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NON-DESTRUCTIVE INVESTIGATION OF MATERIAL PROPERTIES OF THE *VASA* WARSHIP: A PILOT STUDY

Thomas Kruglowa[1], *Robert Kliger*[2]

ABSTRACT

The *Vasa* warship is one of the most important national treasures of Sweden. In 1956, the pride of the Swedish navy was located on the seabed, before the ship was raised in 1961.
In order to maintain the integrity of the *Vasa* warship, conservation treatment was carried out during a period of 17 years after salvage. This PEG (Poly Ethylene Glycol) treatment prevented the ship from serious shrinkage and distortion that would have caused collapse of the cell walls. These degradation processes have diminishing effects on the strength and stiffness of the ship structure. During the last 10 years, interest has focused on the mechanical properties of *Vasa* oak and the influence of PEG penetration in oak. Global non-destructive testing (NDT) of the mechanical properties, combined with semi-destructive tests (SDT) to predict both strength and stiffness parameters of the *Vasa* oak as input information, is of great importance when it comes to defining the real structural behaviour.
The main aim of the paper was to compare the applicability of property prediction through non-destructive and semi-destructive testing. In particular, portable X-ray equipment was used in this study to obtain accurate density measurements on site which are valuable in establishing a relationship between the influence of stiffness parameters and PEG and X-ray density.
It was possible to obtain accurate estimates and a strong correlation with the density of *Vasa* oak structural components using X-rays in combination with digital image processing. The proposed procedure can be used in situ with satisfactory results for the evaluation of timber properties.

Keywords: *On-site investigation,* Vasa *warship, Timber structures, Non-destructive testing, X-ray*

1. INTRODUCTION

In-situ assessment of timber elements and their properties is essential in the continuous maintenance and preservation of historical timber structures. This is especially valid when abnormal structural behaviour has been observed and the survival of the historical timber structure for a long-term period must be guaranteed. Abnormal structural behaviour can be suspected when the strength and stiffness of a structure is diminished due to deterioration, conservation works, changes in climate and natural aging of old timber [1, 2], but also when the compatibility of material in connections and joints results in changes of the load-carrying capacity of the structure. As a result, strategies for the analysis of structures of significant cultural value have to be established and applied.
The *Vasa* warship is one of the most important national treasures of Sweden. In 1956, the pride of the Swedish navy was located on the seabed, before the ship was raised in 1961. In order to maintain the integrity of the *Vasa* warship, conservation treatment was carried out during a period of 17 years after salvage. This PEG (Poly Ethylene Glycol) treatment prevented the ship from serious shrinkage and distortion that would have caused collapse of the cell walls [3].
These degradation processes have diminishing effects on the strength and stiffness of the ship structure, such as decreasing bearing capacity, loss of cross sectional area and global deformations

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[4-6]. During the last 10 years, the focus was on the mechanical properties of *Vasa* oak and the influence of PEG penetration in oak, but no final decisions were made on whether to strengthen or how to support the structure.
A conversion of a three-dimensional ship model to model the real structural behaviour might raise difficulties due to the complexity of the material properties that are needed for input. As a result, a global non-destructive assessment of the mechanical properties combined with semi-destructive tests to predict both strength and stiffness parameters of the *Vasa* oak as input information are of great importance.
Since density has a significant relationship with the mechanical properties of timber and the non-destructive parameters often relate to density, the main aim of the paper was to compare the applicability of property prediction through non-destructive and semi-destructive testing. Particularly, portable X-ray equipment was used in this study to achieve accurate density measurements on-site which are valuable for model updating purposes as well as to establish a relationship of the influence of stiffness parameters and PEG to the X-ray density.

