Transverse mechanical behaviour and moisture absorption of waterlogged archaeological wood from the Vasa ship

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Abstract

Damage on the hull of the 17th century Swedish warship Vasa has been observed recently. Damage in the form of indentations in the wood is caused by high compressive loads from the support structure. In the process of developing an improved support structure, radial mechanical properties and the deformation mechanisms of Vasa oak are particularly important. Causes of differences in PEG content and oak degradation are also of interest. The radial modulus and compressive strength of Vasa oak are 50\% lower than for recent oak. Furthermore, a significant change in failure mechanism is observed. More brittle separation fracture of the rays of Vasa oak is observed compared to the continuous folds of rays in recent oak. Tangential stiffness and strength are also 30\% and 50\% lower, respectively. Comparably small differences in moisture absorption between PEG-extracted Vasa oak and recent oak indicate a low extent of degradation of the Vasa oak.

Keywords: archaeological oak; mechanical properties; PEG; rays.

Introduction

The Vasa is a well-preserved 17th century warship almost entirely made from oak. In 1628, on her maiden voyage, she sank in the centre of Stockholm, where she remained for 333 years. The ship, which was located in 1956, was preserved by impregnation with polyethylene glycol (PEG) and is now displayed in the Vasa museum in Stockholm. Damage in the form of indentations has recently been observed on the hull. These indentations are caused by high compressive reaction forces from the support structure, and design of a new support system is being considered to avoid further damage. For development of a new support, data on properties such as the stiffness and strength of the Vasa oak are needed. A better understanding of how these properties are influenced by moisture, PEG content, loading direction and time of loading is also desirable.

Archaeological wood is defined as old wood showing traces of past workmanship. In the case of waterlogged archaeological wood, degradation mechanisms are of interest. Waterlogged archaeological wood has, in most cases, been subjected to an anaerobic environment in which fungal attack is limited. Instead, degradation in water is caused by bacteria (Blanchette et al. 1991; Björndal et al. 1999). The main effects are a decrease in hemicellulose content and, to a lesser extent, cellulose content, whereas lignin shows few signs of deterioration (Bednar and Fengel 1974; Kommert 1986; Küdel and Reinprecht 1990). Previous studies on compressive mechanical properties of waterlogged archaeological wood of different origins (Bednar and Fengel 1974; Kommert 1986; Küdel and Reinprecht 1990; Schniewind 1990) showed that a significant reduction in strength parallel to the grain is involved, although the woods were often significantly older and more degraded than the Vasa oak.

It is not easy to study the Vasa oak from a more fundamental point of view, since the tissue is degraded and modified by the addition of PEG. PEG was added to the Vasa oak to decrease shrinkage upon drying of the wood and may be present in both the cell wall and the lumen. The Vasa has been sprayed with PEG-water solutions for more than 15 years. PEG diffuses into the oak, but the concentration is higher at the surface than in the interior (Glastrup et al. 2006). Accordingly, not the state of degradation and the PEG content are expected to show gradients through the thickness of the planks.

Based on moisture absorption data, it is possible to develop an understanding of the presence of PEG and the state of degradation of oak planks. Schniewind (1990) reviewed the physical and mechanical properties of several types of archaeological wood and found that, in general, ancient waterlogged wood absorbs more moisture than recent oak, even though the hygroscopic hemicelluloses are degraded. The data reported by Hoffman (1986a) on oak from the Bremen Cog confirm this. The explanation for this phenomenon is that the porosity of degraded cell walls is higher and thus the capillary forces for water absorption are more pronounced.

The objective of this study was to determine transverse mechanical properties for oak from the Vasa for the design of a new support system. The main focus was on radial properties, since the current support system and any new support structure will apply loads to the hull primarily in the radial direction of the wood. Furthermore, a comparison between the properties of the Vasa oak and recent oak is fundamentally important. Moreover, causes of differences in the mechanical behaviour, such as PEG content and differences in moisture content, are of interest.
Materials and methods

Material

Sampling of material from the ship is restricted for obvious reasons. The material described in this study was taken from a piece cut from the bottom of the ship in 1971 when ventilation ducts were installed. In the lengthwise direction of the ship, the sampling location is approximately mid-ship. The dimensions of the piece were 185×99×143 mm³ (L x R x T).

