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Published in:
Climate for Collections Standards and Uncertainties Munich 2012

2013

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Dionisi-Vici, P., Allegretti, O., Braovic, S., Hjulstad, G., Jensen, M., & Storbekk, E. (2013). The Oseberg ship. Long-term physical-mechanical monitoring in an uncontrolled RH exhibition environment. analytical results and hygromechanical modeling . In J. Ashley-Smith, A. Burmester, & M. Eibl (Eds.), *Climate for Collections Standards and Uncertainties Munich 2012* (pp. 283-297). Doerner-Institut.

Total number of authors:
6

The Oseberg ship. Long-term physical-mechanical monitoring in an uncontrolled relative humidity exhibition environment. Analytical results and hygromechanical modeling

Paolo Dionisi-Vici, Ottaviano Allegretti, Susan Braovac,
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Abstract

A continuous monitoring system was installed on the Oseberg ship, a large Viking Age archaeological wooden object (oak), in order to determine the material response to the uncontrolled conditions at the Viking Ship Museum, Oslo, Norway. Four areas have been monitored since July 2009, two boards on the ship and two samples free to deform (recent oak and a sample removed from the ship). Results, reported for 2010/11, showed that extent of deformation is related to extent of restraint. The greatest extent of strain (warping) was found for the recent oak sample, followed by the unrestrained archaeological sample. Of the restrained samples, that with greatest loading showed least strain.

Introduction

Museums worldwide are currently engaged in a lively debate on gallery climate conditions, namely acceptable levels of relative humidity (RH) and temperature (T) and acceptable fluctuation levels. The discussion on appropriate climate is of prime relevance to the conservation staff at the Museum of Cultural History (KHM) in Oslo since renovations to the Viking Ship Museum (VSH) are planned. The Viking Ship Museum, administered by KHM, is dedicated to the display of the Norwegian Viking Age ship burials from Borre, Tune, Gokstad and Oseberg excavated in the late nineteenth and early twentieth centuries.

The collections on display are mainly of archaeological wood. The Viking Ship Museum was built in three stages (1926, 1932, 1956) without an active ventilation system. No major renovations have been carried out since then. Smaller objects are displayed in climate-controlled display cases; however the three large ships and several other wooden archaeological objects are displayed without enclosures. It is a listed building, meaning that any building changes must be approved by the national antiquary.

In light of the planned renovations, the conservation staff must decide whether the climate conditions (RH and T) at the Viking Ship Museum should be improved or left as they are; that is, should we opt for the installation of a full or partial actively-controlled climate system, or should we trust that the objects have become acclimatised to the existing climate?

Today many agree that the decision to improve a non-ideal climate by the installation of active control systems must balance collection preservation needs with energy consumption and the personnel resources required to maintain it, as well as considering the potentially disastrous consequences when such a system fails [1, 2]. Maintaining the status quo may outweigh the potential benefits of an active system in buildings that are not climate-controlled.

The climate history of an object has become recognized as an important factor to consider regarding appropriate climate. The relatively recent European Standard for evaluating climate in museums and galleries for hygroscopic materials maintains that exposure to the same environment over many seasonal cycles may proof the objects, making them less vulnerable to the development of new climate-induced damage [3]. Before the assessment method described in the Standard may be applied to a particular collection, preservation professionals must undertake systematic investigations of the objects in question to ascertain that existing climate conditions are not causing new damage, and thus are acceptable. The authors read this as an explicit statement basically saying we have to start to think of the specific collection environment and not blindly rely on general recommendations. The Standard may also be interpreted as an implicit appeal to intensify systematic research on the effects of climate on hygroscopic materials; otherwise how will we be able to 'evaluate' whether climate-related damage has occurred or not? Which methods should be used to evaluate damage? Which parameters should be measured?

Finding the appropriate climate range in practice

The Viking ships have been subjected to an uncontrolled climate since their installation in VSH in 1926 and 1932. The display area is therefore influenced by seasonal changes in RH, which rise above 70 % in summer, at times up to 80 % RH (May to October) and drop

