Strength grading of wet Norway spruce side boards for use as laminations in wet-glued laminated beams

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Abstract

Strength grading of Norway spruce side boards in the wet state was investigated. For a sample of 58 boards of dimensions 25×120×3000 mm^3, density and dynamic modulus of elasticity in the axial direction, MOE_{dyn}, were determined in the wet state. The boards were then split into two parts and the procedure of determining MOE_{dyn} was repeated both before and after the boards were dried to a target moisture content of 12 %. Tensile strength of the split boards was finally measured and its relation to MOE_{dyn} for both split and unsplit boards determined. The investigation also included an evaluation of a so called reversed lamination effect on the stiffness caused by the splitting of boards into two parts. The results show that strength grading of split boards in the wet state could give just as good results as grading performed after drying. The coefficient of determination between MOE_{dyn} in wet and dried states was as high as R^2=0.92, and the relation between MOE_{dyn} in the wet state and tensile strength in the dried state, σ_t, was of the same order (R^2=0.55) as the relation between MOE_{dyn} in the dried state and σ_t (R^2=0.52). Regarding the reversed lamination effect on the stiffness of split boards, it was found to be of low order.

1 Introduction

About 30 % of the volume of sawn timber produced at a typical Swedish sawmill consists of side boards, *i.e.* boards of narrow dimensions sawn from the outer parts of a log. Large production volumes and small dimensions imply that considerable numbers of side board pieces have to be handled in the sawmilling process and the costs for production, storage and sales are in many cases not met by the selling price on the market.

From previous research it is well known that several wood characteristics that influence the structural properties of sawn timber vary in a distinct way in the direction from pith to bark. For example, the modulus of elasticity (MOE) in softwood trees increases significantly from the pith and outwards (Wormuth

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1993). Similar behaviour has in some investigations also been found for density (Steffen *et al.* 1997). Accordingly, side boards possess excellent structural properties but due to their small dimensions, they are very seldom used for load bearing purposes. However, since the year of 2005, Växjö University (from 1 January 2010 named Linnæus University) and SP Technical Research Institute of Sweden, carry on research concerning development of high-value products based on softwood side boards. That work concerns the possibility to use undried Norway spruce (Picea abies) side boards as lamellae in wet-glued laminated beams for load-bearing applications. The beams consist of flatwise glued wet boards with cross section dimensions of 25×120 mm^2. For wet boards, the moisture content could vary from the fibre saturation point, which for Norway spruce occurs at about 30 %, to nearly 200 % (Dinwoodie 2000). After gluing, each beam is split, dried and planed into two new beams with width of 50 mm, see Figure 1.

Structural properties of such split beams have been measured and analysed and the results obtained so far are promising (Petersson *et al.* 2009). Despite the fact that the beams have been produced from batches of *ungraded* boards, their performance in terms of *e.g.* stiffness is up to the standard of both glued laminated timber of grade GL36 and structural strength graded timber of grade C35. Furthermore, by gluing already in the wet state, directly after sawing, a higher yield and a much more cost-efficient handling in the sawmills would be achieved.

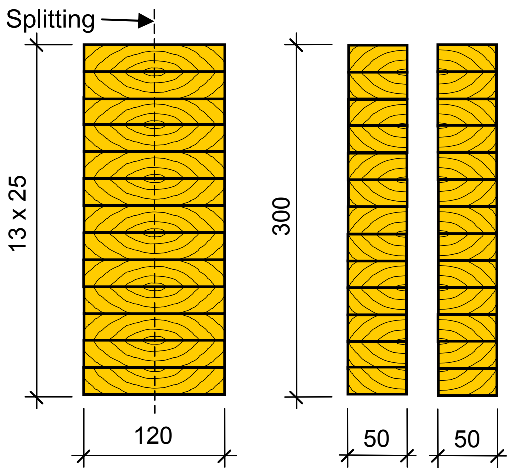

Figure 1: Wet glued beams before (left) and after (right) splitting, drying and planing (Petersson *et al.* 2009).

