Strength and stiffness grading of structural timber

Charlotte Bengtsson SP Trätek
Växjö University
Outline

• General about grading
• Wood properties affecting grading
• Effect of grading accuracy on the yield
• Machine grading principles and machine types
• EN-standards/procedure for grading
• Future
Why strength grading?

• Accurate knowledge about timber characteristics - strength, stiffness, appearance
• Have a common classification within a market
• Obtain an engineering material, gives possibilities to develop the timber building technique
• Optimise the yield
  - Adding value
  - Use of resources
  - Optimise the use (use good enough quality)

• Timber for structural applications requires grading
• Strength, stiffness and density properties need to be known and to be controlled to stay within desirable limits
### Examples from EN 338

<table>
<thead>
<tr>
<th>Characteristic property</th>
<th>Strength class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C18</td>
</tr>
<tr>
<td><strong>Strength properties (MPa), 5%-percentile</strong></td>
<td></td>
</tr>
<tr>
<td>Bending strength</td>
<td>( f_{m,k} )</td>
</tr>
<tr>
<td>Tension strength, parallel to the grain</td>
<td>( f_{t,0.k} )</td>
</tr>
<tr>
<td>Tension strength, perpendicular to the grain</td>
<td>( f_{t,90.k} )</td>
</tr>
<tr>
<td>Compression strength, parallel to the grain</td>
<td>( f_{c,0.k} )</td>
</tr>
<tr>
<td>Compression strength, perpendicular to the grain</td>
<td>( f_{c,90.k} )</td>
</tr>
<tr>
<td>Shear strength</td>
<td>( f_{v,k} )</td>
</tr>
<tr>
<td><strong>Stiffness properties (MPa)</strong></td>
<td></td>
</tr>
<tr>
<td>MoE parallel to the grain, mean value</td>
<td>( E_{0,mean} )</td>
</tr>
<tr>
<td>MoE parallel to the grain, 5%-percentile</td>
<td>( E_{0,05} )</td>
</tr>
<tr>
<td>MoE, perpendicular to the grain, mean value</td>
<td>( E_{90,mean} )</td>
</tr>
<tr>
<td>Shear modulus, mean value</td>
<td>( G_{mean} )</td>
</tr>
<tr>
<td><strong>Density (kg/m³)</strong></td>
<td></td>
</tr>
<tr>
<td>Density, 5%-percentile</td>
<td>( \rho_{12,k} )</td>
</tr>
<tr>
<td>Density, mean value</td>
<td>( \rho_{12,mean} )</td>
</tr>
</tbody>
</table>

- Grades can also be defined elsewhere, ex. LS, L, LD for glulam laminations
Actual topic

• Implementation of new standards which allow CE-marking of strength graded timber and glulam.
• Introduction of scannersystems on sawmills is increasing.
• New grading machines on the market
• Gradewood, european research project
Production of machine graded timber in Sweden

(m³ per år)

- **Total volym**
- **Exporterad volym**
- **Inhemsk förbrukning**

SP Technical Research Institute of Sweden
Basics

- **Visual grading**
  Grading rules, with maximum knot size etc
  Trained graders
  Scanners

- **Machine strength grading**
  Prediction of strength properties
  Classification into strength classes, i.e. C18, C24 etc
Visual grading

- Visual strength grading has a long tradition
- Formal grading rules were established beginning of 20th century (US)
- 1930 and onwards visual grading rules were introduced in Europe
Visual grading

• Basis
  - Rules with criteria for each grade
  - Trained graders

• Advantages
  - Simple and cheap
  - Easy to check the quality

• Disadvantage
  - Low capacity
  - Low yield
    • Only visually recognisable characteristics can be used
    • Only simple combinations possible
**Machine grading**

- NDT for grading timber introduced in US and Australia late 1950s
- The “Machine control” system was developed in Europe in the late 1960s
- EN 519 was published 1995
- Focus on softwood species
- Machine strength grading is usually complemented with visual override requirements
- More “complicated” combinations possible
Principer för hållfasthetssortering

Två system finns:
• Maskin kontroll
• Out-put kontroll
  (resultatstyrd metod)

$R^2 \approx 0.45 - 0.60$ för vanliga maskiner
Clear Wood – Correlation between physical properties

- **Strength**
- **Density**
- **MOE**

Density 1500 kg/m³

- Primary wall
- Secondary wall
- Outer layer (S₁)
- Middle layer (S₂)
- Inner layer (S₃)
- Middle lamella

R²=0.76
R²=0.66
R²=0.64

Clear wood
Timber characteristics

Clear wood with varying properties
   Low density
   High density

Strength reducing characteristics
Knots
   • 95 % of failures in redwood (Sequoia S.)
   • 91 % of failures in Norway spruce
Slope of grain
Top failure
   • serious
   • but very frequent
Compression wood
   • not so serious
   • hard to detect
Cracks
Rot