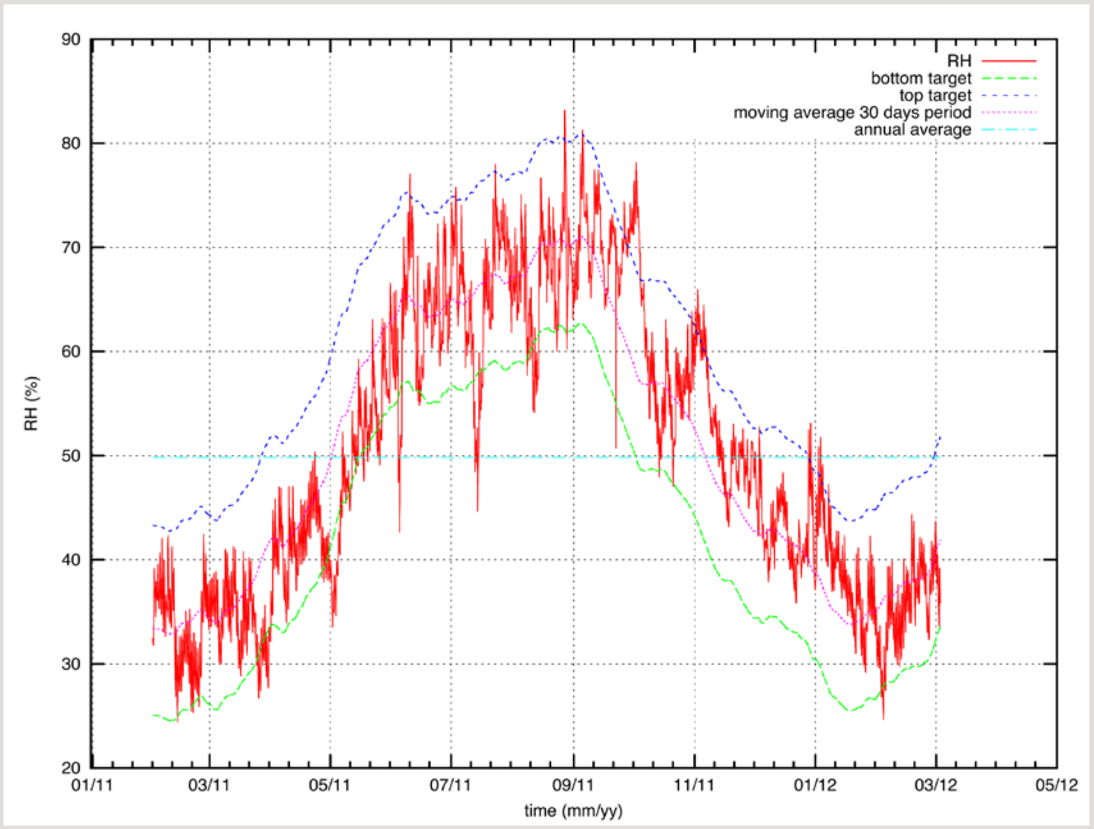

Figure 1. The climate (RH and T) measured in the Viking Ship Museum between 2011 and 2012. Bottom and top target levels were calculated according to the procedure given in the EN 15757:2010 standard [3]

below 30 % in winter (November to April). Annual temperature ranges from 9 to 25 °C, and can rise to 28 °C in summer for short periods.

Relative humidity fluctuations in summer range from 10 % in half a day to 20 % in 1.5 days and in winter are approximately 10 % over the course of half a day to one day. Figure 1 illustrates the climate from January 2011 to March 2012, calculated according to the procedure given in the European climate standard, if we assume that the objects openly displayed are proofed [3]. The climate data is shown for a three-year period to demonstrate the rather regular climatic cycling between winter and summer seasons in the museum.

When conservation staff at KHM attempted to visually examine the condition of the archaeological wooden ships to determine whether the regular climate conditions had in fact proofed them, we found that it was difficult to assess whether existing cracks in the wood were of a recent nature, were the result of older acclimatization processes or whether they had originated from post-excavation drying stresses. We could, however, see relatively recent damage in the wood due to inadequate supports: sagging between the points of support. Although it is known that dynamic short- and long-term RH and T cycling can contribute to permanent plastic deformation of wood under loaded conditions [4, 5], we were unsure whether the material itself, in areas where there was not much gravity loading, had become proofed.

Thus, there are two aspects to consider about the climate conditions at the Viking Ship Museum:

1. The effect of the climatic variation on the material of the ships;
2. The long term effect of the fluctuating climate on permanent deformation of the lower parts of the object under loading from gravity, as well as from the weight of supporting upper boards.

Preliminary results for the first aspect will be described in this paper. The second issue will be addressed in a future project.

The monitoring project

Because plans for upgrading the Viking Ship Museum have been known for several years, conservation staff tried to anticipate the information which architects and engineers would need when the time came for starting the renovation process, such as climate specifications for the collection. There is little information available in the literature about wood-moisture relations for archaeological wood. This is probably because archaeological wood's response to climate fluctuations can vary considerably, depending on its condition and how it had been treated prior to drying [6]. The authors were therefore unsure to what extent the existing literature on non-archaeological/un-degraded wood could be used to assess our ships with regard to their response to fluctuations in T and RH.

Thus, in March 2009 a project was initiated at the Viking Ship Museum to monitor the effect of the uncontrolled display environment on the dimensional changes in the wood of one openly displayed archaeological wooden object, the Oseberg ship (Figure 2). We were interested in understanding how current seasonal and short term T and RH fluctuations affect dimensional changes of the wood making up the ship to eventually determine which fluctuations would be most important to avoid. We were also interested in seeing to what extent the data from the Oseberg ship was comparable to the information found in the literature (on undegraded wood).

The Oseberg ship, dating from c. 820 AD [7], is one of the most important discoveries of the Viking age period in Norway. The fact that it consists of 90 % original material makes it a unique find. The ship is 21.5 m long, built with radially cut 2.5 cm thick oak planks and is 5 m at its widest. Originally the ship was built upwards from the keel in the 'clinker' type of construction, where boards are attached to each other in an overlapping fashion.

In 1904 the waterlogged wood was conserved with linseed oil and creosote and allowed to air dry. In 1957 the surface was coated once again with linseed oil diluted in white spirit [8]. The ship was reconstructed in the same clinker fashion from over 2000 pieces, using both original and modern rivets, as well as screws, nails, adhesive and new wood. Steam had been used to shape the boards during reconstruction. It is currently supported at points placed at regular intervals along the lower boards of the ship. The support system is undergoing improvement.

The measurement campaign on the Oseberg ship started in July 2009, and is still ongoing. Due to the amount of data, the period from January 2010 to December 2011 will be presented here.
To our knowledge, this is the first example of long term hygromechanical [9] monitoring on an archaeological wooden artefact. The Oseberg ship can be considered representative of the three ships on display, since all ships are made of heartwood oak, and it was treated in the same way as the Gokstad ship (the Tune ship was not treated at all).

