Variability in strength and stiffness of structural Norway spruce timber - influence of raw material parameters

Johansson, Marie[1]; Kliger, Robert[2]

ABSTRACT

The most basic requirements for any material used in engineered construction are that it should have sufficient strength to guarantee the desired level of structural safety and sufficient stiffness to meet the stability requirements and any desirable serviceability criteria. In this study approximately 750 battens from 23 different stands and with 12 different dimensions have been strength tested according to European standard EN 408. The modulus of elasticity and bending strength were determined. Linear regression between bending strength and modulus of elasticity produced a coefficient of determination of 0.51. A depth effect factor was established. Some material parameters such as density, ring width, knot area ratio, grain angle and distortion were measured on more than half of the battens. A multiple regression analysis with all the material properties measured and the modulus of elasticity produced a coefficient of determination with bending strength of 0.65. The parameters which showed the largest influence on bending strength were modulus of elasticity, knot area ratio and grain angle.

BACKGROUND AND OBJECTIVES

The most basic requirements for any material used in engineered construction are that it should have sufficient strength to guarantee the desired level of structural safety and sufficient stiffness to meet the stability requirements and any desirable serviceability criteria. The main disadvantage of timber as an engineering material is that it does not have consistent, predictable, reproducible and uniform properties. The great variability between individual trees, as well as within and between stands, indicates that there is real potential for more efficient and optimised forest and log utilisation.

This study was conducted as a part of a large European project "STUD". Norway spruce (*Picea abies*) is the main species used in this project. The reason for this is that the entire European “STUD” project targets the building industry and this industry is the main end user of sawn timber from Norway spruce. Timber (more than 750 pieces) with 12 different dimensions and from 23 different stands (Sweden, Finland and France) was loaded to failure in accordance with the European Standard EN 408 to obtain its strength and stiffness. The results of these experimentally-recorded strength and stiffness properties in the "STUD" project will be used; in a database for Norway spruce and to model mechanical properties based on material parameters. In the future we are planing to compare the forest resources (mechanical properties obtained) with the requirements of end users.

Furthermore, material properties such as the dynamic E-modulus, distortion, spiral grain angel, density, KAR, ring width and distance to the pith were measured on some of these timber pieces. These measurement are made on most of the Swedish material, i.e. in total material properties were measured on 401 battens.

METHODOLOGY

Material

The timber from Norway spruce came from Sweden (12 stands, no. 11-28), Finland (7 stands, no 51-58) and France (4 stands, no. 31-34). These stands have grown in many different locations: the latitude of the stands in Sweden varied between 57° and 64°, for example. The age of these stands varied between 60 years and 135 years. For a more detailed description of the stands, see Björklund et al. 1998.

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[1] PhD. Student, Dept. Steel and Timber Structures, Chalmers University of Technology, SE-412 96 Göteborg, Sweden
[2] Assoc. Professor, Dept. Steel and Timber Structures, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

Table 1. Number (n) of trees, logs and timber battens split into different dimensions. (N) – total number of battens for each stand.

			Dimension (mm) (width/depth)											
Stand	**Trees**	**Logs**	**45**	**34**	**45**	**45**	**45**	**58**	**45**	**45**	**58**	**70**	**45**	**70**
AA(N)	**n**	**n**	**70**	**95**	**95**	**120**	**145**	**145**	**170**	**195**	**195**	**195**	**220**	**220**
11 (40)	6	20		4	6	6		14				8		2
12 (32)	6	16		4	6	6		6			2	4		4
13 (30)	6	17		10	4	2		8			3	2		1
14 (25)	6	13			5	2		10				2		6
21 (94)	6	30	6		4	6	30		8	12			28	
22 (81)	6	28	12		4	10	28		15				12	
23 (48)	6	20	12		6	9	17		4					
24 (45)	6	19	11		2	10	10		4	8				
25 (38)	6	18	11		2	10	15							
26 (43)	6	19	7		6	6	16			8				
27 (30)	6	15	8		6	10	4		2					
28 (34)	6	17	13		6	7	6		2					
31 (22)	6	11			2	2		12				4		2
32 (38)	6	19			2	8	4	12			2	8		2
33 (32)	6	16			4	4	2	16				6		
34 (34)	6	17				2	4	12			2	10		4
51 (4)	1	1					4							
53 (4)	1	1											4	
54 (12)	2	3					8			4				
55(20)	2	5					4			4			12	
56 (6)	2	2					6							
57 (25)	4	6					16			5				
58 (19)	2	5					11			4				
Total:	**110**	**318**	**80**	**18**	**65**	**100**	**185**	**90**	**35**	**45**	**9**	**44**	**64**	**21**

