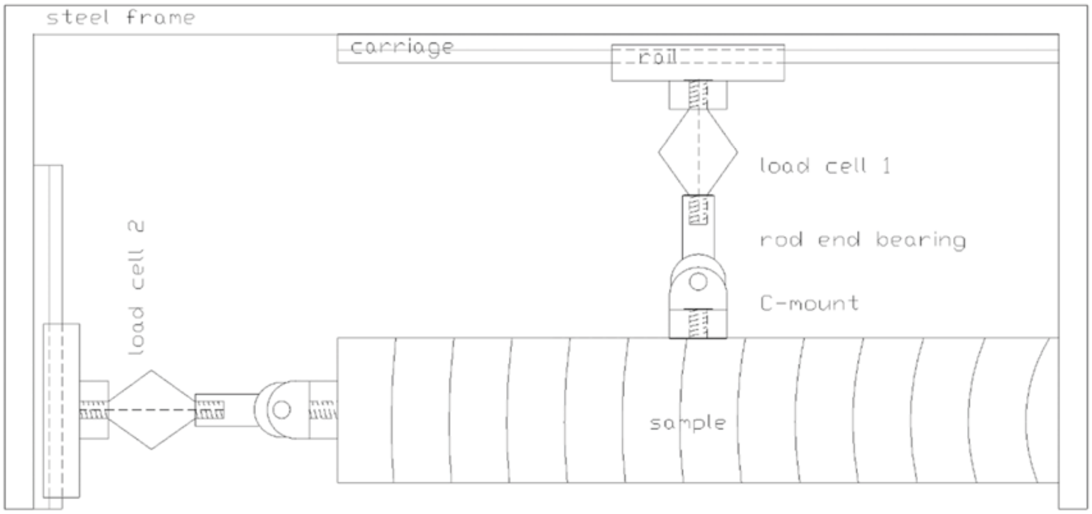

Figure 2: The mechanical connection diagram for the test specimens

The bases of the specimens are rigidly fixed to the steel frame with screws. The specimens were isolated on the transverse faces with aluminum tape to minimize moisture exchange in the longitudinal direction, since the boards in the ship do not have exposed end-grain.

The sensors used in the kit (Deltatech©, model P397.MSA, specifically designed for this test) have a maximum force range of +/- 500 Newtons (N). As there is a linear relationship between the transducers' output voltage (0 to 5 V) and force (-500 to 500 N), the volt signal can be easilyconverted to N by a simple calibration step, allowing a resolution of ~0.25 N/digit. The mechanical connection diagram for the test specimens is shown in Figure 2. Figure 3 shows the experimental setup as it is installed in the climate chamber.

The methodology is a modified version from a previously adopted geometry in a work on the characteristics of the stress of warping of panel paintings (Dionisi-Vici *et al.* 2006).

The data acquisition is performed using a data logger (Pace-Sci XR5-SE), connected to all four force sensors and a sensor for temperature (T) and relative humidity (RH). The real-time data visualization interface was developed using open source software designed by the first author, and it will be fully described in a future publication.

Figure 3: The *Oseberg* and the *fresh oak* samples with the force measurement kit mounted on them. The two couples of force sensors, one radial and one tangential for each sample, are connected to a datalogger, which also monitors RH and T