Compressive testing

Compressive testing was performed in a climate-controlled environment using an Instron universal testing machine with a 5-kN load cell. The test specimen was placed between two parallel plates and compressed at 2 mm min⁻¹. A CCD camera was focused on the cross-section of the specimen and six images per second were collected. The photographs were analysed using ARAMIS software developed by GOM GmbH in Germany, which calculates displacement and strain. For compressive testing, seven test specimens for each direction (tangential and radial) of approximately 10×10×10 mm³ were taken from different depths. The specimens were cut, planed and conditioned at room temperature at approximately 55% relative humidity (RH) for 4 weeks, which represents the climate held in the museum.

To ensure parallel loading, end planes were milled. Density was determined by measuring the weight and volume of conditioned specimens. Details for calculating Young’s modulus and compressive strength are described in Ljungdahl et al. (2006).

PEG content determination

PEG was extracted with chloroform in a Soxhlet apparatus for 7 h in room temperature. The PEG content is presented as weight percentage based on the evaporated extract related to the dry specimen weight prior to extraction.

Dynamic vapour sorption (DVS) analysis

Sorption experiments were performed in a Surface Measurement Systems Plus II DVS oven. Approximately 20 mg of material was required for analysis. First, the DVS system was programmed to run at 0% RH for 2 h to completely dry the sample. The RH was then increased in nine steps up to 95% RH, which is the upper limit of the system. The sample was considered to be in a steady-state condition when the weight gain per min was lower than 0.01%. The “Vasa PEG” was extracted from Vasa oak at room temperature with water as the solvent. It also contains water-soluble substances other than PEG.

Results and discussion

Mechanical behaviour in radial and tangential compression

Figure 1 shows compression test data for the radial and tangential directions of oak from the Vasa in comparison with data from Ljungdahl et al. (2006) for recent Quercus robur. Vasa oak shows greater scatter in Young’s modulus and yield strength than recent oak. From these curves, Young’s modulus (E) was calculated by the averaging method described by Ljungdahl et al. (2006). Tables 1 and 2 provide data for each specimen, together with the PEG content and density in the radial and tangential directions. Mean values for recent oak data from Ljungdahl et al. (2006) are also included. It is evident that stiffness and strength in radial compression are significantly lower in Vasa compared to recent oak, regardless of the distance from the outer surface. The radial Young’s modulus and yield stress of Vasa oak are approximately 50% lower.

Failure in radial compression of Vasa oak takes place by a different mechanism compared to recent oak. In the latter, multisieriate rays collapsed in the earlywood via a microbuckling mechanism (Ljungdahl et al. 2006). In the Vasa oak, rays also collapsed in the same region, although the collapse appeared to take place by a more brittle separation fracture. Figure 2 presents sketches of the difference in ray failure patterns, showing continuous ductile folds for recent oak and more abrupt ray fracture for Vasa oak.