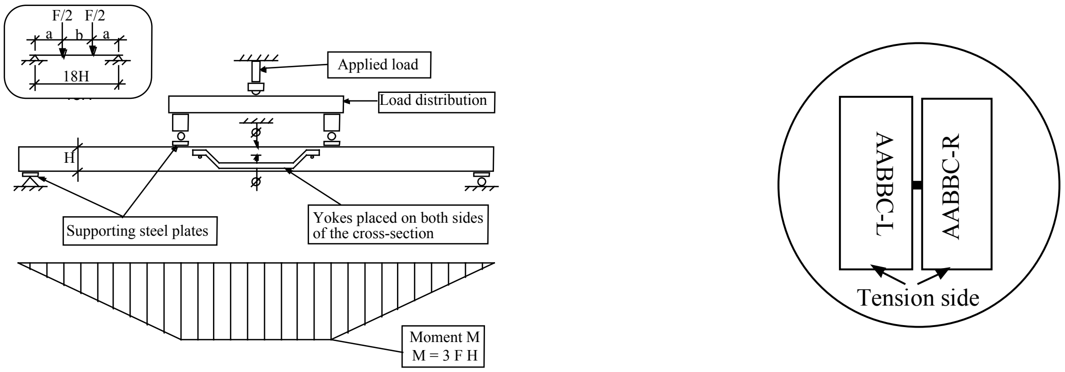
A different number of logs per tree was used in this study. In all, 756 battens were sawn from 318 logs originating from 110 trees, see Table 1.

This project was part of a large project involving several partners. Stand and tree characteristics such as tree spacing, altitude, knots and branches were recorded by one partner. All the logs were CT-scanned before conversion and the battens were then CT-scanned by another partner. The sawing patterns were chosen by the CT-scanning partner. A commercial sawing pattern was used on all the logs to obtain commercial dimensions of the optimum standard size for two battens from each log, see Figure 1b. In order to obtain battens further away from the pith, it was decided that some of the material should be sawn to battens with a width of 50 mm and a large depth. As a result, logs from Swedish stands (11 to 14) and all the logs from France were sawn into two battens with varying thickness (width), i.e. from 34 to 70 mm (plane measurements). This way of sawing represented approximately half the obtained material. The sawn dimension of all battens varied more than was envisaged at the start of this project and, instead of seven dimensions (the same width and varying depth), 12 dimensions were obtained. The number of battens (per tree, per stand or per dimension) was split unevenly, see Table 1, which created a problem in the statistical evaluation.

Destructive tests to failure

To determine the bending strength f_m and the modulus of elasticity E_m, the method specified in the European Standard EN 408 was applied. E-modulus was measured using two yokes placed on both sides of the cross-section. Figure 1a shows the experimental set-up. All the battens were pre-cut to a length of 19H taken from the butt end and always placed on the supports in the same way as shown in Figure 1b. This meant that the part of the batten with the worst strength-reducing defect was not placed within the middle third between the loads (constant moment area) and, as a result, the placing of each batten should be regarded as random and the European Standard EN 384 did not apply in this case.

The mode of failure was established by studying the appearance of the load-deflection curve and photographs of the broken battens after failure.



a) Experimental set-up.

b) Placing of battens in the test apparatus during the loading procedure (log seen from the butt end).

Figure 1. Methodology of experiments

Raw material parameters

A number of material parameters were measured on 401 battens from the Swedish stands (11-28) were conducted. This study of influence of raw material parameters was done as a part of a MSc diploma work (Blomquist 1999). The measured material properties were: dynamic E-modulus, grain angle (GA), density (Dens), Knot Area Ratio (KAR), ring width (RW), twist (TW), spring (SP), bow (BO) and distance from the pith to the centre-point of the battens cross-section (DIST).