To improve the structural properties of the beams further, strength grading and/or defect elimination by finger jointing of the wet side boards before gluing is considered. Grading of timber into different strength classes means that strength, MOE and density of timber members are predicted or measured by visual inspection or non-destructive machine testing. The market is dominated by machine grading techniques based on the relationship between a measured MOE of a timber member and the bending strength. One grading method that has won large market shares during the last decade is based on dynamic excitation and measurement of the first eigenfrequency, or resonance frequency, $f_{A1,}$ in the axial direction of dried members. This frequency is related to member length L [m], density ρ [kg/m^3] and dynamic MOE [Pa] in the axial direction (E_{An}) of a board, according to Equation 1 (Ohlsson & Perstorper 1992)

$$E_{An} = 4 \cdot \rho \cdot \left(\frac{f_{An} \cdot L}{n} \right)^2$$ Equation 1

in which n denotes the mode number. Since MOE is a material property that varies along the length of a board, E_{An} is an apparent MOE that reflects the average MOE value in a board. The described method is today used for strength grading of structural timber in the dried state, *i.e.* typically timber with a moisture content of about 16-18 %. In connection with the described research concerning wet glued beams, the possibility to grade side boards in the wet state by axial dynamic excitation has been investigated and the results are presented in this paper. For a sample of boards, the E_{An} was determined by dynamic excitation under both wet and dried conditions. Subsequently, tensile strength and local static MOE in tension were measured in the dried state and the correlation between results in wet and dried states were analysed. This paper also includes an evaluation of a possible reversed lamination effect on the stiffness, *i.e.* an evaluation of the effect of splitting the boards into two parts. As the wet glued beams described above are split beams with narrow dimensions, this effect is important to consider.

2 Material, experiments and measurement equipment

A sample of 58 wet Norway spruce side boards of dimensions 25×120×3900 mm^3 was used in this project. The length of the boards was reduced to 3000 mm by removing 450 mm from each end and a small specimen of 100 mm length was, for each board, cut from one of the removed lengths, see Figure 2. The moisture content for the small (100 mm) specimens was determined according to the oven dry method described in EN 13183-1 (CEN 2002). Boards and specimens were marked in corresponding consecutive orders from no. 1 to 58, each specimen being marked with the same number as the board from which it was cut.

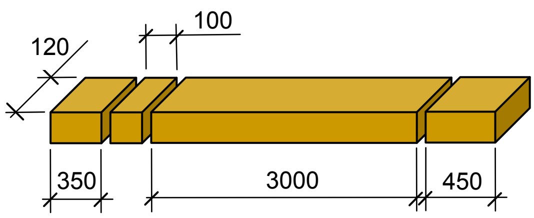

Figure 2: Cross cutting of boards.

The first axial resonance frequency f_{A1} was then measured for each board using a Timber Grader MTG, see Figure 3, which is a wireless measuring instrument for strength grading of structural timber (Brookhuis Micro-Electronics BV 2009). It is approved as a machine grading system with settings listed in EN 14081-4 (CEN 2009) and the approval concerns timber with mean moisture content between 10 and 25 %. A grading set includes grader, balance and computer software and hardware. In this investigation, a board's weight and f_{A1} were obtained from the balance and the grader, respectively. Density and E_{An} was calculated manually, the last parameter from Equation 1.


Figure 3: Timber Grader MTG.

In the next step each board was split in two parts, one marked with an “A” and the other one with a ”B” to supplement the marking from the previous step. The procedure for determination of resonance frequency, density and E_{An} were then repeated for each split board. After drying to a moisture content varying between 12 and 14 %, the measurement procedure was carried out once again.

Finally, tensile strength and local static MOE in tension were measured on the basis of requirements in EN 408 (CEN 2003). The test setup is shown in Figure 4 (left). Wedge type grips were used, which prevent rotation of the board ends, and the distance between the grips was 1500 mm. The load application was force controlled with a constant loading rate of 7 or 8 kN/minute and the average time to failure for the tested boards was 304 seconds. The local static MOE was determined from the elongation, measured by two transducers, between two points 275 mm apart, corresponding to a length of five times the width of the boards. The transducers were placed on opposite narrow board edges, see Figure 4 (right) at the worst defect, *i.e.* at the board section where the fracture was expected to occur.

