Visual strength grading supported by mechanical grading

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ABSTRACT

This article describes how to allocate structural timber (spruce from Central Europe) into strength class C35 according to EN 338 by means of combined visual and machine strength grading methods. Three different visual-machine strength grading combinations are developed and discussed. They are composed of visual grading in accordance with German standard DIN 4074-1 and of machine strength grading of green or dry sawn timber by measuring the apparent density or the dynamic MOE. For these combinations appropriate settings for the machine grading parameter are estimated. Combinations based on the dynamic MOE are suitable for strength grading of boards in general, glulam-lamellae and joists. The combination based on the apparent density is only suitable for strength grading of boards in general and glulam-lamellae.

INTRODUCTION

General remarks

This Cost E53 conference addresses among other things the improvement of existing methods for fast and accurate assessment of strength and stiffness of structural timber. At this point of view, the following conference contribution aims to once more show scientific results of a former research project dealing with combined visual and machine strength grading (see Blaß and Frese 2004) against a new background in regard to both harmonized standards at European level and new findings towards glulam bending strength.

Strength grading in brief

The strength and stiffness properties of timber scatter in a wide range. There are two main reasons for the large variability: 1. Wood is a natural raw material causing a natural variation of physical and mechanical properties. 2. Quite a lot of sawing patterns and timber sizes/cross-sections have different effect on knots and slope of grain and therefore on the mechanical properties.

In general, the application of timber as a construction product requires a reliable strength grading method which finally has to ensure certain characteristic strength values of the timber allocated to different strength classes. EN 338 is the European standard for those strength classes for later use in codes for the design of timber structures (EN 1995-1-1 or DIN 1052).

Sawn softwood timber may be strength graded visually or mechanically. Visual grading is a simple method to grade structural timber. An overview about visual grading methods established in the EU member states is summarized in the annex of EN 1912. Through visual grading each piece of timber is evaluated based on visual parameters. But since the density or MOE affecting the strength can hardly be determined by visual grading, the strength is generally limited to C30
in case of visual grading. Exceptions are Douglas fir (C35), certain hardwoods (D40) and woods from tropical forests (D70).

Multiple sensing grading machines function according to the principles – for the most part combinations of them – bending, vibration, weighing, X-ray radiation and optical scanning in order to particularly determine the density, MOE or knot size. In practice mechanical strength grading is used to grade up to strength class C40 or – in case of glulam-lamellae – up to a characteristic board tensile strength of 26 MPa (compare EN 14081-4). However, those machines are quite expensive. Especially small glulam producers or timber traders cannot economically exploit these grading machines.

European standardization – impact of the Construction Products Directive

The Construction Products Directive (89/106/EEC), inter alia, aims to remove technical barriers in the construction field in order to achieve the greatest possible advantage for a single internal market, to afford access to that market for as many manufacturers as possible and to ensure the greatest possible degree of market transparency. This directive will also have impact on the structural timber market since the co-existence period end date of EN 14081, a harmonised standard at European level with regard to strength graded structural timber, is the 1st of September in 2008. After that free trade with structural timber complying with the terms of this harmonised standard is freely possible. In general, that requires along with other terms strength grading in accordance with EN 14081-1. Due to the lack of strength grading in quite a lot of small and medium enterprises working or trading with timber there is the necessity for them to establish strength grading to be prepared for future changes on the timber market and to make use of its advantages.

This article in particular describes the development of device-supported visual strength grading methods, which will be in accordance with EN 14081-1. These methods are composed of the visual strength grading according to German standard DIN 4074-1 additionally supported by simply measuring the apparent density of sawn timber – or if even possible the dynamic MOE from longitudinal vibrations. In accordance with DIN 4074-1 the label of the grade, obtained from device-supported methods, is S15. It is very likely to be expected that grade S15 will be assigned to C35 in EN 1912, since S15 is not yet included.

The device-supported visual strength grading methods would then allow increasing the value of timber with a limited expense for the additional devices measuring the apparent density or MOE. Therefore, the methods would particularly be suitable for small and medium enterprises of the timber trade or eg for glulam manufacturer.