Grain angle and KAR were measured in the middle half of each batten. Ring width and distance from the pith was measured in both ends of the batten and the average values were used in the analysis. The dynamic E-modulus was measured as axial eigenfrequency in the free-free condition. To be able to calculate the E-modulus from the eigenfrequency the density had to be known. The distortion modes (twist, spring and bow) were measured prior to the bending tests and were in the analysis given as distortion per two meter length. After the tests the moisture content was determined on a small sample sawn in the vicinity of failure.

TEST RESULTS

Modulus of elasticity

In all, 743 battens were tested destructively. The average moisture content was just under 10% and, as a result, the modulus of elasticity was adjusted individually for every batten with two percent increase in MOE per percent decrease in moisture content. The results of the bending tests are described in detail in Kliger and Johansson (1999). The mean values for the adjusted modulus of elasticity ($E_{m,adj}$) for all battens split into different dimensions are presented in Table 2. Note that the number of battens varied from 1 to 30 for each group, cf. Table 1. The average modulus of elasticity was 12.5 GPa and varied between 8 GPa (for timber from the most fast-grown stand 56) to 15.7 GPa for stand 13.

Height in a tree

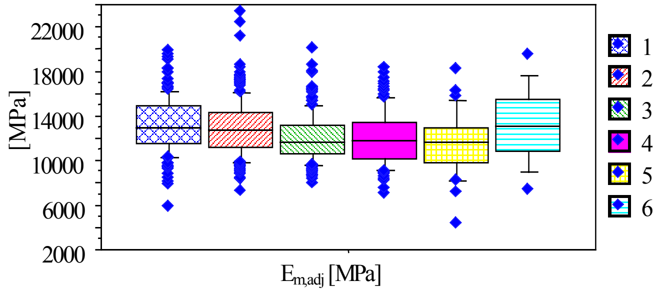


Figure 2. Box plot of modulus of elasticity $E_{m,adj}$ divided into six groups for battens from different logs in relation to the distance from the ground: i.e. no. 1 for butt logs to no. 6 for top logs. (Box plot showing 10th, 25th, 50th, 75th and 90th percentile).

There is no major difference in terms of stiffness as a result of the type of log, see Figure 2. However, the first two logs (logs 1 and 2) taken from the butt end of the tree have a significantly higher modulus of elasticity than logs 3, 4 and 5 taken higher up in the tree. Too few battens from log 6 (12 in number) were available and, as a result the statistical evaluation was not reliable.

Table 2. Modulus of elasticity, $E_{m,adj}$ (GPa), for all battens split into different dimensions. (N) – total number of battens for each stand.