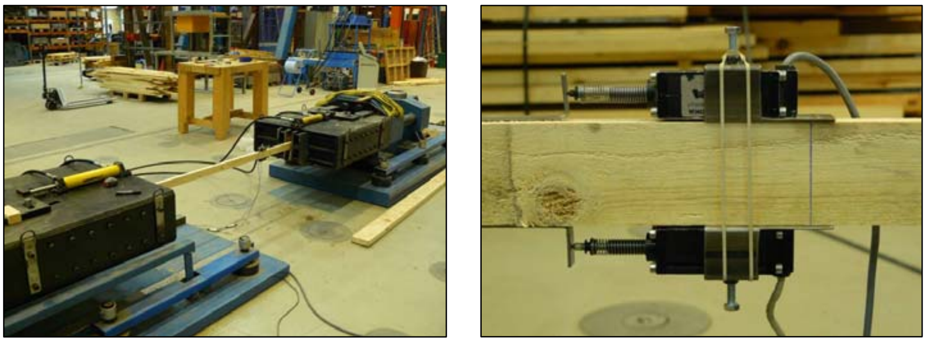

Figure 4: Test setup for tension tests (left) and transducers for elongation measurement (right).

3 Test results and evaluation

3.1 Grading of wet side boards

The principal purpose of this study was to evaluate the possibility to implement strength grading of side boards in the wet state. To secure that such conditions were applied, the moisture content (MC) of the 58 unsplit boards (width 120 mm) was determined. As expected, the amount of water in the boards varied considerably, from a minimum value of 28 % to a maximum of 180 %. The mean MC value was 93 % with a standard deviation of 43 %. Thus, it was confirmed that wet state conditions were at hand. It should be noted that 7 out of the 58 unsplit boards were disregarded due to rot.

To evaluate the possibility to grade wet boards, the following relations between different material parameters were calculated (indices “56” and “120” refer to the average width of split boards and unsplit boards, respectively):

- axial dynamic MOE measured for the split boards in the wet state, denoted $E_{56dynwet}$, in relation to axial dynamic MOE for split boards in the dried state (12-14 % MC), denoted $E_{56dyndry}$ (Figure 5),

- local static MOE measured in the dried state, $E_{56statdry}$, in relation to the tensile strength, σ_t (Figure 6),
- $E_{56dynwet}$ and $E_{56dyndry}$, respectively, in relation to σ_t (Figures 7-8),
- density before drying, ρ_{wet}, in relation to $E_{56dynwet}$ (Figure 9), and
- density after drying, ρ_{dry}, in relation to $E_{56dyndry}$ (Figure 10).

Mean values and standard deviations of mentioned parameters and for axial dynamic MOE measured for unsplit wet boards, $E_{120dynwet}$, are shown in Table 1.

Table 1: Mean values and standard deviations of $E_{120dynwet}$, $E_{56dynwet}$, $E_{56dyndry}$, $E_{56statdry}$, σ_t, ρ_{wet} and ρ_{dry}.

	Unit	Mean value	Standard deviation	Number of boards
$E_{120dynwet}$	GPa	11.10	2.57	50[1]
$E_{56dynwet}$	GPa	10.84	2.58	108[2]
$E_{56dyndry}$	GPa	13.04	2.93	108[2]
$E_{56statdry}$	GPa	9.59	3.40	106[3]
σ_t	MPa	24.8	13.5	96[4]
ρ_{wet}	kg/m^3	785	141	108[2]
ρ_{dry}	kg/m^3	471	53	108[2]

1) 8 boards disregarded due to rot (7) and measurement error (1).
2) 8 boards disregarded due to rot.
3) 10 boards disregarded due to rot (8) and damage (2).
4) 20 boards disregarded due to rot (8), damage (2) and failure in grips (10).