Figure 2. The Oseberg ship, openly displayed in the uncontrolled exhibition environment

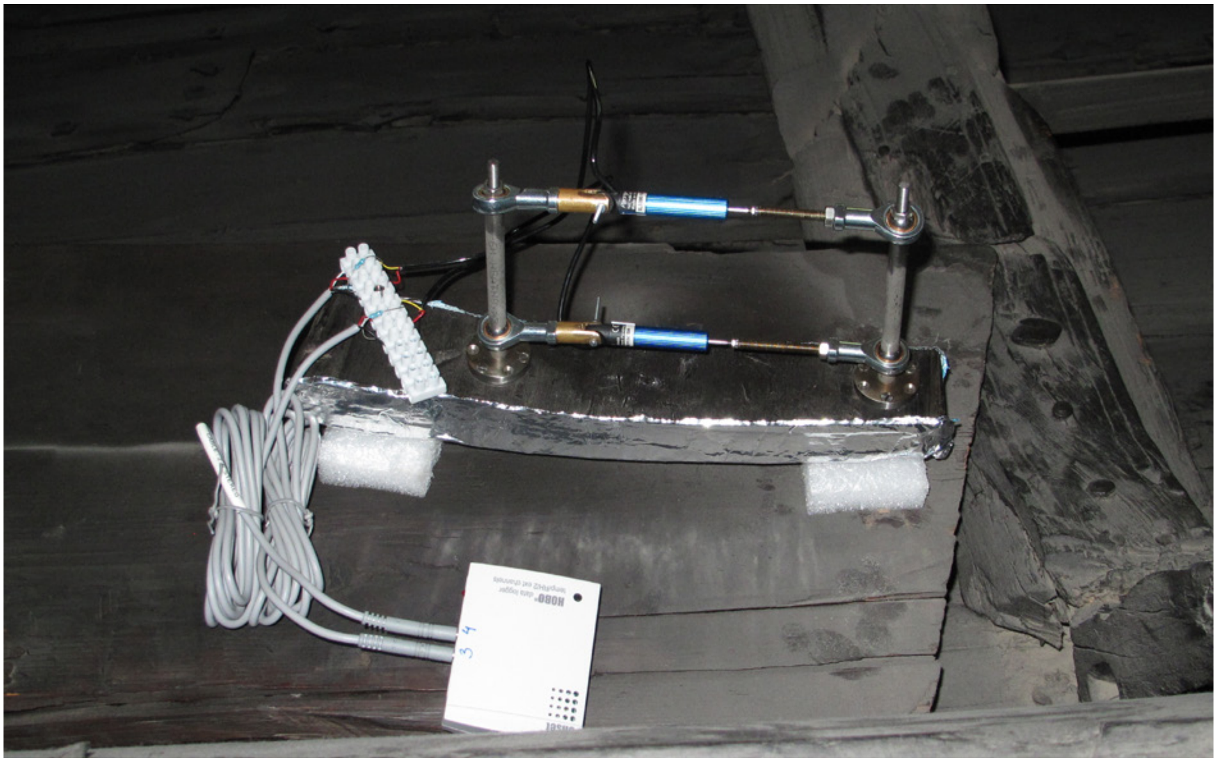

Figure 3. The **dendro oak** sample with the deformometric kit mounted on it. The two transducers making up the Deformometric Kit (DK) are each connected to a datalogger, which also monitors RH and T

The technique used to measure dimensional changes on the Oseberg ship, described in more detail in the Methods section below, establishes a direct relationship between the hygro-mechanical response of the wood to changes in its surrounding climate and involves continuous monitoring. This minimally-invasive method has been successfully implemented on different types of works of art in various museums, and is a useful tool that gives solid experimental data for further analysis [10]. This paper presents a work in progress. Further developments need to be established.

Materials and methods

Materials

Four samples are involved in the monitoring project: two planks on the Oseberg ship and two samples free to warp, one of which is a sample taken several years ago for dendrochronological dating (**dendro oak**) and the other of recent oak (**fresh oak**). All four samples are of nearly radially cut oak heartwood.

The **dendro oak** sample had been cut from the lower part of the reconstructed ship across the entire width of the board in the early 1990s (Figure 3). Its dimensions are 30 x 5 x 2.4 cm (length x width x thickness), with the grain direction across the short side.

The Oseberg boards (**upper ship, lower ship**) have a thickness of c. 25 mm. The width of the boards is c. 300 mm.

As already mentioned, 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 average mass density of the Oseberg oak samples is 0.605 g/cm^3 [11].