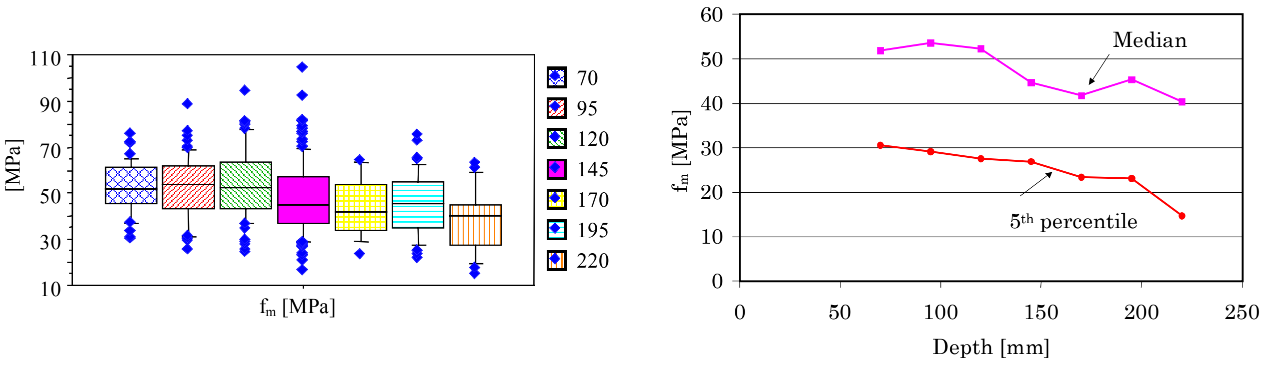
Dimension (mm)/ (thickness/depth) E_{mean}(GPa)													
Stand	**E_{mean}**	**45**	**34**	**45**	**45**	**45**	**58**	**45**	**45**	**58**	**70**	**45**	**70**
(N)		**70**	**95**	**95**	**120**	**145**	**145**	**170**	**195**	**195**	**195**	**220**	**220**
11 (40)	13.8		14.9	13.6	14.6		13.9				12.7		13.2
12 (32)	13.7		13.1	13.2	16.0		14.6			9.9	13.4		12.8
13 (30)	15.7		14.1	14.4	18.9		17.2			16.2	17.0		14.6
14 (25)	10.5		10.3	9.3	11.0		10				10.4		10.4
21 (94)	13.5	9.7		12.7	13.5	14.2		12.4	13.5			14.1	
22 (94)	12.4	9.7		12.4	11.6	14.0		11.5				13.2	
23 (48)	11.6	10.5		14.0	13.4	10.9		10.0					
24 (45)	11.2	9.9		14.2	13.1	11.0		11.4	10.0				
25 (38)	11.3	10.0		12.2	12.3	11.4							
26 (43)	12.4	12.0		11.7	13.8	12.2			12.5				
27 (30)	12.5	11.0		12.2	13.7	11.8		14.6					
28 (34)	11.7	10.3		11.6	14.0	11.1		13.9					
31 (22)	12.3			14.6	13.8		12.6				10.8		9.3
32 (38)	13.1			11.3	12.4	11.9	12.5			17.5	13.7		17.1
33 (32)	12.4			12.3	14.0	13.4	11.8				13.0		
34 (34)	12.7				9.5	10.3	12.9			12.7	13.8		13.1
51 (4)	9.4					9.4							
53 (4)	11.9											11.9	
54 (12)	14.5					14.8			13.8				
55 (20)	10.5					11.0			9.4			10.9	
56 (6)	8.0					8.0							
57 (25)	12.8					12.8			12.7				
58 (19)	13.6					13.4			14.3				
Mean	**12.5**	**10.3**	**14.1**	**12.6**	**13.3**	**12.5**	**13.0**	**11.8**	**12.3**	**14.3**	**13.2**	**13.0**	**12.4**

Bending strength

Of 743 tested battens, only 404 were registered as battens which develop bending failure, either in the tension zone or, in some cases, in the compression zone. Sixty-seven battens developed shear failure. These battens developed cracks during storage, probably as a result of too high moisture content followed by too intense drying. Nevertheless, the modulus of elasticity for all the tested battens could be evaluated, as it was measured at the beginning of the test (straight line of the load-deformation curve). For battens which did not fail in bending, the registered "bending strength" is probably lower than it would have been if the pure bending failure had been possible to measure. The same thing applies to battens for which the mode of failure was difficult to establish or if combined shear-bending failure occurred, in which crack(s) developed due to shear before the tension failure. The presentation of the results for bending strength, f_m, will only be based on battens failed in bending, i.e. 404 battens.

Battens depth had a large effect on bending strength, see Figure 3. The battens with a depth of 220 mm displayed a much lower bending strength than the other dimensions. The bending strength, f_m, was therefore adjusted with Eq. 1 according to European standard EN 384, due to the depth effect for the large number of sizes measured in this study and only $f_{m,adj}$ will be presented.

$$f_{m,adj} = \frac{f_m}{\left(150/H\right)^{0.2}} \qquad \text{Eq. 1}$$



a) Box plot of bending strength split by depth (Only battens with width 45 mm are included. Box plot showing 10th, 25th, 50th, 75th and 90th percentile).

b) Median and 5th percentile of bending strength for different depth of battens.

Figure 3. Influence of batten depth on bending strength. a) Box plot. b) Median and 5th percentile.

The mean values for the adjusted bending strength, $f_{m,adj}$, are only based on battens failed in bending, i.e. 404 battens split into different dimensions are presented in Table 3. The number of battens for each group was even more reduced in comparison to the numbers shown in Table 1. The scatter of mean bending strength is very large between different stands and different dimensions. The very unequal number of battens in every group makes statistical comparisons between groups very uncertain. The only reasonable comparison can be made between different stands in terms of the mean strength when all dimensions are included. However, mean strength values for stands 51-58 should be excluded in this comparison due to the lack of sufficient data and the mean values are therefore not shown in Table 3. The average bending strength (50th percentile and based on adjusted values) was 47.6 MPa and varied between 38.1 MPa and 58.5 MPa. The average bending strength was very similar for every timber dimension with the exception of the size of 45 x 220 mm.

