Strength data of Italian red spruce (*Picea abies*)

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Summary
Strength data of Italian grown spruce that has been gathered during various research projects over the last 13 years have been combined into one large dataset. The data has been analysed for mechanical properties such as bending strength, modulus of elasticity as well as density. Visual grades have been determined using the German and Italian standards and were analysed for their strength profiles. Normal, Lognormal and Weibull distributions have been determined. The use of ultrasound grading as an additional parameter has been tried, but was found not very useful in improving the yield in higher strength classes.

Acknowledgement
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Introduction
The Val di Fiemme region in Trentino is one of the largest softwood producing areas of Italy for use in structural applications. The whole province of Trentino produces around 400.000 m^3 of sawn timber each year, of which a large part is used structurally. In the last 15 years strength data has been gathered in several research projects consisting of a variety of material sizes, origins and qualities. The projects dealt with both visual and machine strength grading using ultrasound. The visual grading rules applied were in accordance with Italian standards which closely resemble the German visual grading rules for softwoods. Besides visual grading all beams were also graded using ultrasound. Strength profiles have been determined in accordance with European standards EN 384. Characteristic values and the strength profiles of the subsamples have been determined and the scatter in mean and characteristic values for bending strength, modulus of elasticity and density are analysed statistically. In addition, the whole sample is analysed for the depth effect, which was found to comply well with EN 384. Ultrasound grading has been performed and the efficiency is analysed. The yield in higher strength classes is determined. A combination of both visual and ultrasound grading improved the yield in high strength classes considerably. Boundaries for the ultrasound wave speed have been determined. It was found that traditional strength profiles of EN 338 are not satisfactory for the timber studied, and for use in combination with a design standard a specific strength profile has been determined.

2. Material and methods
The Val di Fiemme region in Trentino is one of the largest softwood producing regions in Italy, with a production of more than 50.000 m^3 each year. White and Red Spruce are the main species. Over the last fifteen years several projects have been performed to determine the characteristic strength values of the timber. The samples from a number of these projects are gathered in table 1.
Due to the different research projects not all beams were graded and tested according to the same principles. However, from all beams the visual classification according to DIN

4074/UNI 11035 has been determined and a 'knot ratio' has been determined as knot size divided by the face dimension on which the knot is visible. Furthermore, density, local MoE and bending strength have been determined in the laboratory, including ultrasound wave speed and dynamic MoE.

Table 1. Samples of Italian spruce over 13 year span.

Sample	Year	No.	Sizes			
			width	depth	length	test length
1	1991/1992	215	90	150	4000	2700
2	2003	45	45	70	1400	1260
3	2003	50	45	70	2000	1260
4	2003	45	70	110	2200	1980
5	2003	45	85	150	3000	2700
6	2004	45	90	150	2200	2100
7	2004	45	90	145	2200	2100
8	2004	42	90	145	2200	2100
9	2004	24	125	260	4000	3800
10	2004	78	75	200	4200	3800
11	2004	72	90	250	4200	3800
12	2005	48	60	150	3000	2700

3. Visual grades

Italian standard UNI 11035 is approximately similar to DIN 4074 with regard to the knot requirements. Three grades and reject are considered, namely Grade S1, S2 and S3, corresponding to the German grades S13, S10, S7 and Reject.

Table 2 Visual grades and yield for each subsample.

Sample				S1	S2	S3	Reject	Whole
No.	width	depth						
1	90	150	n.	67	117	28	1	215[1)]
			%	*31.2*	*54.4*	*13.0*	*0.4*	*100*
2	45	70	n.	10	17	11	7	45
			%	*22.2*	*37.8*	*24.4*	*15.6*	*100*
3	45	70	n.	10	11	24	5	50
			%	*20.0*	*22.0*	*48.0*	*10.0*	*100*
4	70	110	n.	15	20	6	4	45
			%	*33.3*	*44.4*	*13.3*	*8.9*	*100*
5	85	150	n.	15	24	4	2	45
			%	*33.3*	*53.3*	*8.9*	*4.4*	*100*
6	90	150	n.	9	26	9	0	44
			%	*20.4*	*59.2*	*20.4*	*0*	*100*
7	90	145	n.	3	25	17	0	45
			%	*6.7*	*55.5*	*37.7*	*0*	*100*
8	90	145	n.	8	14	15	0	37
			%	*21.6*	*37.8*	*40.5*	*0*	*100*
9	120	260	n.	4	12	4	3	23
			%	*18.2*	*54.5*	*17.3*	*13.6*	*100*
10	75	200	n.	3	21	23	25	72
			%	*4.2*	*29.2*	*31.9*	*34.7*	*100*
11	90	250	n.	0	30	13	27	71
			%	*0*	*42.8*	*18.5*	*38.6*	*100*
12	60	150	n.	10	17	16	5	48
			%	*20.8*	*35.4*	*33.3*	*10.4*	*100*