SP Technical Research Institute of Sweden
Typical within member variability

Clear Wood Area Ratio

Longitudinal direction of the beam [mm]

CWAR [%]

150 mm
Between members variability

![Graph showing between members variability](image)

- **Stiff with small knots**
- **Less stiff with large knots**

**Flatwise MOE (N/mm²)**

- 0
- 5000
- 10000
- 15000
- 20000

**Length position (mm)**

- 0
- 1000
- 2000
- 3000
- 4000
- 5000

SP Technical Research Institute of Sweden
Radial variation

![Graph showing radial variation of density and MOE](image-url)
Anomalies

Compression wood with low MOE
Timber – Correlation between physical properties

\[ R^2 = 0.63 \]

\[ CV_r = 18\% \]

\[ N = 407 \]

Clear wood: \( R^2 = 0.76 \)

40x145 mm Norway spruce

Modulus of elasticity [MPa]

Bending strength [MPa]
Timber – Correlation between physical properties

\[ R^2 = 0.1759 \]

Clear wood: \[ R^2 = 0.66 \]
Timber characteristics

Reasons for visual downgrading

Narrow face knots

NFK 74%

KNC 4%

BAP 1%

TOR 1%

COW 1%

LT40 18%

ARW 1%
## Prediction of strength

<table>
<thead>
<tr>
<th>Characteristics that can be measured non-destructively</th>
<th>Coefficient of determination R²</th>
<th>Source</th>
<th></th>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>1</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Bending strength</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knots</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual ring width</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MoE, bending or tension</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MoE, flatwise, short span</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knots and annual ring width</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knots and density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knots and MoE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: 1, 2, 3, 4, 5, 6

---

SP Technical Research Institute of Sweden
Prediction of strength

1 tension strength, 2 bending strength
Grading accuracy

- How well the measured characteristic predicts strength ($R^2$)
- How accurate the characteristics can be measured (CoV)
Effect of grading accuracy

- Grading C30 and better
  - CoV=0.05
  - CoV=0.1
  - CoV=0.2
  - CoV=0.3
  - CoV=0.4

- Prediction using MOE
- Prediction using knots

Coefficient of determination, $r^2$

Yield (%)

Modulus of elasticity [MPa]

Bending strength [MPa]

SP Technical Research Institute of Sweden
Yield vs. $R^2$

If $R^2 = 1$ then
- 5% C24
- 40% C30
- 55% C40

If $R^2 = 0.5$ then
- 15% C24
- 65% C30
- 20% C40

CoV = 0.1
**Machine grading principles**

- Measurement of bending stiffness
- Optical detection of knots and other characteristics
- Near-Infrared-Reflection spectroscopy (NIR)
- Resonant vibrations
- Wave propagation speed
- Neural nets
- Deconvolution technique
- Radiation methods
  - micro waves
  - x-ray
  - $\gamma$-radiation
- Combination of techniques
Machine grading principles

Flatwise bending
• Span ca 900 mm
• Deflection const. measure load
• Load const. measure deflection

Density
γ-ray
x-ray
Detectors
Density profile

Resonant vibrations
• Measures
  • length
  • frequency
  • density

\[ E_A = 4 \cdot \rho \cdot L^2 \cdot f_A^2 \]
Bending

Advantages
• Simple – not very expensive
• Measures MOE along the whole pieces
• Rather accurate at low speeds

Disadvantages
• Low speed
• Inaccurate already at moderate speed

SP Technical Research Institute of Sweden
Resonant vibrations

Advantages
• Simple – not very expensive
• Very fast

Disadvantages
• Measured MOE a weighted mean
• Low accuracy for less homogenous species with large single defects
Dynagrade™ /Precigrader™

- Capacity 100-240 pcs/min
- Used in 100+ saw mills
Sorteringsmaskiner på den Europeiska marknaden

<table>
<thead>
<tr>
<th>Name</th>
<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computermatic/Micromatic</td>
<td>Flatwise bending, measurement of deflection</td>
</tr>
<tr>
<td>CookBolinders/Techmach</td>
<td>Flatwise bending, measurement of load</td>
</tr>
<tr>
<td>Grademaster</td>
<td>Vibration and scanning</td>
</tr>
<tr>
<td>GoldenEye 702/EuroGreComat 702</td>
<td>X-ray</td>
</tr>
<tr>
<td>EuroGreComat 704</td>
<td>X-ray and bending</td>
</tr>
<tr>
<td>GoldenEye 706/EuroGreComat 706</td>
<td>X-ray and vibrations</td>
</tr>
<tr>
<td>GoldenEye 80/1</td>
<td>X-ray and laser scanner</td>
</tr>
<tr>
<td>GoldenEye 80/2</td>
<td>X-ray and laser scanner</td>
</tr>
<tr>
<td>VM Grader 1.0</td>
<td>Visual grading &amp; gravimetric density</td>
</tr>
<tr>
<td>Dynagrade</td>
<td>Vibrations in longitudinal direction</td>
</tr>
<tr>
<td>Raute Timgrader</td>
<td>Flatwise bending, measurement of load</td>
</tr>
<tr>
<td>Newnes</td>
<td>X-ray</td>
</tr>
<tr>
<td>Ersson ESG-240</td>
<td>Flatwise bending, measurement of load</td>
</tr>
<tr>
<td>Metriguard 7200 HCLT</td>
<td>Flatwise bending, measurement of load</td>
</tr>
<tr>
<td>Sylvatest</td>
<td>Ultrasonic waves</td>
</tr>
</tbody>
</table>