To attest conformity of strength graded timber with the terms of EN 14081-1, the manufacturer has to declare conformity of his product (for details see Construction Products Directive 89/106/EEC, Annex III, 2, (ii), first possibility). From the manufacturer’s declaration device-supported strength graded timber can be accorded the CE marking and can be sold on the European internal market. Free use is allowed for the intended purpose.
Consequences in regard to glulam strength
New findings towards glulam revealed that standardized glulam beams according to EN 1194 do not meet the strength targets of the glulam grades defined (Blaß et al 2008). That has a severe effect on the requirements on board and finger joint strength. Fig. 1 summarizes the findings by means of a new strength model in comparison with the established one in EN 1194: On the left-hand side the characteristic glulam bending strength is plotted over the required characteristic board tensile strength. On the right-hand side, according to the new strength model the relation between required finger joint bending strength and characteristic board tensile strength is shown. The new strength model refers to homogeneous glulam 600 mm in depth. The reference lines in the plots hereinafter in particular exemplify, that lamellae allocated in strength class C35 with a characteristic tensile strength of 21 MPa lead to GL28h. This new relation is of importance since at present some glulam manufacturers make use of the combined visual and machine strength grading method to produce GL32.

![Figure 1: Glulam bending strength (left) and finger joint bending strength (right) over board tensile strength; reference lines exemplarily propose requirements for GL28h](image)

MATERIALS AND METHODS

Material
The testing material is divided in eighteen samples of spruce timber. The material came from four saw mills located in Germany. Each mill delivered about one quarter. The boards and joists particularly cover the application range of glulam-lamellae and nail plate trusses. The length of the material was from 3.8 m to 5.2 m. Different cross-sectional dimensions present in the samples were chosen to take proportionally into account the size effect on the strength. ‘Glulam-lamellae’ are hereinafter referred to as ‘lamellae’.
Table 1: Testing material – cross-sectional dimensions [mm] and sample size

<table>
<thead>
<tr>
<th></th>
<th>Boards</th>
<th>Joists</th>
</tr>
</thead>
<tbody>
<tr>
<td>depth</td>
<td>width</td>
<td>height</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>60+89</td>
<td>50</td>
</tr>
<tr>
<td>175</td>
<td>50+60+56</td>
<td>60</td>
</tr>
<tr>
<td>220</td>
<td>64</td>
<td>53+61</td>
</tr>
</tbody>
</table>

Methods
A combination of visual strength grading and machine strength grading should complement each other since visual grading is used to detect the weakest cross-section and machine strength grading in general provides the overall timber quality by means of a density or a MOE value.
All the testing material was first graded visually taking all the visual grading parameters in DIN 4074-1 into account. Fig. 2 exemplarily shows the requirements on the knot ratio of typical single knots for the grades S7, S10 and S13 in DIN 4074-1.

Figure 2: Visual strength grading according to DIN 4074-1 exemplified through a typical single knot in a board cross section: grades S7, S10 and S13

The following properties, for later use as explanatory machine grading parameters, were measured: 1st depth or height, 2nd width, 3rd apparent density and with that 4th dynamic MOE, 5th apparent density of green sawn timber and with that 6th dynamic MOE of green sawn timber. The apparent density was calculated from the mass over volume for each piece of sawn timber. The dynamic MOE is based on longitudinal vibrations.
In order to increase the reliability of combined visual and machine strength grading, not only the characteristic bending strength but also the characteristic tensile strength of the testing material was determined. Consequently, one half of each sample, present in Table 1, was tested in bending and the other half in tension. The bending strength of boards was determined flat-wise and of joists edge-wise. The tests were carried out according to EN 408 with the weakest cross-section, obtained through visual grading, in the area of the maximum bending moment. This applies analogously to the tension tests.
VISUAL GRADING AND MACHINE STRENGTH GRADING

Relation between visual grading and strength

Fig. 3 (top) shows the yield of visual grading from the comparison between boards in general and joists. In addition, Fig. 3 (bottom) shows the higher yield in grade S10 and S13 obtained for lamellae, since in case of grading for glulam a certain knot criterion, leading to less downgrading, can be omitted. Fig. 4 shows the relation between bending (left) and tensile strength (right), respectively, and knot ratio each. For lamellae the knot cluster and for joists the single knot was used in the diagrams as reference. Symbols representing reject or grade S7 occur in an area indicating a higher visual grade, if a different grading parameter was grade determining. As an example the occurrence of pith in the cross-section downgrades S13 to S10. The coefficients of determination (= r², indicating the proportion of the total variation attributed to the fit) reveal the weak point of visual grading. Since there is a moderate correlation between the knot ratio according to DIN 4074-1 and strength, visual grading does not allow grading timber with reliable and high characteristic strength.

Figure 3: Yield based on DIN 4074-1: boards in general and joists (top) and lamellae (bottom)
Relation between machine strength grading and strength

The scatter plots in Fig. 5 show the strength-MOE- and strength-density-relation for boards (a) and joists (b). The diagrams are arranged so that the strength prediction through the dynamic MOE can easily be compared with the one through the apparent density. The 95% confidence limits (dashed lines) and the coefficient of determination show the generally better prediction of strength through the dynamic MOE.