2. EVALUATION OF NDT/SDT METHODS

In the case of structures of great heritage value, there are usually restrictions in the access of material, which makes the predictions of material parameters more difficult. The available methods might raise differences in the test results, depending on which method is used. A combination of both semi-destructive and non-destructive methods therefore might gain higher accuracy in the prediction of mechanical and physical parameters.
The use of NDT/SDT methods is however highly valuable support tools for the diagnosis and the control of intervention work in the on-site assessment of structures.
Due to the size and complexity of the *Vasa* structure, an efficient, fast and easy procedure to (directly or indirectly) scan the global parameters and analyse the critical sections of the warship should be established.
The most appropriate methods to determine the in situ density of the material proposed in this paper is considered to be the density calibration procedure using X-ray equipment, which has showed good agreement between the rendered greyscale images and the measured density of the evaluated timber specimens. In case of the *Vasa* warship, slightly larger deviations might be expected due to the effect of the attenuation coefficient from PEG. Complementary measurements might be carried out with the Resistograph® (drilling resistance) in order to verify the accuracy.
In combination with the determination of the density, ultrasonic measurements could also be of great interest for determining estimate the Young's modulus of the load-bearing ship structure. The stress-wave techniques for the determination of the E-modulus are mainly governed by the speed of the wave propagation which is though dependent on the density of the material, the internal condition of the timber, but also the moisture content. Tables for the speed of flight exist for different wood species [7]. However, due to the PEG treatment tests on the *Vasa* oak have to be performed, first on-site and the results should thereafter be verified with additional static tests. The stress wave techniques are also appropriate in the determination of internal condition of the timber.
Hardness tests have good correlations to density, but also to compressive strength and E-modulus. The fact that results are based on surface hardness might however render the tests less useful in the assessment of the (interior) *Vasa* oak due to the softening of the timber surface through the PEG treatment. Comparisons of data from surface hardness tests on waterlogged *Vasa* oak performed before the salvage of the warship [8] and PEG-penetrated *Vasa* oak might also result in erroneous conclusions due to the different nature of the two types of wood. Besides the methods described and evaluated here, there exists a number of additional NDT/SDT methods (e.g. Pilodyn method and screw withdrawal resistance method) which are expected to be less efficient for the global survey of the material and therefore should be treated as possible complementary test methods.
All additional NDT/SDT methods are expected to be less efficient for the global survey of the material, strength and stiffness properties and therefore should be treated as possible complementary tests to locally determine and verify properties where unclear problems were obtained.

3. METHOD AND MATERIALS

In this study, the opportunity to explore the average density/mass properties of on-site of the *Vasa* warship was investigated using an X-ray density calibration procedure according to Kruglowa [9].

Furthermore, laboratory tests were carried out on a limited amount of samples from the *Vasa* warship. One sample comes from a planking board at starboard side (ID 65742) and the other one from port side (ID 65743). Those samples were cut into 16 (ID 65742) and 12 (ID 65743) cubes respectively with a size 26 × 26 × 26 mm^3.
10 reference specimens of fresh oak with the same size were also included in this study to study the trend and tendency of the density and material properties. The density of the *Vasa* oak samples ranged between 800 and 1000 kg/m^3 and for the reference specimens between 650 and 690 kg/m^3. The cubes were tested in the elastic range of the material in compression in all directions, longitudinal (L), radial (R) and tangential (T) using an Instron® measurement device to log the load-deformation. The outcome of load-deformation-curve was presented as relative stiffness in each direction.
The samples were also X-rayed using the calibration procedure [9] to perceive a relation between the measured relative stiffness and the X-rayed density properties.
Furthermore, a PEG extraction using quantitative one-dimensional NMR-spectroscopy (nuclear magnetic resonance) from 8 samples, 4 from each block ID65742 and ID65743 respectively was carried out. The PEG content was then related to the stiffness and density properties of the *Vasa* oak.

4. RESULTS

A summary of some results from the tests are provided in this paper and in Kruglowa [10].

4.1. Density determination

The correlation between the measured and the X-rayed density of the tested specimens, both *Vasa* oak and reference specimens, were established. The correlation of the density was 0.85. The results show a slight overestimation of the density properties of both the *Vasa* oak and the reference specimens. The mean value of the ratio between the X-rayed density and the measured density for the *Vasa* specimens was 1.073 (0.073), using the two methods. The X-ray equipment is well-suited for estimation of the density. This slight overestimation might be due to the PEG content, but also to a small extent to the uncertainty of the sensitivity of the portable low energy level X-ray equipment. In case of the density from the reference specimens, the mean differences of 4% were in the range of the uncertainty of the method which was proposed by Kruglowa [9].
Regarding the influence of PEG concentrations on the density properties, there exists a clear increasing correlation (0.64) with increasing PEG content which makes it possible to reach good agreement in the approximation of the density of *Vasa* oak in ranges from 30% to 50% in PEG content (Fig. 1).