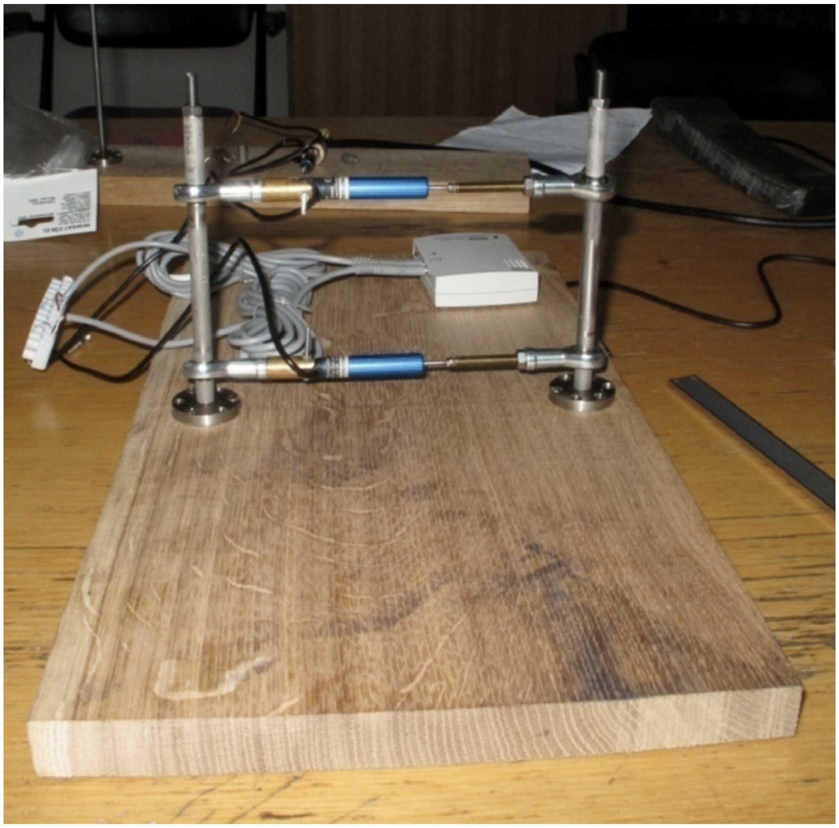

Figure 4. The DK mounted on the **fresh oak** sample

The fourth sample is of un-aged seasoned oak (41 x 22 x 2.2 cm, mass density 0.632 g/cm^3), and is termed **fresh oak** in the study. It has not been surface-treated.

The two smaller samples (**dendro oak, fresh oak**) had their end-grain sealed by aluminum foil tape in order to eliminate water adsorption in this direction, since the boards measured in the ship do not have exposed end-grain.

The measurement system

The Deformometric Kit (DK) is made up of two linear displacement sensors which are set up parallel to each other. The system is screwed directly into the sample. The parallel arrangement of the transducers allows for the use of basic geometrical equations to calculate different parameters from the data, including both in-plane and out-of-plane deformation [10].

The transducers used in the kits have a maximum displacement of 10 mm. The DK is approximately 150 mm in total length. As there is a linear relationship between the transducers' output voltage (0 to 2.5 V) and displacement (0 to 10 mm), the volt signal can be easily converted to mm by a simple calibration step, allowing a resolution of 10 µm/digit.

The two transducers making up the DK are each connected to a channel in the 4-channel HOBO data logger. The remaining two channels in the logger record RH and T. The sample rate is 15 minutes. The loggers are manually downloaded and the data are transferred into spreadsheets.

Set-up of the measurement campaign

Four kits are used in the measurement campaign: two installed directly onto ship boards that are partially restrained by rivets and nails, but which are not in direct contact with the exterior support posts (**upper ship** and **lower ship**) and two installed on samples (Figure 3, 4) which are free to deform (**fresh oak, dendro oak**). The unrestrained samples were placed in the ship after the DK was installed.

The **lower ship** board carries more of the weight of the ship than the **upper ship** boards, since it is located lower down in the structure. The **lower ship** board is also aligned more parallel to the plane of the floor than the **upper ship** board, and is thus more affected by gravitational forces.

The DK was installed across the grain on the nearly radially cut oak planks on crack-free, knot-free areas of the planks (as far as this was possible).

We have chosen to present data from January 2010 to December 2011. Results are expressed as % cupping arc length Δ across the width of the board. Measurements are reported for the concave side of the samples.

Results and discussion

Analysis of the data

The displayed values have the goal to represent the magnitude of the phenomena involved and cannot be extrapolated as characteristic values, directly comparable to other values that have been proposed in the literature [12, 13]. Though the quality