As expected, there is a high correlation between the MOE of dry and green sawn timber. The correlation coefficient amounts 0.98. The moisture content of green timber after sawing generally is above 30% and after kiln-drying about 10% in case of boards and 12.3% in case of joists. The high correlation between the two MOE values allows determining the machine grading parameter immediately after sawing. This is advantageous since reject, detected mechanically, may be taken out of the production line as soon as possible.

Figure 4: Bending (left) and tensile strength (right) over knot ratio
Figure 5a: Boards - bending (top) and tensile strength (bottom) over dynamic MOE of dry sawn timber (left) and apparent density (right)
COMBINING VISUAL AND MACHINE STRENGTH GRADING

Regression equations for grading parameter
The machine grading parameter, obtained from a multiple linear regression analysis, predicts the minimum value of the bending strength of each piece of structural timber since the strength was by all appearances determined at the weakest cross-section. In the regression analysis, the bending strength is the response variable and the cross-section dimensions, the apparent density and the MOE are the explanatory variables. Only those observations, meeting the criteria for S10 and S13 (compare Fig. 2), were used to specify the regression equations. Hence reject and grade S7 were omitted in the regression analysis. Table 2 summarizes the most important regression equations relevant for a practical application. Further equations can be found in the research report Blaß and Frese 2002.
Table 2: Regression equations

<table>
<thead>
<tr>
<th>equation</th>
<th>machine grading parameter [MPa]</th>
<th>intercept [-]</th>
<th>width [mm]</th>
<th>depth [mm]</th>
<th>height [mm]</th>
<th>apparent density [kg/m³]</th>
<th>MOE dry wood [MPa]</th>
<th>MOE green wood [MPa]</th>
<th>coefficient of correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( f_{\text{m}} = -44.8 )</td>
<td>-0.01710</td>
<td>+0.1160</td>
<td>+0.2080</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.592</td>
</tr>
<tr>
<td>2</td>
<td>( f_{\text{m}} = +13.4 )</td>
<td>-0.01320</td>
<td>-0.0449</td>
<td>-0.0414</td>
<td>+0.00454</td>
<td></td>
<td></td>
<td></td>
<td>0.729</td>
</tr>
<tr>
<td>3</td>
<td>( f_{\text{m}} = +4.98 )</td>
<td>-0.00474</td>
<td>-0.0492</td>
<td>-0.0492</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.713</td>
</tr>
</tbody>
</table>

The minimum value for the machine grading parameter (this value is hereinafter referred to as ‘limit’, compare Fig. 6 and Table 3) was stepwise raised to determine a reliable limit to grade C35. For that, the yield obtained has to ensure a characteristic bending strength of at least 35 MPa. In addition, the regression equations and their limits were verified through grading the testing material, from which the tensile strength was determined. For the same limits the characteristic tensile strength was evaluated. Finally, this value has to exceed at least 21 MPa.

Fig. 6 shows the bending and tensile strength over machine grading parameter according to Eq. 1 and Eq. 2. The additional dashed reference lines indicate the limits (vertical: 52 MPa and 48 MPa) and the characteristic strength values (horizontal: 35 MPa and 21 MPa). Now, Fig. 6 points out why only the testing material fulfilling the requirements of S10 and S13 were used to specify the regression equations. Although observations belonging to grade S7 and reject can be found in the range of the grading parameter values – 30 to 80 MPa – according to Eq. 1, they mainly show bending strength values below 35 N/mm². Hence it is reasonable to use only grades S10 and better within a combined method.

Fig. 6c and 6d differ from 6a and 6b, respectively, in regard to the distribution of grade S7 and reject: In Fig. 6c and 6d, the predicted bending strength is mainly situated below the 48-MPa-limit while in Fig. 6a and 6b obviously more values exceed the 52-MPa-limit. That reveals that the density, being the main explanatory variable in Eq. 1, is not as strongly correlated with the knot ratio like the dynamic MOE. The MOE is obviously affected by the knottiness and vice versa.

Figure 6: Bending (a) and tensile strength (b) over grading parameter according to Eq. 1
Figure 6: (Continuation): Bending (c) and tensile strength (d) over grading parameter according to Eq. 2

In addition, Fig. 6a and 6c show, that observations of grade S7 and reject do not fit in the linear relationship between bending strength and grading parameter. These observations are mainly situated below the regression line (=bisection line) exclusively fitted to the observations of S10 and S13. This is a further reason why grade S7 and reject were disregarded in the regression analysis.