SP Technical Research Institute of Sweden
## Sorteringsmaskiner på den Europeiska marknaden, forts.

<table>
<thead>
<tr>
<th>Name</th>
<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precigrader</td>
<td>Vibration and density</td>
</tr>
<tr>
<td>Timber Grader MTG</td>
<td>Vibration</td>
</tr>
<tr>
<td>VISCAN</td>
<td>Vibration</td>
</tr>
<tr>
<td>Triomatic</td>
<td>Ultrasonic waves</td>
</tr>
<tr>
<td>E-Scan</td>
<td>Vibration</td>
</tr>
<tr>
<td>JRT MSR Machine</td>
<td>Bending, measurement of deflection</td>
</tr>
</tbody>
</table>

Maskiner som har inställningsvärden enligt EN 14081

[Image of equipment]
Visual vs machine grading

<table>
<thead>
<tr>
<th>Grade</th>
<th>Grade</th>
<th>$COV_{MOE}$ (%)</th>
<th>$COV_{MOR}$ (%)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual</td>
<td>S10</td>
<td>17</td>
<td>22</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>$f_{m, char} = 35,1$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$E_{mean}=14650$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine</td>
<td>T30M</td>
<td>14</td>
<td>19</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>$f_{m, char} = 35,1$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$E_{mean}=14540$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual</td>
<td>S8</td>
<td>18</td>
<td>23</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>$f_{m, char} = 28,5$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$E_{mean}=12920$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine</td>
<td>T24M</td>
<td>13</td>
<td>10</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>$f_{m, char} = 28,2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$E_{mean}=11460$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
EN-standards for grading

- EN 14081 Timber Structures – Strength graded structural timber with rectangular cross section, allowing CE-marking of graded structural timber, becomes mandatory September 2009
- This standard replaces EN 519

- Four parts
  - Part 1: General Requirements
  - Part 2: Machine Grading; additional requirements for initial type testing
  - Part 3: Machine Grading; additional requirements for factory production control
  - Part 4: Machine Grading; Grading machine settings for machine controlled systems
Standardisation

• New procedure for derivation of machine settings

• Settings applicable for one country or some countries

• Two principles
  – Machine control
  – Output control

• The standard covers both visual and machine strength grading

• Visual override requirements as previously
Machine control

• Machine control, mainly used in Europe
  – Settings based on testing, at least 900 pieces from one country or group of countries

1. Establish database containing raw material arranged in sub-samples
2. Optimum grading
3. Model building

\[ f_{\text{mod,}h=150} = k \cdot \left( \frac{t}{50} \right)^a \cdot \left( \frac{h}{150} \right)^b \cdot (IP)^c \]
Machine Control

4. Settings for actual grades when one sub-sample is left out. Repeat for all combinations.

5. Determine "production settings"

6. Grade by using the "production settings" to assigned grades
Machine control

7. Establish size matrix

<table>
<thead>
<tr>
<th>Optimum grade</th>
<th>Assigned grade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C35</td>
</tr>
<tr>
<td>C35</td>
<td>554</td>
</tr>
<tr>
<td>C24</td>
<td>34</td>
</tr>
<tr>
<td>C18</td>
<td>1</td>
</tr>
<tr>
<td>Reject</td>
<td>0</td>
</tr>
</tbody>
</table>

8. Elementary cost matrix (“weight factors”)

<table>
<thead>
<tr>
<th>Optimum grade</th>
<th>Assigned grade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C35</td>
</tr>
<tr>
<td>C35</td>
<td>0</td>
</tr>
<tr>
<td>C24</td>
<td>1,53</td>
</tr>
<tr>
<td>C18</td>
<td>3,15</td>
</tr>
<tr>
<td>Reject</td>
<td>5,418</td>
</tr>
</tbody>
</table>
Machine control