Table 3. Bending strength, $f_{m,adj}$ (MPa), for battens split into different dimension. (N) – total number of tested battens from each stand.

Dimension (mm) (thickness/depth) fmean (MPa)													
Stand	**fmean**	**45**	**34**	**45**	**45**	**45**	**58**	**45**	**45**	**58**	**70**	**45**	**70**
(N)		**70**	**95**	**95**	**120**	**145**	**145**	**170**	**195**	**195**	**195**	**220**	**220**
11 (23)	56.4		65.1	50.5	62.5		50.6				61.4		-
12 (20)	44.1		32.7	45.0	63.2		14.6			24.4	41.8		45.0
13 (21)	58.5		51.2	42.8	83.6		68.9			68.8	-		-
14 (22)	38.1		-	28.0	25.7		42.0				35.4		44.5
21 (37)	44.7	42.9		42.1	41.0	52.5		42.0	58.1			29.5	
22 (44)	46.1	39.9		47.5	39.5	53.7		40.3				44.2	
23 (29)	46.5	41.9		54.8	51.1	42.3		37.6					
24 (20)	51.2	42.7		58.3	56.7	56.7		47.7	45.4				
25 (19)	47.5	48.2		60.3	45.8	41.3							
26 (22)	53.9	53.8		42.6	60.8	57.3			47.9				
27 (18)	52.4	49.8		49.5	56.4	49.7		65.1					
28 (16)	52.6	46.4		55.3	51.7	58.4		65.4					
31 (12)	39.0			-	46.6		41.1				33.0		26.6
32 (29)	46.1			44.1	43.4	47.3	41.6			-	50.8		56.0
33 (24)	42.7			40.5	53.3	39.1	38.1				52.0		
34 (18)	43.8				33.4	37.1	41.9			-	51.1		57.5

Height in a tree

In general, battens sawn from butt logs and second logs (lower down in a tree) produced stronger timber, cf. Figure 4. However, there is very little or no difference between the 5th percentile values for each group. Battens from log 1 and 2 have significantly higher bending strength than battens from logs taken higher up in the tree. Too few battens from log 6 were available and, as a result the statistical evaluation was not reliable.

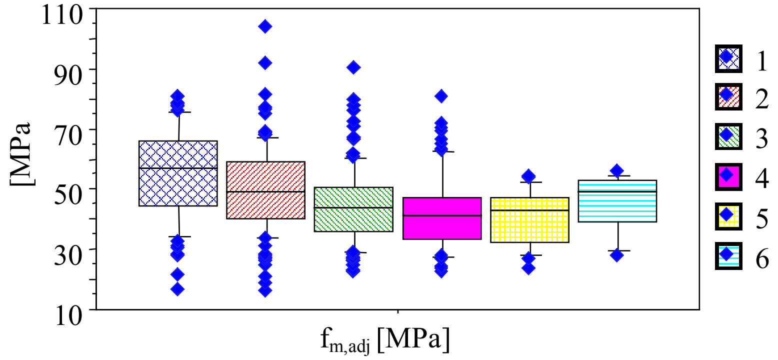


Figure 4. Box plot of bending strength $f_{m,adj}$ divided into six groups for battens from different logs in relation to the distance from the ground: i.e. no. 1 for butt logs and no. 6 for top logs. (Box plot showing 10th, 25th, 50th, 75th and 90th percentile).

Relationship between strength and stiffness

The linear regression for all the battens that failed in bending (N = 404) is shown in Figure 5. The coefficient of determination, $R^2 = 0.51$, is of a somewhat lower magnitude than that previously reported in various literature sources. The relationship between bending strength and the modulus of elasticity was found by Johansson et al. 1992 to be $f_m = -2.4 + 3.8\ E_m$ and is the basis for setting values for mechanical stress-grading machines in Sweden. This relationship is of a similar magnitude to that obtained in this study, cf. Figure 5.