Discussion of the regression equations and the grading results
To simplify matters the following considerations refer to lamellae. Due to the more rigorous criteria for boards in DIN 4074-1 a lower yield has to be accepted when grading boards. Grading structural timber with a method according to Eq. 1 is simple particularly with regard to the explanatory machine grading parameter, since only the apparent density has to be determined. Just two requirements have to be fulfilled to grade lamellae in strength class C35: the material corresponds to grade S10 or better and the grading parameter exceeds 52 N/mm². This method is not appropriate to grade joists because of the moderate correlation of only 0.47 between bending strength and apparent density in case of joists (compare Fig. 5b). The missing effect of knots on the grading parameter according to Eq. 1 makes visual grading more important in this combined method (see Fig. 6a). In addition, that involves high local fibre deviation as well as compression wood. Using the dynamic MOE of dry sawn timber makes possible to increase the yield significantly. This leads to Eq. 2. Determining the dynamic MOE for one thing requires more mechanical expense but has some advantages. This method is suitable to grade lamellae and joists. The evident influence of knots on the grading parameter (see Fig. 6c) according to Eq. 2 makes this method more insensitive with regard to the inaccuracy of the visual grading. The close correlation between the dynamic MOE of dry and green sawn timber produces the same limits of 48 MPa and basically the same yield for determining the MOE of dry or green sawn timber. Table 3 summarizes the limits, characteristic bending strength and tensile strength and the yield for each of the three methods. Strength class C35 according to EN 338 requires a
mean MOE of 13000 N/mm² and a characteristic density of 400 kg/m³. The structural timber graded into strength class C35 has a mean dynamic MOE of at least 14300 N/mm² and a characteristic density of at least 400 kg/m³.

Table 3: Characteristic bending and tensile strength and yield based on combined visual and machine strength grading

<table>
<thead>
<tr>
<th>Equation</th>
<th>Collective</th>
<th>Limit Yield of C35</th>
<th>fₘₖ</th>
<th>Number</th>
<th>fₗₖ</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>lamellae</td>
<td>52</td>
<td>27%</td>
<td>35.9</td>
<td>102</td>
<td>21.4</td>
</tr>
<tr>
<td></td>
<td>lamellae</td>
<td></td>
<td>41%</td>
<td>38.4</td>
<td>147*</td>
<td>21.1</td>
</tr>
<tr>
<td>2</td>
<td>joists</td>
<td>48</td>
<td>18%</td>
<td>31.3</td>
<td>44</td>
<td>35.4</td>
</tr>
<tr>
<td></td>
<td>lamellae + joists</td>
<td></td>
<td>31%</td>
<td>36.1</td>
<td>191</td>
<td>22.5</td>
</tr>
<tr>
<td></td>
<td>lamellae</td>
<td></td>
<td>40%</td>
<td>39.0</td>
<td>109*</td>
<td>20.6</td>
</tr>
<tr>
<td>3</td>
<td>joists</td>
<td>48</td>
<td>18%</td>
<td>31.4</td>
<td>45</td>
<td>29.6</td>
</tr>
<tr>
<td></td>
<td>lamellae + joists</td>
<td></td>
<td>30%</td>
<td>36.3</td>
<td>154</td>
<td>21.4</td>
</tr>
</tbody>
</table>

*the dynamic MOE of 60 lamellae was not determined hence the number of 109 deviates from the number of 147

CONCLUSIONS

Three different device-supported visual grading methods are suitable to grade structural timber into so called grade S15 which will very likely assigned to strength class C35. The methods consist of visual grading according to DIN 4074-1 and machine strength grading. Machine strength grading requires as explanatory machine grading parameter the apparent density and/or the dynamic MOE of dry or green sawn timber. The grading parameter predicting the bending strength is based on these properties. Additionally a visual grading is necessary. Structural timber has to fulfil at least the criteria of S10 in accordance with DIN 4074-1.

Combined methods based on the dynamic MOE are suitable to grade lamellae and joists. It is also possible to determine the dynamic MOE of green sawn timber to grade structural timber immediately after sawing. The combined method based on the apparent density is only suitable to grade lamellae.

This study proves the possibility to combine visual and machine strength grading. Both visual grading and machine strength grading are well known methods. This eases the introduction of a combined method in practice. The methods will comply with the terms of EN 14081, a harmonised standard at European level. Therefore strength graded timber obtained from device-supported visual grading can be accorded the CE marking and can be sold on the common European internal market.

REFERENCES


EN 338:2003 Structural timber – Strength classes.


EN 1194:1999 Glued laminated timber – Strength classes and determination of characteristic values.