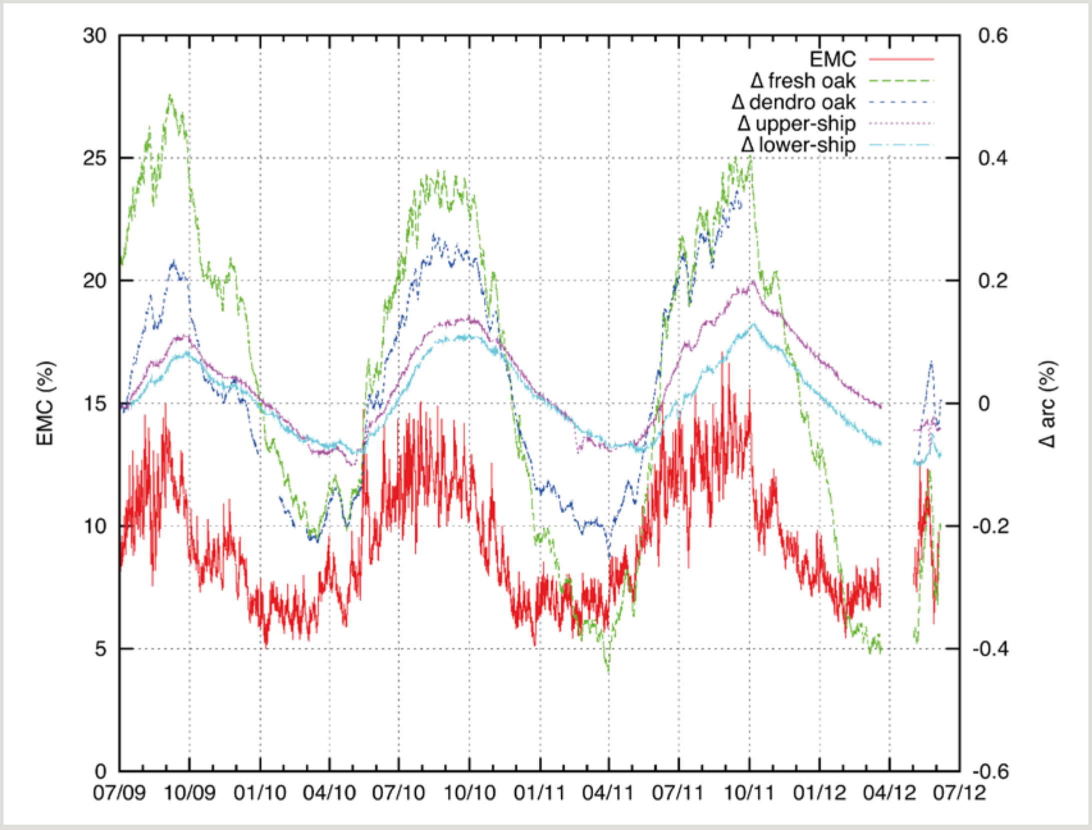

Figure 5. Percent strain across the width of the boards and EMC plotted vs. the timeframe 2009/12

of the measurements has been carefully verified, filtering out data that were disturbed by connection problems (as visible on the charts), the setup is not standard because of the constraints for the installation posed by the ship. The analyses presented here focus on the trends of the response of the chosen samples, which are obviously limited if considered in terms of an experimental population. Nevertheless, this is an aspect of the challenge of facing monitoring problems on real objects and, at this stage of the work, the results can be considered valid as a support for specific choices.

Generally, the response of the restrained samples is visibly different in relation to both sample type (recent oak vs. archaeological oak) and to the extent of constraint of the wood. The extent of % cupping arc length Δ is shown in figure 5 for each sample. Results are also summarized in table 1. The values used for equilibrium moisture content (EMC) were calculated using the Hailwood-Horrobin equation, converting each couple of measured RH and T in the corresponding EMC value [14]. The choice of using the Hailwood-Horrobin equation was based on the known assumption that wood also changes its moisture content (MC), even if in a smaller amount, under temperature variations at constant relative humidity values (Figure 6).

The adopted parameter (EMC) takes a snapshot of the potential MC that a wooden sample would achieve in stable conditions but, as already proposed in a previous paper [15], it can be used as a synthetic parameter involving both temperature and relative humidity in a single, physically- and wood-related value.

Considering the previously described wide temperature fluctuations in the exhibiting environment, the potential loss of information deriving from using only the relative humidity parameter makes it worth using this approach. The Hailwood-Horrobin equation has been adopted because of its widely verified reliability, even if the authors are aware of the need for specific isotherms for this particular material. The need for more species-related specific isotherms is also declared in a recent paper by other authors [16].

Dendro oak vs. fresh oak

There were significant differences in the climate response of the **dendro oak** sample relative to the **fresh oak** sample. Our measurements showed that although both samples followed a

Table 1: Measured strain range is given as per cent values. Overall climate conditions in the exhibition hall at VSH between January 2010 and December 2011 had a temperature range between 9 and 27 °C and RH between 22 and 83 %
* missing data from period 1/1/2010 to 25/1/2010, 16/2/10 to 3/3/2010, 23/9/2011 to 31/12/2011 – only 1 winter (2010)
** missing data from period 4/4/11 to 3/5/11

		fresh oak	dates fresh	dendro oak*	dates dendro	upper Ship**	dates upper	lower ship	dates lower
Max swelling, min shrinkage and total % strain	max	0.404	13.09.11 17:20	0.347	14.9.11 18:22	0.200	04.10.11 18:19	0.130	04.10.11 18:16
	min	-0.439	31.03.11 08:18	-0.252	01.4.11 03:03	-0.102	29.04.10 02:23	-0.083	01.5.10 09:08
	Δ %	0.843		0.599		0.302		0.213	