The difference between mean stiffnesses $E_{56dynwet}$ and $E_{56dyndry}$ corresponds fairly well with results referred to in Dinwoodie (2000) and the mean value of $E_{56statdry}$ is lower than $E_{56dynwet}$ and $E_{56dyndry}$. The last observation is partly explained by the fact that the dynamically measured MOEs relate to an average MOE value for the entire board, whereas the local static MOE is measured locally, at the section where the worst defect is located. Scatter plots and coefficients of determination, R^2, for relations between $E_{56dynwet}$, $E_{56dyndry}$, $E_{56statdry}$, σ_t, ρ_{wet} and ρ_{dry} are shown in Figures 5-10.

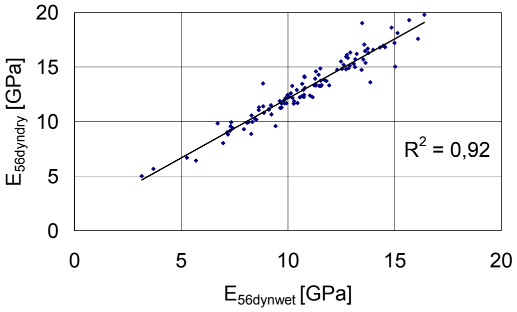

Figure 5: Relation between $E_{56dynwet}$ and $E_{56dyndry}$.

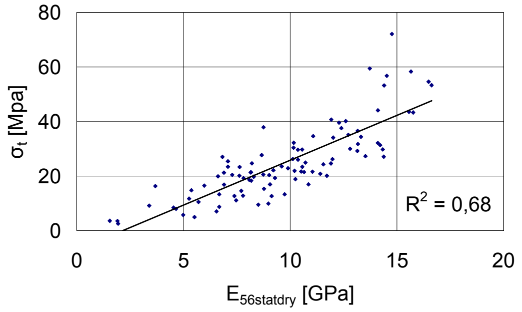

Figure 6: Relation between $E_{56statdry}$ and σ_t.

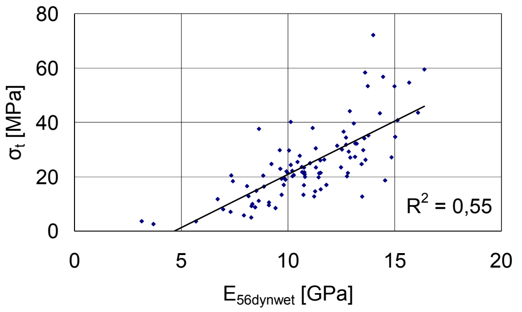

Figure 7: Relation between $E_{56dynwet}$ and σ_t.

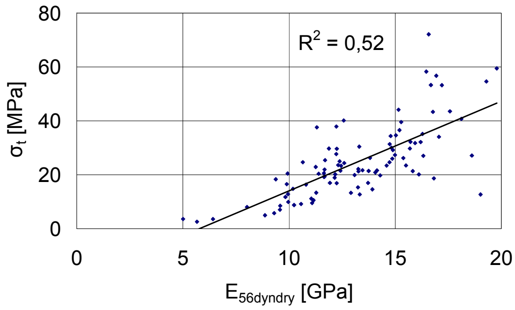

Figure 8: Relation between $E_{56dyndry}$ and σ_t.

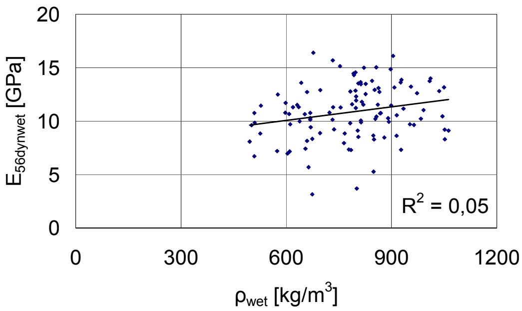

Figure 9: Relation between ρ_{wet} and $E_{56dynwet}$.