The German grades have been assigned to strength classes C30, C24, C16 of EN 338 respectively, wheras for the Italian grades specific profiles have been set up in the national standard [UNI 11035-2]. The typical characteristic density values for strength classes C30, C24 and C16 are 380, 350, and 310 kg/m^3. Mean values are approximately 20% higher. The Italian grades S1, S2 and S3 are assigned to EN 338 strength classes C27, C22 and C16 respectively, having characteristic density values of 370, 340 and 310 kg/m^3. The characteristic density of the samples are gathered in Annex A show that in a number of cases the minimum requirements are not met. This is especially the case for strength class C30.

4. Test results

The data for density, static modulus of elasticity and bending strength have been gathered for each of the subsamples in Annex A, B and C respectively. If all samples are regarded as one, the dataset contains more than 750 test results. Correlation coefficients have been determined for this basic data as well as the graded data and are gathered in Table 3 and 4 respectively.

Table 3. Basic properties of ungraded spruce

Property	Density	Modulus of Elasticity	Bending strength
Average	420.0	10131	39.1
Standard deviation	30.6	2141	12.9

Table 4. Basic properties for graded spruce

			Density kg/m^3		Modulus of Elasticity N/mm^2		Bending strength N/mm^2	
Grade	n	%	Average	St.dev.	Average	St.dev	Average	St.dev
S1	155	10.8	420.1	31.6	11315	1864	49.5	11.6
S2	355	21.0	420.5	31.6	10207	1966	38.8	11.2
S3	168	45.4	422.9	29.2	9375	2139	33.8	12.3
R	80	22.8	411.9	26.5	9085	2196	31.5	10.1

The low correlation coefficient between density and bending strength (R^2 = 0.09) indicates that visual grading may have an effect on the bending strength and modulus of elasticity, but hardly or no effect whatsoever on the density values. This influences the strength class assignment considerably. In table 5 the correlation coefficients between the different parameters are given.

Table 5. Correlation coefficients

Property	Density	Modulus of Elasticity	Bending strength	KAR
Density	1			
Modulus of Elasticity	0.43	1		
Bending strength	0.30	0.71	1	
KAR	-0.03	-0.47	-0.52	1

The relationship between the knot ratio (KAR), calculated as minimum knot diameter divided by the face dimension on which the knot is visible, is show in Figure 1. The existence of a depth effect has been studied by fitting a power- equation to the basic data. Therefore, all data-values have been divided by the average bending strength and the ratio has been plotted against the depth, see Figure 2. The depth effect could be described using the following relationship:

$$k_h = \left(\frac{150}{h}\right)^{0.2425} \qquad (1)$$

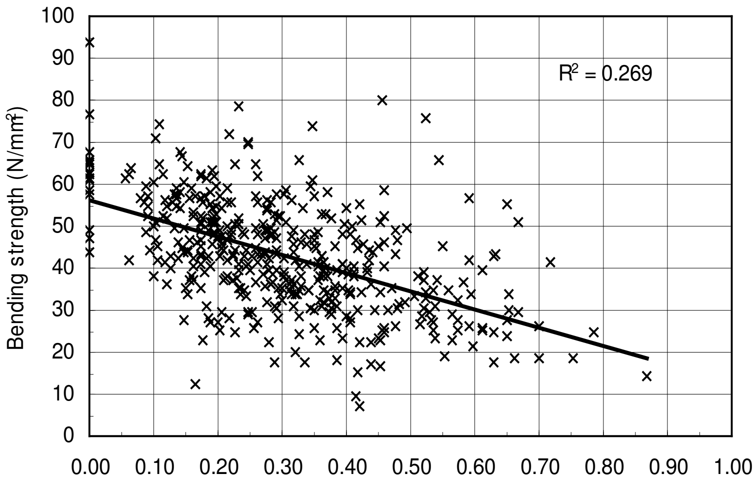

Figure 1. Relationship between KAR and bending strength

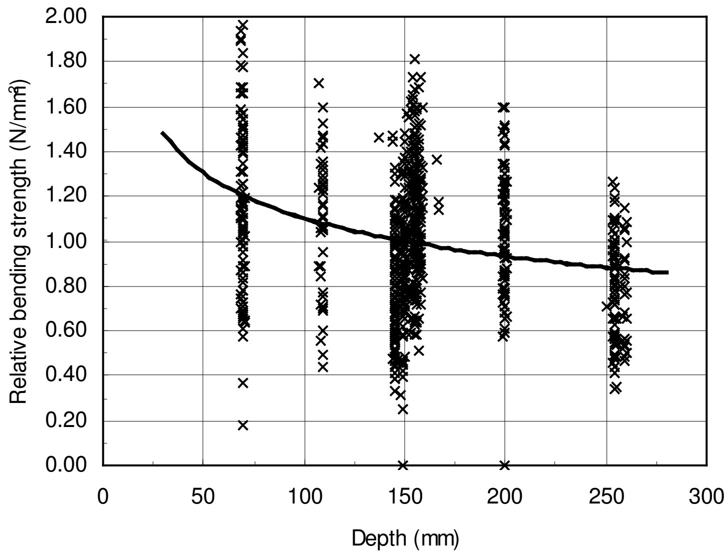

Figure 2. Depth effect for the full dataset

5. Frequency distributions and characteristic values

For the three grades (data adjusted for the depth effect) as well as for the full (ungraded) dataset, the distribution functions have been determined. In all cases it was found that Weibull and Normal distributions described the data better than log-normal distributions. the parameters of the distributions have been gathered in Table 6. In Figure 3 the data and the distributions are shown. The cumulative frequency distributions of the three grades are shown in Figure 4.

The non-parametric characteristic strength values have been determined for the three different grades as well as for the ungraded material, see Table 7. In addition, the characteristic values using the three distributions are also given. From the lower tail shown in Figure 3 it can be concluded that Normal and Lognormal give an underprediction of the 5-th percentile value of the strength data whereas the Lognormal distribution gives an overprediction.

Table 6. Distribution parameters of spruce of Val di Fiemme

	Normal		Lognormal		Weibull (2-parameter)	
Dataset	m	s	m	s	m	v
All data	38.96	12.09	3.633	0.339	42.987	3.421
Grade S1	48.17	10.97	3.844	0.262	52.265	5.127
Grade S2	38.25	10.11	3.628	0.283	41.884	4.091
Grade S3	32.47	10.98	3.433	0.359	35.531	3.204

Table 7. Characteristic values of the bending strength

Dataset	Normal	Lognormal	Weibull	Non-parametric
All data	18.98	21.65	18.04	20.27
Grade S1	30.10	30.34	29.28	27.62
Grade S2	21.61	23.63	20.26	21.97
Grade S3	14.42	17.16	14.06	16.22