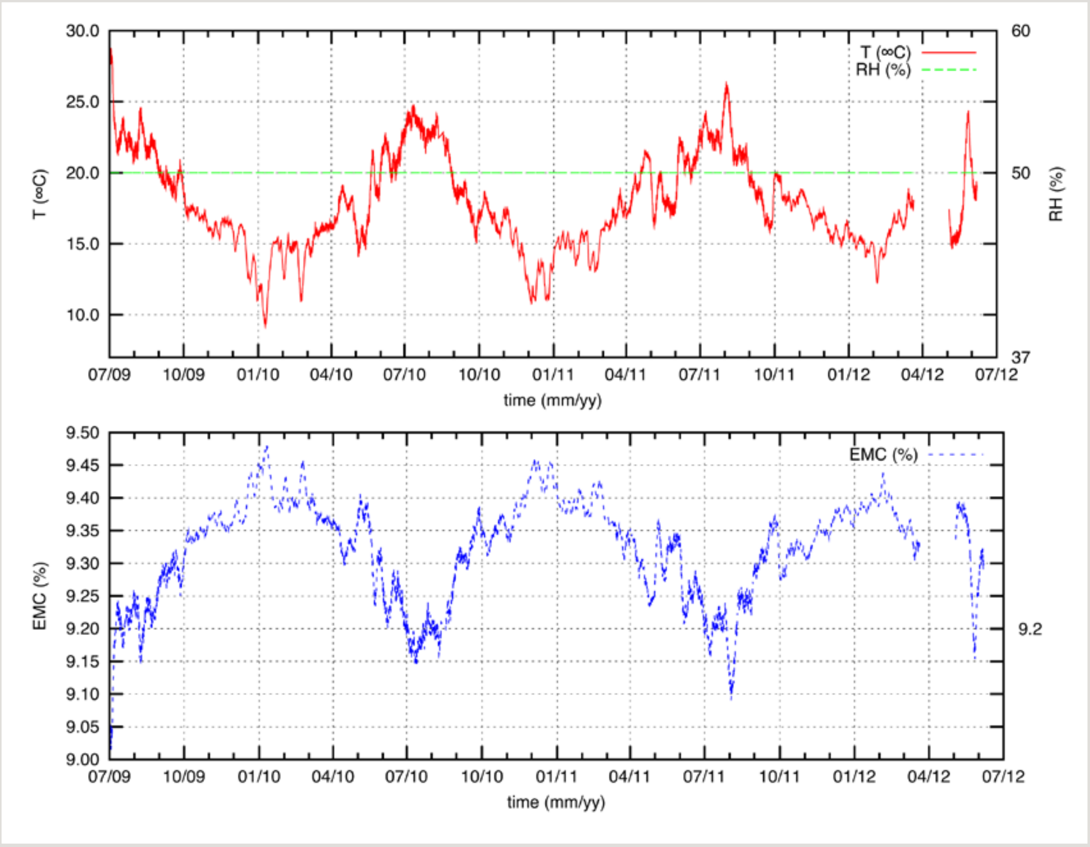

Figure 6. The potential EMC variations under hypothetically stable RH and temperature fluctuating in the experimental range

similar trend, the maximum strain across the width of the boards for instance, is smaller in the **dendro oak** sample (0.605 %) than that found in the **fresh oak** sample (0.850 %). Our measured values are much greater than those reported by Klein and Bröker [13] but are similar to those reported by Brewer and Forno [12].

Klein and Bröker measured 0.2 % and 0.15 % strain across the grain in 15 mm thick radially cut **fresh oak** and aged oak (not archaeological) respectively, when the RH increased from 55 to 85 %. They attributed the difference between fresh and aged oak to differences in the density of the two samples they measured. Brewer and Forno measured a 0.69 % strain in the unrestrained part of a 3.3 mm thick cradled panel made of radially cut oak (unaged) when the RH was increased from 33 % to 72 %. They also measured 0.47 % strain in an uncradled panel (unaged wood) when RH increased from 29 % to 80 %. The strain values in the latter study corresponded better to our **dendro oak** sample, while strain values for the **fresh oak** sample were much higher than in either study. The variation in results in the two studies compared to ours may be due to several factors: the extent of seasoning of the **fresh oak** sample or the measurement systems used, in addition to the fact that the **dendro oak** is chemically and structurally more deteriorated than fresh wood.

Chemical analyses of the Oseberg oak showed that it is highly depleted in both hemicellulose and amorphous cellulose, which would theoretically make it less polar than fresh wood; the lignin is more oxidized than that found in **fresh oak**, making it more polar than that found in **fresh oak** [17]. Modulus and strength measurements in the grain direction showed that Oseberg oak had between 15 to 30 % of the bending strength and about 20 % of the modulus of elasticity compared to that of **fresh oak** [11].

Another factor to consider when comparing the **fresh oak** sample with the **dendro oak** sample is the treatment received by the Oseberg wood (linseed oil and creosote). To what extent does this surface treatment affect our results? It is difficult to answer this question without further analysis of the data, but when considering short-term fluctuations in RH, the surface treatment will most likely buffer the wood to some extent, however for long-term fluctuations (summer vs. winter) we observed that the **fresh oak** and **dendro oak** samples follow the same pattern.

Unrestrained (dendro oak) vs. restrained samples (upper ship and lower ship)

Relative to the **dendro oak** sample, the maximum extent of % strain from the restrained samples were significantly smaller. The extent of maximum strain for the **upper ship** was 0.302 %, while that for the **lower ship** was 0.213 % (Table 1). The difference in response of the restrained samples was expected when compared to **dendro oak**, since they cannot freely respond because they are riveted into place.

What does this mean?

If we consider the threshold value of 0.4 % strain as the average yield point for un-degraded wood (when deformation becomes permanent) we can see that the measurements for both **fresh oak** and **dendro oak** samples go beyond this value (0.599 % strain for **dendro oak**). However, the strain at which the yield point occurs for the **dendro oak** may be quite different from 0.4 %. We must also evaluate whether strain hardening has occurred in a similar way as it would for fresh wood. Strain hardening of wood is the phenomenon observed after climatic cycling, where permanent