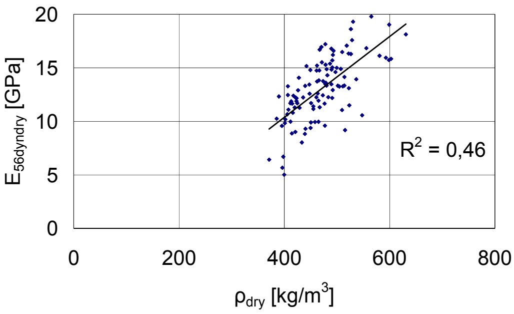

Figure 10: Relation between ρ_{dry} and $E_{56dyndry}$.

According to Figure 5, the relationship between dynamic MOEs measured in wet and dried states is very strong (R^2=0.92). Similar results was found by Unterwieser & Schickhofer (2007) who investigated the possibility of grading sawn timber, both centre boards and side boards, in the green state. Furthermore, a comparison of Figures 7 and 8 shows that the correlation between tensile strength and dynamic MOE in wet condition is of the same order as the correlation between tensile strength and dynamic MOE in dried condition.

As regards relations between density and dynamic MOE in wet and dried states, Figures 9-10 indicate that there is an evident correlation between density and dynamic MOE in the dried state (R^2=0.46), whereas no such relationship is found in the wet state (R^2=0.05). The explanation to the independency between MOE and density above the fibre saturation point is that the tracheids are filled with considerable quantities of water that have an immediate effect on the density, and of course also on the MC value, whereas the stiffness is more or less unaffected by the amount of free water (Dinwoodie 2000).

From Figures 5-10 it could be concluded that it is possible to grade split side boards in the wet state by using axial dynamic excitation since, firstly, the dynamic MOEs in wet and dried states are strongly correlated and, secondly, the tensile strength is as correlated to axial dynamic MOE measured in the wet state as it is to axial dynamic MOE measured in the dried state. However, the presented coefficients of determination require that the actual densities in both wet and dried states are regarded when axial dynamic MOEs are calculated.

For comparison, the relation between axial dynamic MOE measured for unsplit wet boards, $E_{120dynwet}$, and σ_t of dried split boards is shown in Figure 11 and the relation between σ_t of pairs of split boards coming from the same original board is shown in Figure 12. According to Figure 11, a certain degree of correlation was found between σ_t for dried split boards and $E_{120dynwet}$ (R^2=0.45), but it was weaker than the correlation between σ_t and $E_{56dynwet}$ (R^2=0.55, see Figure 7). It is not very surprising though that the R^2 value between strength and stiffness measured for a split board is higher than the R^2 value between strength of a split board and stiffness of the corresponding unsplit board.

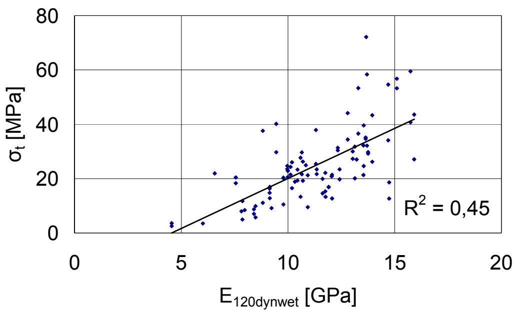

Figure 11: Relation between $E_{120dynwet}$ and σ_t for split boards.

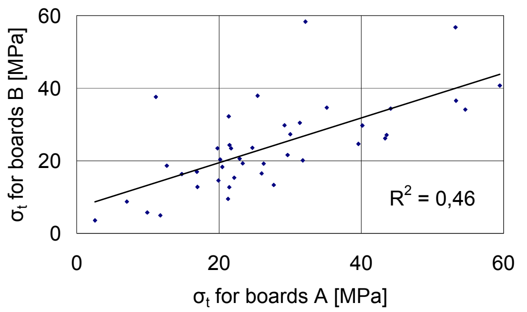

Figure 12: Relation between σ_t for pairs of split boards A and B.