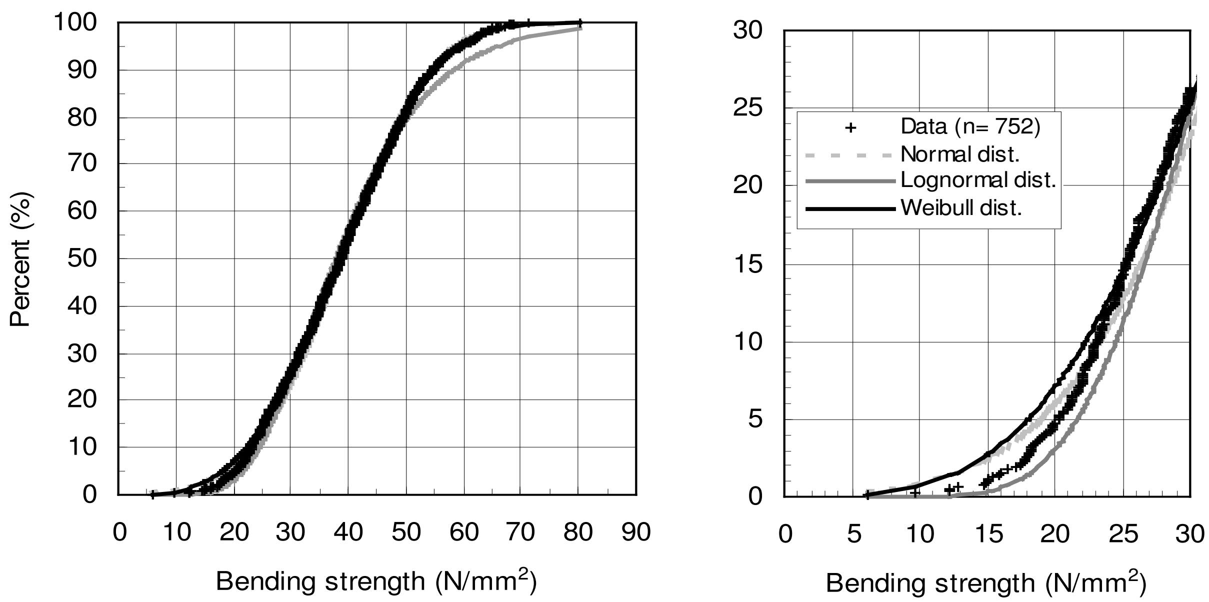

Figure 3. Ungraded data of spruce of Val di Fiemme. Left: full distribution, Right: lower tale

Whereas in most cases the Non-parametric value is in between the values of the three distributions, this is not the case for Grade S1. A lower value of close to 8% is observed in this case. The non-parametric values indicate that the grades exactly fulfil the requirements for C27, C22 and C16 strength classes.

With regard to the modulus of elasticity it may be concluded that not all the requirements for the strength classes C27, C22 and C16 have been met. The requirements are 11500, 10000 and 8000 respectively and from the test results it follows that for the S1 grade the average modulus of elasticity is 11315 and for the S2 and S3 grade 10200 and 9375 respectively. So the S1 grade fails the modulus of elasticity by 1.7%. The characteristic density values for the three classes are 368, 368 and 375 kg/m^3 for S1, S2 and S3 respectively. Officially, also here the S1 grade fails the requirement, but the difference is extremely small. (368 versus 370 required) . It can be concluded that all requirements for the strength classes have been met, except for the modulus of elasticity for the S1 grade, which is slightly to low. The characteristic modulus of elasticity parallel to the grain however is 8240 based on a standard normal distribution, whereas EN 384 specifies a value of $0.67E_{0,mean}$ = 7580 N/mm^2.