Figure 3 shows micrographs of the failed rays. For recent oak, the ray is buckled, but still shows a continuous structure, in contrast to the fractures and separation of individual ray cells in the case of Vasa oak. The intercellular adhesion between cells in Vasa oak appears to be weakened. Although lignin is more stable than hemicelluloses and cellulose, there are reports of lignin degradation in waterlogged archaeological oak (Singh et al. 2003). Weakening of the middle lamellae is probably due to the elimination of pectins and changes
Table 1  Radial compressive test results.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Surface distance (mm)</th>
<th>Density (kg m⁻³)</th>
<th>Moisture content (%)</th>
<th>Yield stress (MPa)</th>
<th>Yield strain (%)</th>
<th>PEG content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial 1</td>
<td>6</td>
<td>1069</td>
<td>9.8</td>
<td>1.04</td>
<td>8.7</td>
<td>1.04</td>
</tr>
<tr>
<td>Radial 2</td>
<td>18</td>
<td>1026</td>
<td>8.1</td>
<td>1.05</td>
<td>8.5</td>
<td>1.05</td>
</tr>
<tr>
<td>Radial 3</td>
<td>31</td>
<td>1063</td>
<td>9.6</td>
<td>0.98</td>
<td>9.3</td>
<td>1.15</td>
</tr>
<tr>
<td>Radial 4</td>
<td>50</td>
<td>1013</td>
<td>11.1</td>
<td>0.90</td>
<td>7.8</td>
<td>1.07</td>
</tr>
<tr>
<td>Radial 5</td>
<td>65</td>
<td>1028</td>
<td>9.5</td>
<td>0.95</td>
<td>9.7</td>
<td>1.22</td>
</tr>
<tr>
<td>Radial 6</td>
<td>77</td>
<td>1027</td>
<td>9.7</td>
<td>0.81</td>
<td>6.7</td>
<td>1.03</td>
</tr>
<tr>
<td>Radial 7</td>
<td>90</td>
<td>984</td>
<td>10.2</td>
<td>0.88</td>
<td>8.5</td>
<td>1.17</td>
</tr>
<tr>
<td>Vasa oak average</td>
<td>–</td>
<td>1030</td>
<td>9.7</td>
<td>0.95</td>
<td>8.5</td>
<td>1.10</td>
</tr>
<tr>
<td>SD</td>
<td>–</td>
<td>29</td>
<td>0.9</td>
<td>0.09</td>
<td>0.99</td>
<td>0.07</td>
</tr>
<tr>
<td>Recent oak average (n=5)</td>
<td>–</td>
<td>780</td>
<td>11.9</td>
<td>1.75</td>
<td>16.1</td>
<td>1.13</td>
</tr>
<tr>
<td>SD</td>
<td>–</td>
<td>9</td>
<td>0.6</td>
<td>0.02</td>
<td>0.68</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 2  Tangential compressive test results.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Surface distance (mm)</th>
<th>Density (kg m⁻³)</th>
<th>Moisture content (%)</th>
<th>Yield stress (MPa)</th>
<th>Yield strain (%)</th>
<th>PEG content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangential 1</td>
<td>6</td>
<td>1082</td>
<td>9.8</td>
<td>0.87</td>
<td>5.5</td>
<td>0.91</td>
</tr>
<tr>
<td>Tangential 2</td>
<td>19</td>
<td>1040</td>
<td>9.7</td>
<td>0.53</td>
<td>4.0</td>
<td>0.96</td>
</tr>
<tr>
<td>Tangential 3</td>
<td>32</td>
<td>1046</td>
<td>9.4</td>
<td>0.62</td>
<td>5.5</td>
<td>1.08</td>
</tr>
<tr>
<td>Tangential 4</td>
<td>45</td>
<td>998</td>
<td>9.2</td>
<td>0.69</td>
<td>5.2</td>
<td>0.95</td>
</tr>
<tr>
<td>Tangential 5</td>
<td>58</td>
<td>1063</td>
<td>9.2</td>
<td>0.86</td>
<td>6.2</td>
<td>0.93</td>
</tr>
<tr>
<td>Tangential 6</td>
<td>75</td>
<td>1100</td>
<td>9.2</td>
<td>0.90</td>
<td>7.1</td>
<td>0.99</td>
</tr>
<tr>
<td>Tangential 7</td>
<td>88</td>
<td>1038</td>
<td>9.3</td>
<td>0.54</td>
<td>5.8</td>
<td>1.05</td>
</tr>
<tr>
<td>Vasa oak average</td>
<td>–</td>
<td>1052</td>
<td>9.4</td>
<td>0.72</td>
<td>5.6</td>
<td>0.98</td>
</tr>
<tr>
<td>SD</td>
<td>–</td>
<td>33</td>
<td>0.3</td>
<td>0.16</td>
<td>1.0</td>
<td>0.06</td>
</tr>
<tr>
<td>Recent oak average (n=5)</td>
<td>–</td>
<td>771</td>
<td>11.7</td>
<td>1.04</td>
<td>10.4</td>
<td>1.11</td>
</tr>
<tr>
<td>SD</td>
<td>–</td>
<td>6</td>
<td>0.6</td>
<td>0.02</td>
<td>0.1</td>
<td>0.02</td>
</tr>
</tbody>
</table>

in the supramolecular structure of all macromolecules in the compound middle lamellae. In both oaks, ray failure was followed by plastic collapse in the earlywood layer. The more brittle ray separation fracture in Vasa oak is remarkable. As mentioned in the introduction, water-

Figure 2  Sketches of ray collapse in (a) recent and (b) Vasa oak.