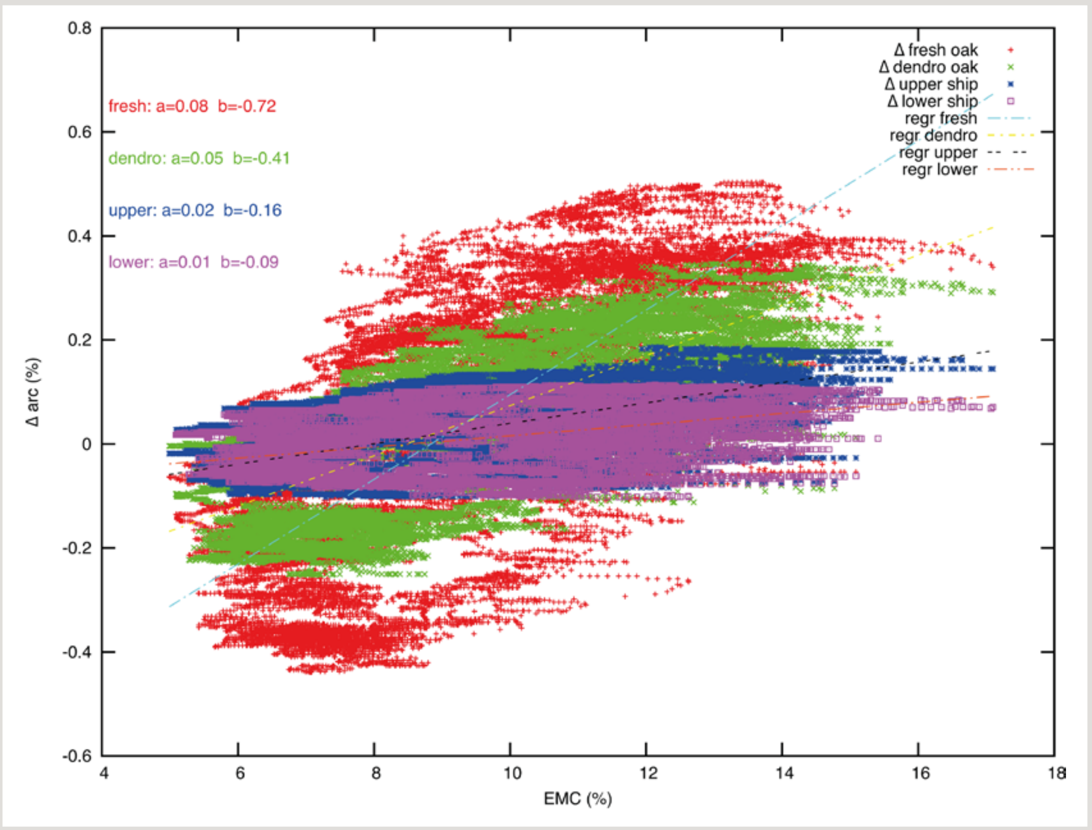

Figure 7. The plot of % strain for each sample vs. EMC for the period 2010/11. Linear regression was calculated without taking into account the delayed response time

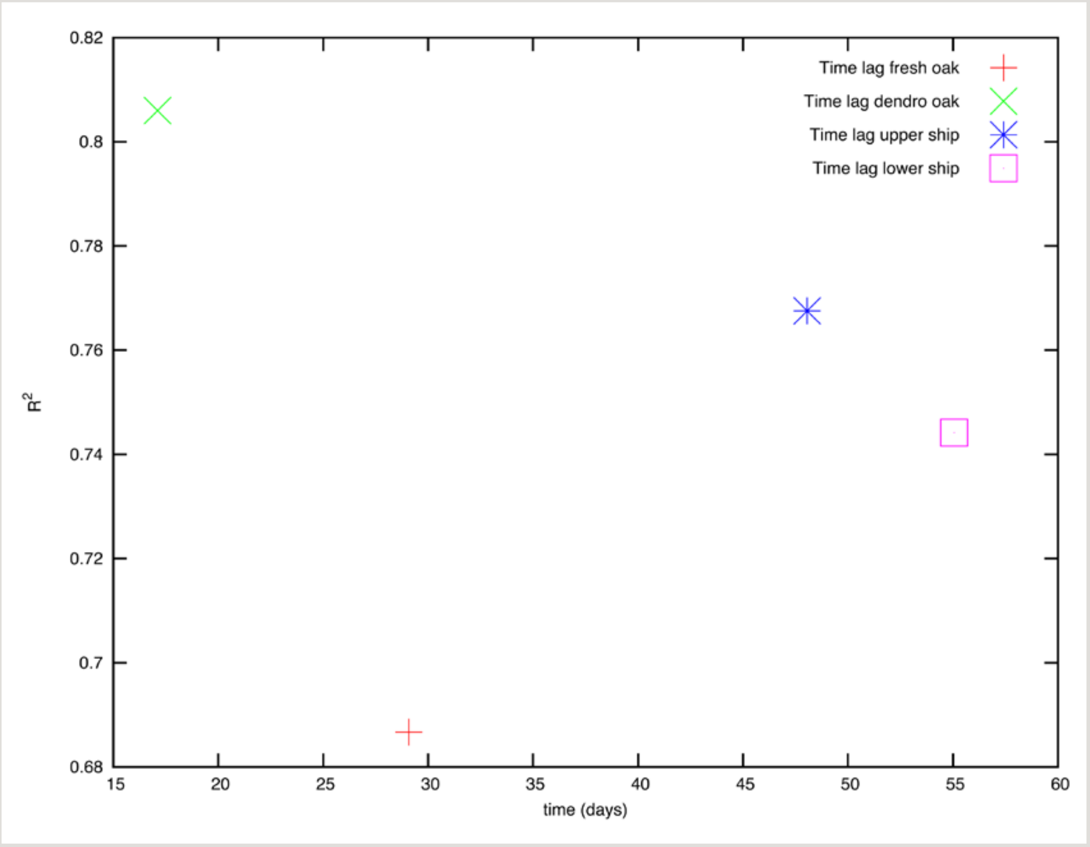

Figure 8.
Estimation of the response delay of the different samples using the maximization of the R^2

(plastic) deformation occurs at a higher level of strain [18]. The presence of existing cracks must also be considered for the archaeological samples as they may contribute to the alleviation of the absorbed stresses, without necessarily affecting the dimensions of the gross sample.