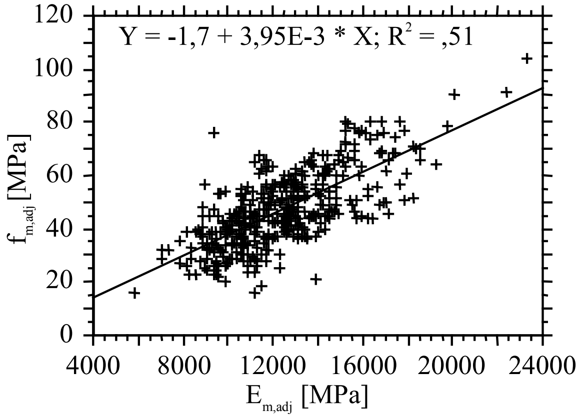


Figure 5. Linear regression between bending strength ($f_{m,adj}$) and modulus of elasticity ($E_{m,adj}$) based on more than 400 battens from 22 stands and in 12 different dimensions.

Influence of batten depth

Batten depth had a large effect on bending strength in this test series, cf. Figure 3. According to European standard EN 384, the depth effect can be taken into account using the depth effect factor k^{std}_H, see Eq. 2.

$$k^{std}{}_H = \left(150/H\right)^{0.2} \qquad \text{Eq. 2.}$$

In European standard EN 384, the depth factor is applied to all the strength data and thus affects the median value. In Eurocode 5, the depth effect is taken into account for batten depths of less than 150 mm, see Eq. 3. In Eurocode 5, this depth factor is used to correct the characteristic strength (5th percentile).

$$k^{code}{}_H = \begin{cases} \left(150/H\right)^{0.2} \\ 1.3 \end{cases} \qquad \text{Eq. 3.}$$

A "new" depth effect factor k^{cal}_H was established on the basis of the tested material. A depth factor was established both for the median values and for the 5th percentile values. The material used in this analysis comprised all the battens which failed in bending. The depth effect factor used in European standard EN 384 agreed well with the one established with this material, see Eq. 4. This factor was established without taking the battens with a depth of 220 mm into account. This was done since the average strength of this group was very low and this could be the result of the inadequate handling of the material prior to testing. Some of these battens were very wet due to rain and many of them therefore developed cracks due to heavy drying after arriving at our laboratory. If the battens with a depth of 220 mm were taken into account, the exponent in the $k^{cal}{}_H$ formula increased to 0.25.

$$k^{cal}{}_H = \left(150/H\right)^{0.22} \qquad \text{Eq. 4.}$$

If the depth effect factor is established for the 5th percentile values instead the formula presented in Eurocode 5 underestimates the depth effect. The exponent in this case becomes 0.3 when the dimension of 220 mm is excluded. This shows that the depth effect is larger for values of the 5th percentile than for the median values.

Influence of raw material parameters on strength and stiffness

The analysis of influence of raw material parameters on bending strength are based on 207 specimens which failed in bending and on which material parameters were measured. The parameters that showed an influence on bending strength were MOE measured statically and dynamically. Other parameters with influence were RW and KAR.

Table 4. Correlation matrix (R) between material parameters and bending strength.

	$f_{m,adj}$	$E_{m,adj}$	E_{dyn}	Dens	RW	KAR	MKAR	GA	DIST	TW	BO	SP
$f_{m,adj}$	1.00	0.68	0.70	0.43	-0.52	-0.58	-0.45	-0.40	0.11	-0.37	-0.16	0.03
$E_{m,adj}$		1.00	0.94	0.75	-0.43	-0.40	-0.33	-0.22	0.04	-0.27	-0.13	0.04
E_{dyn}			1.00	0.79	-0.51	-0.42	-0.31	-0.29	0.14	-0.32	-0.17	0.01
Dens				1.00	-0.42	-0.07	-0.01	-0.23	-0.05	-0.14	0.03	0.14
RW					1.00	0.53	0.40	0.39	-0.14	0.31	-0.01	-0.17
KAR						1.00	0.74	0.21	-0.26	0.30	0.10	0.06
MKAR							1.00	0.10	-0.18	0.20	0.07	0.05
GA								1.00	-0.11	0.51	0.02	-0.05
DIST									1.00	-0.27	-0.04	-0.32
TW										1.00	0.19	0.10
BO											1.00	-0.02
SP												1.00

If all the parameters above were used in a multiple regression analysis to predict $f_{m,adj}$ a coefficient of determination of 0.65 could be found. A model with just $E_{m,adj}$, KAR and GA explained 62% of the variation in bending strength.