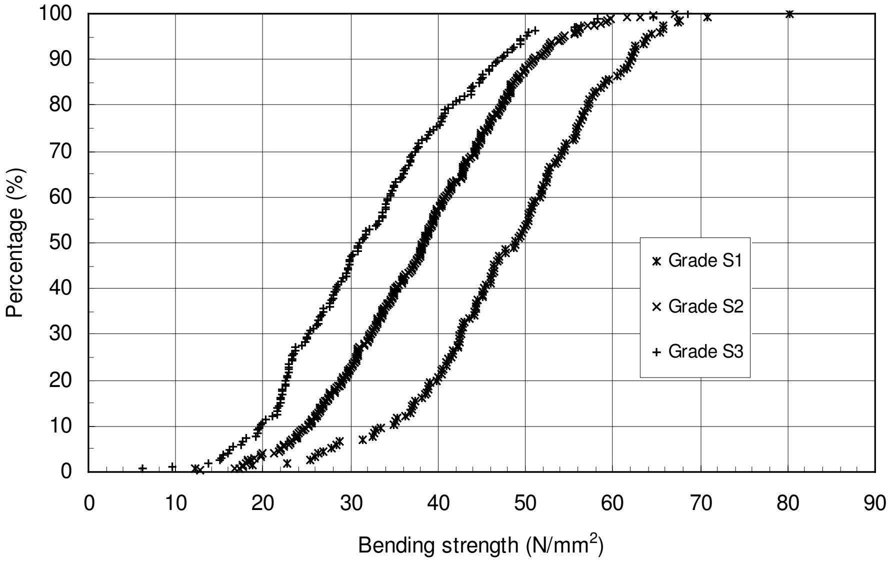

Figure 4. Cumulative frequency distributions of Grades S1, S2 and S3

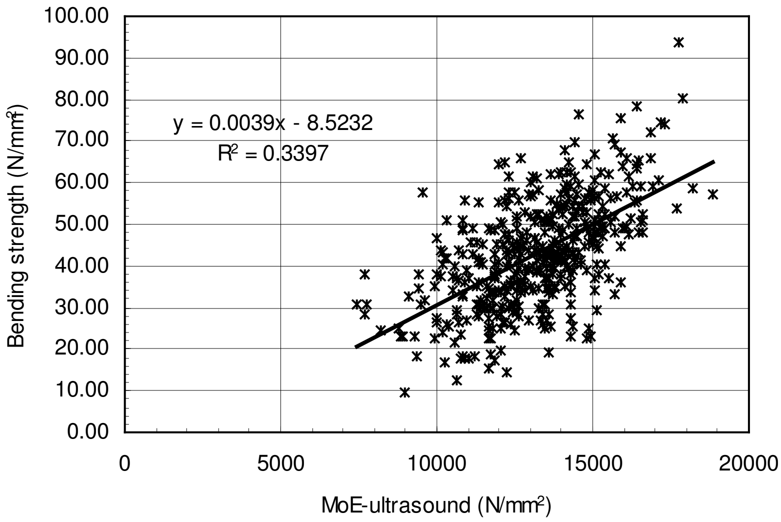

Figure 5. Relationship between MoE determined using ultrasound and the bending strength

6. Ultrasound measurements

All beams have been measured with the Sylvatest strength grading machine. The ultrasonic wave velocity has been determined and on that basis the ultrasound modulus of elasticity. The correlation with the bending strength is shown in Figure 5 and the correlation between dynamic modulus of elasticity and static modulus of elasticity is shown in Figure 6.

Correlation between squared ultrasound speed and bending strength was slightly better than ultrasound velocity with $R^2 = 0.325$ versus $R^2 = 0.317$. This has previously also been found by Ceccotti et al. [1]. With these relatively low coefficients of determination there seems to be no benefit in applying a grading machine based on ultrasound in the industry. Multiple regression analysis using MoE_{static} and knot parameter gives the following results:

$f_m = 3.643 \cdot 10^{-3} MoE_{stat} - 18.563 \cdot KAR + 10.847$ with $R^2 = 0.572$ and shown in Figure 7.

or:

$f_m = 3.332 \cdot 10^{-3} MoE_{ultrasound} - 33.766 \cdot KAR + 9.327$ with $R^2 = 0.505$ when using $MoE_{ultrasound}$
The use of density as a strength determining parameter does not give an improved prediction.