Estimating response time of the wood to climatic variation

The slope of the linear regression undertaken for each sample vs. EMC estimates their different hygro-mechanical reactivity magnitudes (Figure 7). The greater the slope of the regressed linear equation, the greater the warping sample response to climate variations [19]. The slopes obtained using this analytical tool show clearly the different magnitudes of reactivity of the samples: the **fresh oak** has the highest reactivity magnitude, as expected, followed by the **dendro oak**, at a slightly lower level. Both the **upper ship** and the **lower ship** have much lower slopes, with the **upper ship** having a slightly higher value. This difference can reasonably be related to the different constraint level.

The slope found for the **dendro oak** sample is about three times greater than those for the **upper ship** and **lower ship**. Since the material is reasonably similar in all samples, the differences in % strain could suggest the accumulation of stress due to constraint in **upper-** and **lower ship** samples. Figure 5 shows that the response of the wood samples to seasonal climate fluctuations are significantly delayed. By maximizing the coefficient of determination (R^2) of the sample's response relative to EMC, response time can be estimated. The estimated response times for each sample (as shown in figure 8) may then be used to generate a new scatter plot (Figure 9) which takes into account the response delay parameter, decreasing data dispersion. While the delay

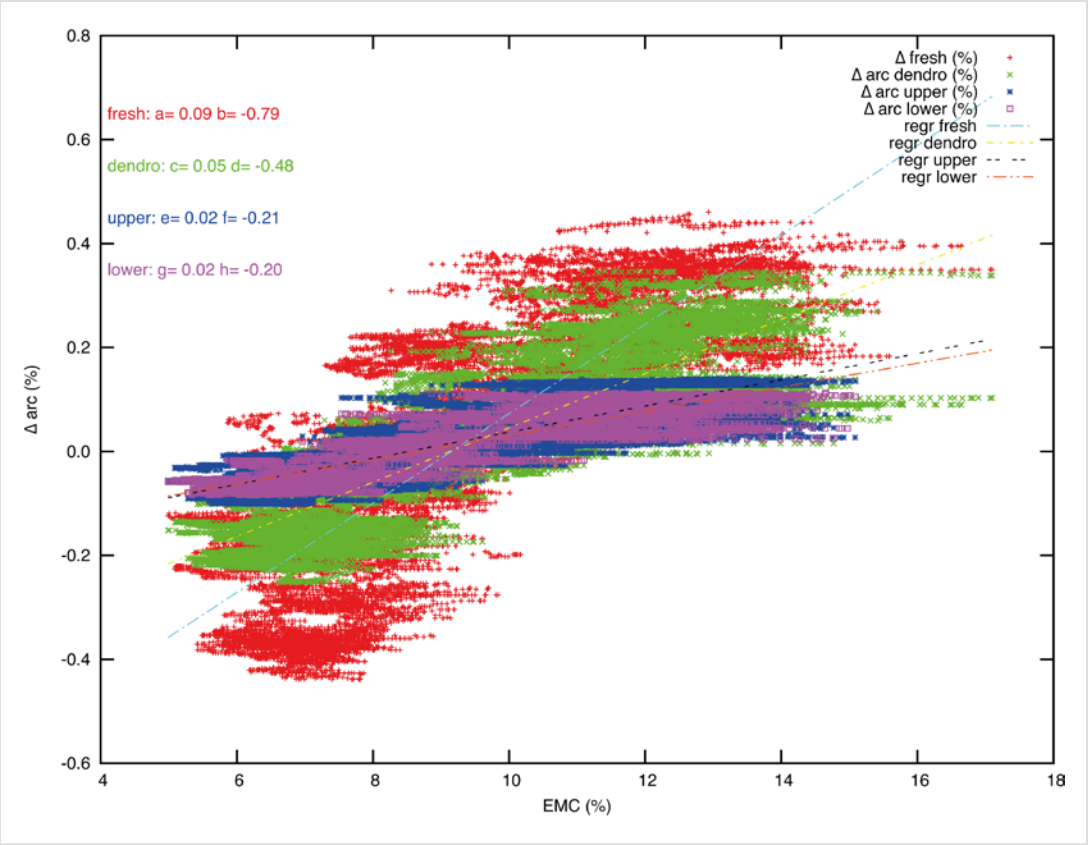

Figure 9. The plot of % strain for each sample vs. EMC for the period 2010/11. Linear regression was calculated by taking into account the delayed response time

values obtained for the archaeological samples are very consistent, according to the different constraint level, it is unclear why the **fresh oak** delay is higher than the **dendro oak**.

Conclusion

For both in-plane and out-of plane deformations, greatest changes were observed in the **fresh oak** followed by the **dendro oak**. The **upper ship** showed a greater extent of % strain than that measured in the **lower ship**. The results demonstrated that the extent of restraint affects the response, which was expected. The **fresh oak** sample was very reactive, showing large variations in % strain.

Has the material making up the ship stabilized after all these years in the same conditions? Has the object been proofed after being exposed to repeated annual cycling? An understanding of the general trend will be evident as we continue to monitor changes over the years.

A further experimental setup has been designed and is planned to be implemented in order to determine the magnitude of forces absorbed by the restrained samples in the ship. In this way, long-term hygro-mechanical effects of absorbed stresses in structural elements can be better understood. These data will eventually be used to validate a Finite Element Model aiming to describe the hygro-mechanical behavior of archaeological wood.

Acknowledgements

The authors gratefully acknowledge the generous support of COST ACTION IE0601, Wood Science for Cultural Heritage, which provided funding for Paolo Dionisi-Vici's stays in Oslo during the planning and installation phases of the monitoring system. The authors would also like to thank the reviewers for their helpful comments to the paper.

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