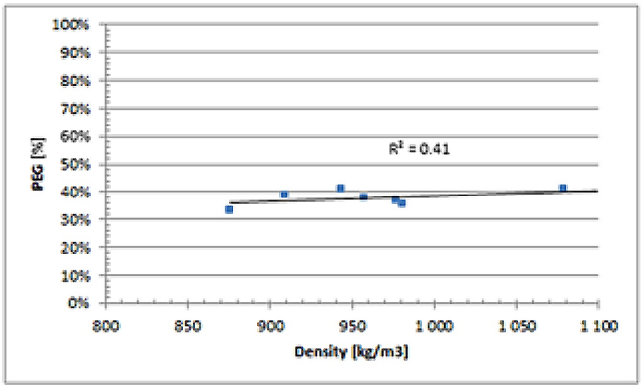

Fig. 1 Relationship between the PEG content and the density of *Vasa* oak [10]

4.2. Verification of density on structural components

To predict the timber density on the *Vasa* warship, the *in-situ* density measurement using a calibrated wedge was tested and verified on a well-known *Vasa* oak specimen (Fig. 2). The application and determination of the density is well described by Kruglowa [9].
The coefficient of determination (R^2) for the evaluation of the density properties ranged between 0.77 and 0.98, i.e. that the density properties were highly correlated to the greyscale values and therefore had to be judged as satisfying results in the determination of the in situ density properties of the *Vasa* oak. The summary of the results on the density from the on-site investigation on different locations are presented in [10]. The results show variations in the density measurements, which can be referred

mainly to the chemical treatment (PEG). It is also assumed that the PEG had less erroneous X-ray impact in the density evaluation of structural components than on the clear wood specimens.

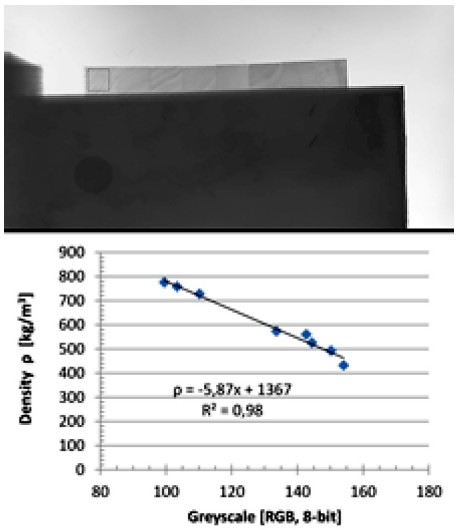

Fig. 2 Example of on-site verification of the greyscale density calibration procedure on an oak-specimen (ID 65542) from the *Vasa* warship [10]

4.3. Stiffness properties

The relationship between the density of the test specimens and the relative stiffness was investigated. The relative stiffness parameter describes only the relation of the differences from the results between the reference specimens and the *Vasa* specimens.

In all directions (R,T,L) a tendency of decreasing relative stiffness with increasing density was achieved with the reference specimens included. These results can only be used to illustrate that there exists a clear diminishing effect of the stiffness properties. The approximate loss of stiffness might be expected to range between 20% and 35% in the longitudinal direction, whereas the stiffness loss in the tangential and the radial direction showed losses from 30% to about 55%.

The correlation without the reference specimens was very weak, but when PEG was possible to be included in the evaluation, the correlation between the relative stiffness parameter and the PEG content ranged from 0.42 to 0.59 and showed a clear linear tendency of decreasing stiffness with the increase of PEG content for ranges from 30% to 50 % in PEG content (Fig.3). These cross-correlations can in a further step be applied to determine the mechanical properties of *Vasa*'s ship structure in a global survey using NDT testing. The regression equation can be expected to become decreasingly exponential for the whole range from 0% to 50% in PEG content [6] with a correlation of up to 70%.

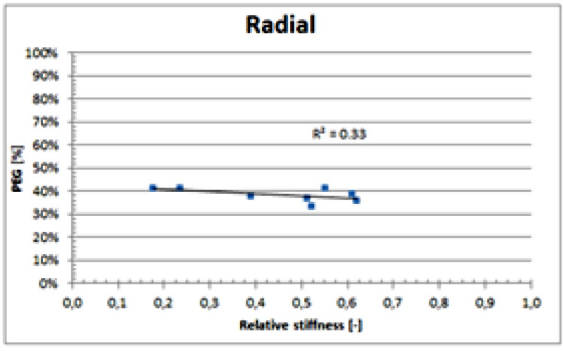

Fig. 3 Example of relationship between the PEG content and the relative stiffness parameters of *Vasa* oak in radial direction. The same tendency applies for the longitudinal and tangential direction

5. CONCLUSIONS

1) It was possible to obtain accurate estimates and a strong correlation with the density of *Vasa* oak structural components using X-rays in combination with digital image processing.

2) The proposed procedure can be used in situ with satisfactory results for the evaluation of timber properties.
3) The negative influence of the PEG content resulted in a slight overestimation of the density which is on the safe side for the evaluation of the load-carrying capacity.
4) The correlation between the indicative stiffness and the density properties was weak, but good agreement between the density properties was reached through cross-correlation between PEG and the density properties and PEG and the indicative stiffness parameters.

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