In some of the split boards there were knots larger than half the board's width, see Figure 13, and in such cases strength values as low as 2.6 MPa was found. The strength of the strongest board was 72.1 MPa. Furthermore, the coefficient of determination between σ_t of boards split from the same original board was R^2=0.46, see Figure 12. This coefficient value, together with standard deviation and mean value for σ_t given in Table 1, indicates that the scattering of measured strength values for the split boards could be considered as rather large, compared with other investigations of lamellae for glued laminated timber (Johansson *et al.* 1998). Even if the strength of many of the boards were very low due to the occurrence of knots, this does not fully reflect the behaviour of the boards when they are used as lamellae in glulam beams. For example, large deformations, both longitudinal and lateral, in flexible sections of a lamella are restrained by adjacent lamellae, and tensile forces in weak lamellae could, to a certain degree, be transferred via bond lines to other lamellae. This explains why high performance wet glued beams could be achieved from ungraded batches of split Norway spruce side boards.

Figure 13: Fractures in two of the weakest split boards in the sample.

3.2 Reversed lamination effect

The question of grading boards in the wet state originates from ongoing research concerning wet glued laminated split beams of side boards. In that context, the issue of a so call reversed lamination effect on the stiffness of split boards was also raised. The effect concerns to what extent the stiffness of such boards of narrow dimensions is reduced due to the splitting, in relation to the stiffness of the corresponding unsplit board. From Table 1, the mean value and standard deviation of the stiffnesses, in the wet state, of split and unsplit boards ($E_{56dynwet}$ and $E_{120dynwet}$) could be compared and the relation between $E_{56dynwet}$ and $E_{120dynwet}$ is shown in Figure 14. According to obtained results, the mean value was 2 % lower after splitting, the standard deviations were almost the same and the correlation was very strong (R^2=0.94). The two variables, before splitting ($E_{120dynwet}$) and after splitting ($E_{56dynwet}$), were compared with a paired t-test and the difference in MOE was found to be statistically significant ($p<0.01$). In the analysis, the value for an unsplit board was compared with values for both split boards.

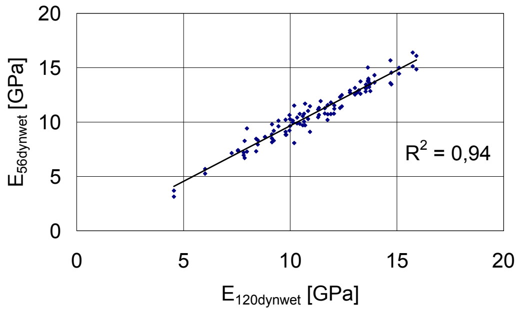

Figure 14: Relation between $E_{120dynwet}$ and $E_{56dynwet}$.

4 Conclusions and future work

The objectives of this research were to investigate the possibility to grade Norway spruce side boards of narrow dimensions in the wet state by using axial dynamic excitation, and to evaluate a possible reversed lamination effect on the stiffness caused by splitting wet boards into two parts. According to the results, strength grading in the wet state using axial dynamic excitation is just as reliable as grading carried out after drying, provided that actual board densities in wet and dried states are regarded. The relation between axial dynamic MOEs for split boards in the wet and dried states, $E_{56dynwet}$ and $E_{56dyndry}$, was found to be as high as R^2=0.92. When each of these MOEs were correlated with the tensile strength, σ_t, the coefficient of determinations were of the same order; R^2=0.55 for the correlation between $E_{56dynwet}$ and σ_t and R^2=0.52 for the correlation between $E_{56dyndry}$ and σ_t. However, the last value was increased to R^2=0.58 when the density was used as a second prediction variable in the dried state. A similar effect was not achieved in the wet state.

As for the relation between axial dynamic MOE of wet unsplit boards, $E_{120dynwet}$, and the tensile strength, σ_t, for dried split boards, the coefficient of determination was found to be R^2=0.45. If this value is compared with R^2 for the relation between $E_{56dynwet}$ and σ_t, the R^2 value is reduced by 0.1 units. However, the difference would most likely be reduced by implementation of defect elimination such as finger jointing of unsplit side boards, since such a measure would result in a reduction of the inhomogeneity of material properties in both split and unsplit boards. This is an issue to be addressed in future work.

Regarding the reversed lamination effect on the stiffness of split boards, it was in this investigation found to be of lower order.

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