Figure 3  SEM micrographs of ray collapse in (a) recent and (b) Vasa oak. Scale bars represent 100 μm.
logged oak is frequently degraded by bacteria (Blanchette et al. 1991; Björndal et al. 1999). Hoffmann (1986b) also observed abiotic hydrolytic degradation of the rays in oak from the Mayence Roman Ships. A microscopic study of the Vasa oak revealed that parenchyma cells are more degraded than the fibres (Barkman 1967). In the Vasa oak it is possible that specific degradation mechanisms in the rays contribute to the lower strength. Another possibility is that the presence of PEG decreases the mechanical properties, as suggested by Rowell and Youngs (1981).

Ray properties are apparently the crucial point for radial collapse in Vasa oak. On the other hand, rays are less important for tangential properties. In the tangential direction, the stiffness of Vasa oak is 30% lower than for recent oak. The tangential compression strength is approximately 50% lower. The scattering of tangential properties is greater than for the radial properties. The plateau region shows a significant upward slope for Vasa oak. This is likely to be due to the PEG present in the lumen. The failure mechanism of Vasa oak in tangential compression is similar to that in recent oak: latewood vessels collapse.

**PEG content**

The PEG content in all the Vasa oak specimens is listed in Tables 1 and 2. Based on these data, we suggest that the PEG content is fairly equal throughout the depth of the original sample, although a gradient can be expected (Glastrup et al. 2006). The history of the specific piece revealed that it absorbed PEG from water solution through the cut surfaces after its removal from the ship. The test specimens used in this study were cut adjacent to such a surface, which explains the similar PEG contents. Figure 4 displays specimens compressed to 20% strain. At this stage, a black liquid was extruded from the Vasa oak, as observed in Figure 4b. This liquid likely consists of a PEG/water solution contaminated by unidentified (humic) compounds, and is apparently present in the lumen of the collapsing wood cells. According to Figure 4b, rays also contain significant amounts of the liquid. At this compression, all earlywood layers showed plastic collapse. The presence of a liquid water solution in Vasa oak at 55% RH is an obvious disadvantage from the point of view of Vasa preservation.

The variation of radial Young's modulus and PEG content through the plank thickness is also presented in Tables 1 and 2. There is no significant correlation between modulus values and position or PEG content. Within the range of PEG contents present in the samples, there is no apparent effect on the modulus. Again, the modulus in the tangential direction shows great scatter.

**Sorption isotherms**

Sorption isotherms may offer insights into the contributions from PEG and oak to moisture absorption. Figure 5 shows sorption isotherms for three types of oak, PEG 1500, and “Vasa PEG” containing PEG and other water-soluble compounds extracted from Vasa oak. Vasa and recent oak samples showed small differences in moisture absorption. The variation of radial Young’s modulus and PEG content through the plank thickness is also presented in Tables 1 and 2. There is no significant correlation between modulus values and position or PEG content. Within the range of PEG contents present in the samples, there is no apparent effect on the modulus. Again, the modulus in the tangential direction shows great scatter.

**Figure 4** (a) Recent and (b) Vasa oak compressed to 20% strain. The black fluid is contaminated PEG/water solution. The horizontal width of specimens is 10 mm.

**Figure 5** Sorption isotherms for several materials. Equilibrium moisture content (EMC) versus relative humidity. (b) Magnification of the lower region of EMC in (a); note the different scales on both axes.
content under the compressive test conditions at 55% RH. Accordingly, the reduced properties of Vasa oak cannot be explained by differences in moisture content.