The factors with an influence on $E_{m,adj}$ were Dens, RW and KAR. A multiple regression analysis of $E_{m,adj}$ against Dens, RW, KAR, MKAR, GA, DIST, TW, BO and SP showed a coefficient of determination of 0.70. The parameters with the largest influence were Dens and KAR. A statistical model with only Dens and KAR produced a coefficient of determination of 0.67. The relationship between the modulus of elasticity measured statically and the modulus of elasticity measured dynamically was good, $R^2 = 0.87$, see Figure 6. The relationship can also be seen in the correlation matrix, see Table 4.

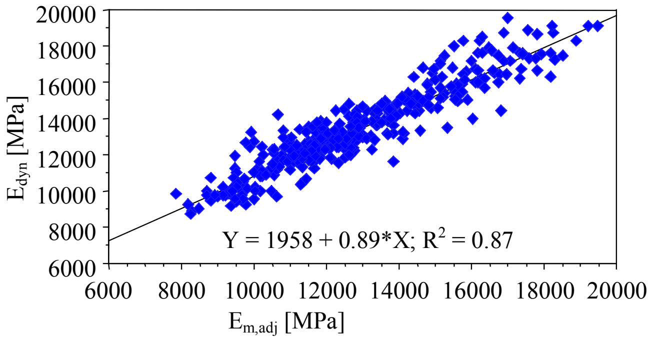


Figure 6. Relationship between modulus of elasticity measured statically and modulus of elasticity measured dynamically.

The correlation between the modulus of elasticity measured statically and the modulus of elasticity measured dynamically was of a somewhat lower magnitude than that obtained in other studies (Perstorper 1993, for example). In the present study, where the tested battens were tested in excellent free-free conditions the coefficient of determination was 0,90. In this study the measurement device had a lower level of accuracy than that in Perstorper´s study, which could explain the somewhat poorer correlation.

SUMMARY

Tests to failure in accordance with the European Standard EN408 have been conducted on approximately 750 battens sawn from 12 different dimensions from 23 different stands (Sweden, Finland and France). The main objective of this test was to determine the mechanical properties of sawn wood in terms of the modulus of elasticity E_m and bending strength f_m. The average modulus of elasticity per stand was 12.6 GPa and varied between 8 GPa (for timber from the most fast-grown stand) and 17.5 GPa. The bending strength was evaluated on battens which failed in pure bending only and they represented about 55% of the total number of tested battens. The obtained bending strength was adjusted to a depth of 150 mm according to European standard EN 384 in order to be able to compare different sizes in terms of strength. The average bending strength per stand (50th percentile and based on adjusted values) was 47.6 MPa and varied between 38.1 MPa and 58.5 MPa

The effect of the type of log reveals that battens from the butt logs had a higher strength and stiffness than other logs (higher up in a tree). However, on the 5th percent level there was no difference in term of bending strength between battens from different longitudinal positions in a tree. Linear regression between bending strength ($f_{m,adj}$) and modulus of elasticity ($E_{m,adj}$) produced the coefficient of determination $R^2 = 0.51$, which is of a somewhat lower magnitude to that previously reported in various literature sources.

A "new" depth effect factor k^{cal}_H was established on the basis of the tested material. The median bending strength was adjusted for the depth effect using $k^{cal}_H = (150/H)^{0.22}$, where the exponent of 0.22 is slightly higher than that given in European standard EN 384.

An analysis of the effect of the material properties on the bending strength reveals that the parameters with the largest influence were $E_{m,adj}$, dynamic E-modulus, RW and KAR. A multiple regression analysis for the effect of $E_{m,adj}$, KAR and GA on bending strength shows a coefficient of determination of 0.62. A multiple regression analysis of $E_{m,adj}$ against Dens, RW, KAR, MKAR, GA, DIST, TW, BO and SP show a coefficient of determination of 0.70. The parameters with the largest influence were Dens and KAR.

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