Beam theory modelling of the performance of medieval yew longbows

Kristofer Gamstedt¹, Ingela Bjurhager¹, Lars Berglund¹, Daniel Keunecke² and Peter Niemz²

¹ Division of Biocomposites, Royal Institute of Technology – KTH, Stockholm, Sweden
² Wood Physics Group, Swiss Federal Institute of Technology – ETH, Zurich, Switzerland
Yew preferred material... Why?
Mary Rose
Excavation of the Mary Rose recovered the remains of:

- 179 members of the crew (43% of the total);
- 138 complete longbows (55% of the total);
- 4000 arrows (42% of the total);
- arrow spacers;
- bracers (wristguards).
- No bowstrings were recovered.
Darker heartwood visible by unaided eye (contains extractives)
Yew bow design

- Hardy (2006): Only remove bark
- Stemmler (1946): Only 1/3 or less sapwood
- Strunk (2000): Sapwood is only cosmetic
- Bertalain (2007): 1/8 – 1/2 sapwood
- Mary Rose (1545): > 1/2 heartwood at belly

No consensus. Suggestions come from tradition, archeologic findings and handicraft experience
This study

- Measure tensile and compressive behaviour of yew
- Model maximum bending storage
- Heartwood vs. “sapwood” vs. Combination
- Compare with juniper and pine
- Is there an optimal combination heartwood/sapwood?
- Why was yew the preferred material?
Microstructure

Earlywood/latewood transition in yew heartwood

Earlywood/latewood transition in yew sapwood

Small density gradients EW/LW
Irregular on knot level for young trees
Tensile and compressive properties

### Tensile properties

<table>
<thead>
<tr>
<th>Wood species</th>
<th>Tensile strain to failure %</th>
<th>Tensile strength MPa</th>
<th>Young’s modulus GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extracted yew</td>
<td>1.24 (0.19)</td>
<td>119 (20)</td>
<td>9.1 (1.4)</td>
</tr>
<tr>
<td>Non extracted yew</td>
<td>1.16 (0.22)</td>
<td>112 (17)</td>
<td>9.2 (1.2)</td>
</tr>
<tr>
<td>Pine</td>
<td>1.31 (0.19)</td>
<td>119 (14)</td>
<td>9.6 (1.3)</td>
</tr>
<tr>
<td>Juniper</td>
<td>1.84 (0.42)</td>
<td>115 (23)</td>
<td>8.1 (0.7)</td>
</tr>
</tbody>
</table>

### Different from compressive properties

<table>
<thead>
<tr>
<th>Wood species</th>
<th>Yield strain %</th>
<th>Yield Strength MPa</th>
<th>Young’s modulus GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extracted yew</td>
<td>1.96 (0.17)</td>
<td>60.5 (9.9)</td>
<td>3.7 (0.3)</td>
</tr>
<tr>
<td>Non extracted yew</td>
<td>2.12 (0.17)</td>
<td>68.0 (9.9)</td>
<td>3.8 (0.5)</td>
</tr>
<tr>
<td>Pine</td>
<td>1.72 (0.09)</td>
<td>51.1 (3.7)</td>
<td>3.9 (0.2)</td>
</tr>
<tr>
<td>Juniper</td>
<td>2.01 (0.13)</td>
<td>50.3 (3.3)</td>
<td>3.1 (0.3)</td>
</tr>
</tbody>
</table>

Yew has better compressive performance, especially with extractives...
Stress-strain curves of yew

Non-extracted Yew tensile specimen

Tension

Compression
Desired mechanics properties
(Hickman et al., 1947)

• High specific bending strength, B/\rho
• Low specific modulus, E/\rho

Generally favours hardwood

Yew is an exception, because
• Unusually fine grained
• High bending strength and lower modulus
Bracing and drawing

Compressive normal force

Moments by drawing

Sapwood at back

Heartwood at belly

$N$

$M$
Stress state in beam element

- Sapwood
- Heartwood

Stress state diagram:
- Compressive failure
- Tensile failure
## Maximum potential energy

<table>
<thead>
<tr>
<th>Wood species</th>
<th>Max Force, N</th>
<th>Max energy/area, kN/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extracted yew</td>
<td>162</td>
<td>47.677</td>
</tr>
<tr>
<td><strong>Non extracted yew</strong></td>
<td><strong>217.5</strong></td>
<td><strong>88.450</strong></td>
</tr>
<tr>
<td>Juniper</td>
<td>137.5</td>
<td>39.439</td>
</tr>
<tr>
<td>Pine</td>
<td>109</td>
<td>20.591</td>
</tr>
</tbody>
</table>

And the winner is: Yew heartwood!
Sapwood/heartwood ratio

Loaded energy vs share of sapwood in yew longbow

Use mainly heartwood
Constitutive properties

Key property: Compression of heartwood
Buckling mechanism in compression

Figure 6. A corrugated cell, showing dimensions.

Gibson, Easterling and Ashby (1981)
Longitudinal compression of balsa

Fig. 15. Set of micrographs showing sites of crushed tracheids at different magnifications for $p/p_\infty = 0.063$. 
Axial buckling of honeycombs (Zhang and Ashby, 1992)

Fig. 4. The axial elastic buckling of a hexagonal cell.
Remarks

- Yew preferred bow material
- Heartwood on compressive belly side
- Regular microstructure compared with other species
- Compressive/tensile properties differ, and control bending performance
- To be cont’d...