The data for recent oak are in good agreement with the literature (Stamm 1968; Dinwoodie 2000). The difference in moisture content at steady-state conditions between PEG-extracted Vasa oak and recent oak is small. This finding indicates that core samples of Vasa oak are not strongly degraded, especially considering that the density of PEG-extracted Vasa oak is in the normal range. Several investigations have demonstrated that the hygroscopicity of archaeological wood increases as a function of the extent and mechanisms of degradation (Schniewind 1989, 1990). A common indicator of the degree of degradation is maximum moisture content, which can be close to 400% for severely degraded oak. Waterlogged recent oak has a maximum moisture content of approximately 130% (Hoffmann 1986a,b, 1988). Furthermore, from Figure 5b it is evident that PEG-impregnated Vasa oak showed a similar moisture uptake (50%) as extracted Vasa oak below 50% RH, after which the PEG-containing Vasa oak absorbed moisture more quickly than the two other oaks. Virgin PEG 1500 has low hygroscopicity at RH levels below 50%, but above this RH level the hygroscopicity increases rapidly. The “Vasa PEG” is more hygroscopic than PEG 1500 in the lower RH range, indicating that it contains PEG of lower molecular mass and other hygroscopic compounds. The results reported by Hoffmann (1986a) for sorption experiments on PEG 200 and PEG 3000 showed that the former is significantly more hygroscopic in the 10–70% RH region than the latter.

Extracted Vasa oak absorbed moisture in a similar manner to recent oak up to approximately 80% RH, after which the extracted Vasa wood became more hygroscopic. The increased absorption at high RH is expected, since degraded wood is more porous and more capillary condensation may occur. Degradation leads to oxidised chemical groups, which increase the hygroscopicity. Moreover, the Vasa oak is more hygroscopic due to the presence of water-extractable “Vasa PEG”. At RH > 83%, capillary condensation of other oak substrates contributes to this effect. These findings are supported by those of Glastrup et al. (2006), who determined the distribution of PEG molar mass in Vasa oak. Large amounts of low-molar-mass PEG (< 1000) were detected, together with distinct peaks at 1500 and 4000 Da.

The Vasa oak does not show the expected reduction in moisture content due to the presence of PEG (Figure 5). One reason may be the large content of PEG in lumina in combination with the presence of low-molar-mass PEG and other hygroscopic compounds, which are probably composed of degradation products.

Conclusions

The radial modulus and compressive strength of Vasa oak are 50% lower than the values for recent oak, although the moisture content and density are similar. Compressive failure occurs by ray microbuckling in the earlywood layer. While rays in recent oak develop continuous folds in earlywood regions, the rays in Vasa oak reveal a more brittle separation fracture in this region. Obviously, the compound middle lamellae became weakened due to 300 years of immersion in water. The separated and fractured ray cells in Vasa oak contribute to its lower strength. The tangential modulus and compressive strength are also 30% and 50% lower, respectively, compared to recent oak. The PEG-swollen state of the Vasa oak may also contribute to the lower physical properties. Moisture sorption isotherms were not essentially different between the two oaks, except at high RH values, at which the Vasa oak is more hygroscopic. The decrease in density of Vasa oak was also low. Biotic and abiotic degradation of the Vasa oak investigated was probably not high.

The water-extracted “Vasa PEG” contains other organic and inorganic extracts from wood, as well as PEG. This extract is more hygroscopic than PEG 1500 and the extracted Vasa oak itself. A significant proportion of the most hygroscopic “Vasa-PEG” fraction is present in earlywood lumina, as indicated by the large amounts of water-containing dark liquid extruded on compression.

Determination of the causes of the property reductions observed remains a challenge.

Acknowledgements

The authors would like to thank the National Maritime Museums of Sweden (JL) and Biofibre Materials Centre (LB) for funding. Docent L. Salmén at STFI-Packforsk AB is gratefully acknowledged for valuable advice and for generously providing access to DVS equipment. Dr. Lennart Wallström at Luleå University of Technology is gratefully acknowledged for the micrographs.

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Received August 22, 2006. Accepted February 7, 2007.
Published online March 29, 2007.