9. Global cost matrix

<table>
<thead>
<tr>
<th>Optimum grade</th>
<th>Assigned grade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C35</td>
</tr>
<tr>
<td>C35</td>
<td>0</td>
</tr>
<tr>
<td>C24</td>
<td>(34*1,53)/589=0,088</td>
</tr>
<tr>
<td>C18</td>
<td>0,005</td>
</tr>
<tr>
<td>Reject</td>
<td>0</td>
</tr>
</tbody>
</table>

10. Check “wrongly upgraded” cells

11. Check characteristic values
# Example from 14081 - 4

## Dynagrade

<table>
<thead>
<tr>
<th>Source country or countries</th>
<th>Source mark a)</th>
<th>Species</th>
<th>Permitted timber sizes b) (mm)</th>
<th>Grade or grade combination</th>
<th>Settings IP (machine units)</th>
<th>Comments and additional requirements</th>
</tr>
</thead>
</table>
| Finland                     | FI             | Spruce, *Picea abies* | $31 \leq t_s \leq 110$  
 $63 \leq b_s \leq 264$ | C24 | 4 300 000 | Actual setting, $IP$ is given in machine units and it is not effected by the timber dimensions. |
| Norway                      | NO             | Fir     | *Abies alba*                  | TR26                      | 6 150 000  
 C16 | 4 300 000 | Requirements for grading: |
| Sweden                      | SE             |         |                               | TR26                      | 6 150 000  
 C18 | 4 300 000 | – Air temperature                10°C – 50 °C  
 – Relative humidity in the air < 85 %  
 – Timber temperature  > -10 °C  
 – Timber mean moisture content between 10% and 16% |
| Estonia                     | ES             |         |                               | TR26                      | 6 150 000  
 C18 | 4 300 000 | Dynagrade  
 – Conveyor speed ≤ 1 m/sec  
 – Spacing between pieces ≥ 200mm  
 – Grading speed ≤ 100 pieces/min |
| Latvia                      | LV             |         |                               | C27 | 6 420 000 |
| Russia 4)                   | RU             |         |                               | C27 | 6 150 000 |
| Poland                      | PL             |         |                               | C30 | 6 900 000 |
| Germany                     | DE             |         |                               | C18 | 4 300 000 |
| Austria                     | AT             |         |                               | C30 | 6 900 000 |
| Czech Republic              | CZ             |         |                               | C24 | 5 770 000 |
|                             |                |         |                               | C18 | 4 650 000 |

### Requirements for grading:
- Conveyor speed ≤ 1 m/sec
- Spacing between pieces ≥ 200mm
- Grading speed ≤ 100 pieces/min

### Dynagrade
- Conveyor speed ≤ 1.3 m/sec
- Spacing between pieces ≥ 225mm
- Grading speed for widths ≤ 150mm: ≤ 150 pieces/min

### Dynagrade HC
- Conveyor speed ≤ 1.3 m/sec
- Spacing between pieces ≥ 225mm
- Grading speed for widths ≤ 250mm: ≤ 240 pieces/min

### Dynagrade XHC
- Conveyor speed ≤ 1.3 m/sec
- Spacing between pieces ≥ 225mm
- Grading speed for widths w ≤ 100mm: ≤ 240 pieces/min where $100 < w \leq 250$
- Grading speed = 78000/(w+225) pieces/min

Where timber has a mean moisture content between 16% and 20% with a minimum value of 14% and a maximum value of 22% then the settings shall be calculated according to equation (1) and rounded to 3 significant digits.

\[
IP_{ap} = IP - 0.0738IP
\]  

### Notes:
- See clause 7.3 in EN14081-1  
- Timber sizes shall be to EN 336.  
- Grades prefixed by C are strength classes given in EN 338  
- Settings apply only to timber grown west of the Ural mountain range in Russia
Exempel

![Diagram showing the relationship between Grading Parameter and Bending strength (MPa) with data points for C18 and C30 grades. The coefficient of determination, R², is 0.43.](image-url)

- Bending strength (MPa) for C18: 4,300,000
- Bending strength (MPa) for C30: 6,480,000

SP Technical Research Institute of Sweden
Output Control

- Used in USA and Australia

- Preliminary setting based on limited testing (60 pieces per species, grade and dimension)
- Proof-loading of limited number of pieces per shift (5 pieces per grade and dimension per shift)
- CUSUM control procedure to follow for controlling the grading
- If the grading is “in control” adjustment of the settings is allowed to increase the yield (requires extra proof-loading)
Future development

- Introduction of scanner systems for automatical visual grading and for visual override requirements
- Machine grading at higher speed
- Grading in raw condition
- Grading of logs
- Pregrading of logs (scanning)
- Combination of measurements
- Development of the new standard 14081 (raw material regions and methodology)
- Proof loading
- New machines?
Log scanning

\[ y = 0.82x + 5.9541 \]

\[ R^2 = 0.5525 \]

Test values from 45x145 mm boards

Predicted strength based on log data

SP Technical Research Institute of Sweden