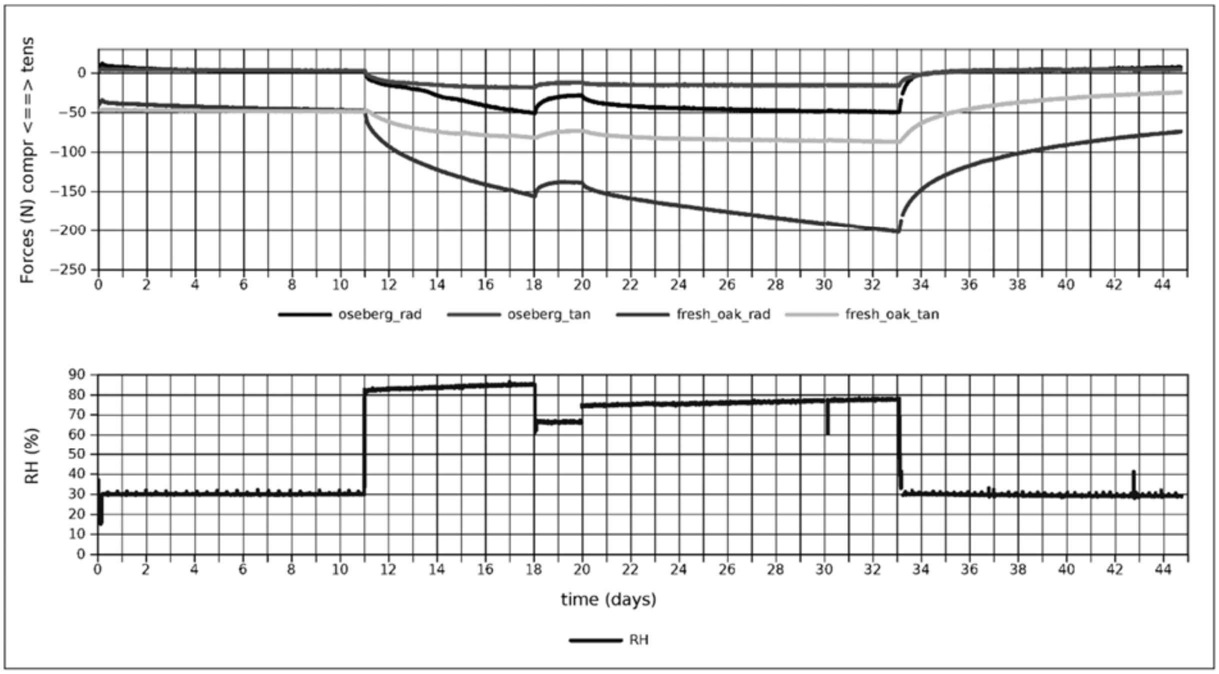

Figure 4: First experimental results of sample response (Newton, N) at two RH levels: 30% and 75% RH. The curves show sample response for both tangential (TAN) and radial (RAD) directions for both fresh oak and Oseberg samples. Compressive forces have negative values, while tensile forces have positive values. Note that we experienced problems with the climate chamber settings at 75% RH, which are now resolved.

First results

Changes in RH (30% and 75% at 20˚C) represent the 'load' applied in these experiments. Measurements take place in a climate chamber, as its controlled environment enables a clearer interpretation of unidirectional climatic events. In this way, the complexity of the overlapping delayed effects of continuous RH variations – as in the existing display environment – is eliminated.

After we have allowed the samples to equilibrate at each RH level a few times, we will continue to cycle each RH level at different frequencies (probably daily and weekly). It is also of interest to verify if the fluctuations carried out in the climate chamber will induce any relaxation in the samples due to mechano-sorptive phenomena (Hoffmeyer and Davidson 1989).

The data collected represent the forces that the samples exert on the sensors while trying to warp under the climate variation. This kind of setup is a simplified representation of the efforts that the riveted and restrained planks undergo when the climate changes in the museum. The goal of this testing campaign is to obtain stress values that can be compared to the ultimate stress to failure of the sample. For the Oseberg oak sample, the stress to failure was found to be 23 MPa (or 23 N/mm^2) in a previous study, that is ca. 19% of fresh oak (Hørte et al. 2006; Sund 2006).

As the values obtained are force (Newton), they will have to be converted to stress values in future work to compare to the strength values measured previously. In the simplest scenario of perfectly oriented (radial or tangential) cut wood, stress (σ) is equal to force (Newton) divided by the surface area (mm^2). But the experimental setup designed for these tests is closer to the real structural complexity of the ship's planks: they are tightly restrained and so the forces are not easily splittable in tangential and radial components. Thus, an in-depth analysis of the constraints geometry must be undertaken before stress values can be usefully exported to the analysis of single planks and of the whole ship. This will require a modelling phase involving finite element method (FEM) software (that will be strongly supported by the experimental values).

At a qualitative initial stage it is possible to highlight some results obtained in the first calibration tests (Figure 4):

- compressive (negative) and tensile (positive) forces are measured in Newton. From low (30%) to high (75%) RH, an increase in compression occurs for both the radial and tangential sensors. When decreasing RH, a decrease in compression occurs;
- the magnitude of forces is very different between the anatomical directions: the radial component is roughly double the tangential for the *Oseberg* sample and triple for the *fresh oak* sample;
- the magnitude of forces is different for *Oseberg* and *fresh oak*: the peaks obtained during the first tests show a factor of three to four times higher for the *fresh oak* compared to the *Oseberg*;
- after RH change, the *Oseberg* sample seems to come to (force) equilibrium more rapidly than the *fresh oak*;
- the magnitude of stress extrapolated from the measured forces on the *Oseberg* sample will be compared to its ultimate strength, as measured on different samples from the same fragment, previously tested in a standard mechanical characterization procedure (Hørte. et al 2006; Sund 2006).

Thus, although the system is currently in its testing phase, the response of the samples to environmental variations is promising, regarding its sensitivity and accuracy.

In the end, we hope that these experimental results – together with the deformation measurements mentioned previously – will contribute to the definition of realistic, sustainable RH set points for the new museum complex, where construction is estimated to begin ca. 2021.

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