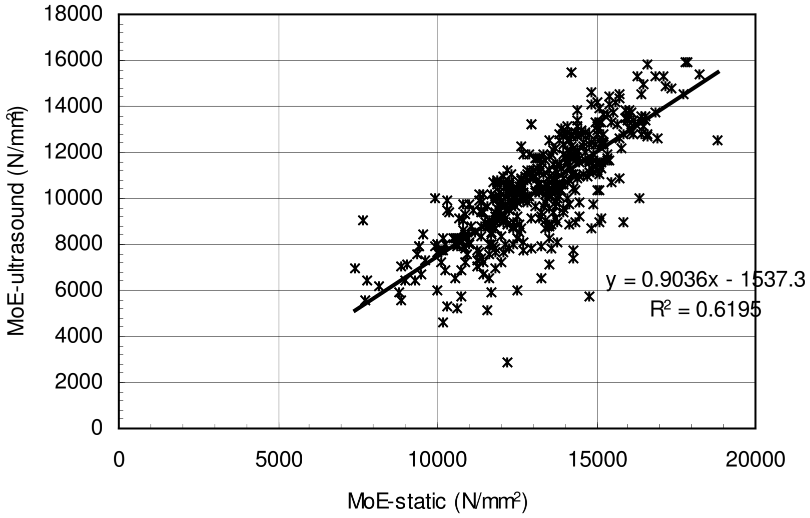

Figure 6. Relationship between static MoE and ultrasonic MoE

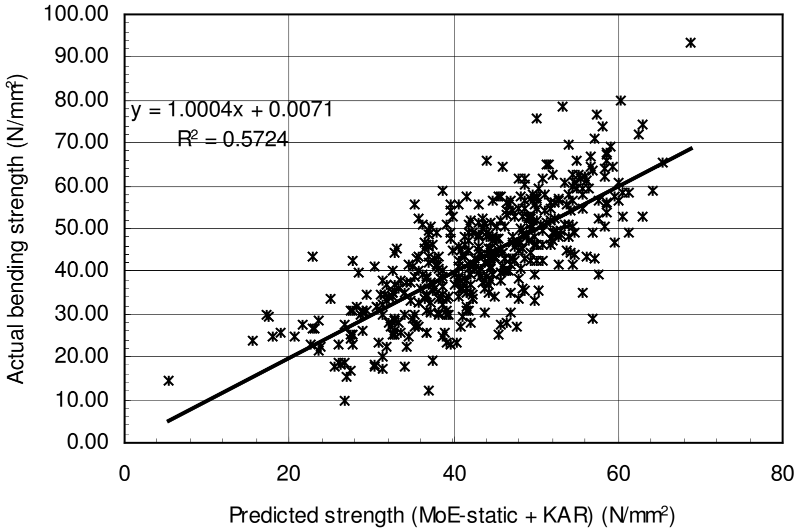

Figure 7. Multiple regression analysis

7. Conclusions

A dataset of Italian red spruce has been created containing on the basis of more than 700 bending tests on visually graded material. Distribution function parameters have been determined which may be used for the derivation of characteristic values and for probabilistic calculations.

Literature

[1] Ceccotti, A., Nakia, T., Togni, M., Strength grading of structural timber by non-destructive methods: a case study in Italy. Proc. First European Symposium on Nondestructive Evaluation of Wood, Vol. 2, September 21-23, 1994, Sopron, Hungary,

Annex A. Density values for subsamples 1 to 12.

Sample				S1	S2	S3	Reject	Whole
No.	width	depth						
1	90	150	n.	67	117	28	1	215[1)]
			ρ_k	***381.7***	***373.3***	***381.0***	*[-]*	***376.9***
			ρ_{mean}	***421.5***	***420.5***	***416.5***		***420.2***
2	45	70	n.	10	17	11	7	45
			ρ_k	***351.5***	***397.3***	***403.8***	***389.9***	***382.4***
			ρ_{mean}	***407.0***	***433.5***	***440.9***	***417.4***	***426.9***
3	45	70	n.	10	11	24	5	50
			ρ_k	***377.6***	***343.8***	***383.5***	***384.6***	***371.2***
			ρ_{mean}	***405.8***	***416.1***	***417.5***	***414.6***	***414.6***
4	70	110	n.	15	20	6	4	45
			ρ_k	***374.2***	***375.4***	***363.2***	***395.5***	***374.1***
			ρ_{mean}	***419.1***	***416.3***	***410.7***	***403.0***	***415.3***
5	85	150	n.	15	24	4	2	45
			ρ_k	***379.0***	***386.1***	***372.1***	***392.4***	***381.2***
			ρ_{mean}	***408.3***	***421.4***	***407.8***	***404.0***	***415.0***
6	90	150	n.	9	26	9	0	44
			ρ_k	***340.2***	***350.1***	***392.4***	*[-]*	***354.8***
			ρ_{mean}	***398.7***	***408.7***	***410.8***		***407.1***
7	90	145	n.	3	25	17	0	45
			ρ_k	***318.9***	***343.1***	***361.4***	*[-]*	***342.2***
			ρ_{mean}	***368.4***	***393.9***	***424.6***		***403.8***
8	90	145	n.	8	14	15	0	37
			ρ_k	***337.8***	***367.0***	***362.6***	*[-]*	***358.7***
			ρ_{mean}	***424.9***	***413.6***	***417.6***		***417.6***
9	120	260	n.	4	12	4	3	23
			ρ_k	***347.9***	***370.7***	***361.8***	***360.4***	***364.4***
			ρ_{mean}	***399.1***	***420.9***	***416.0***	***430.4***	***416.7***
10	75	200	n.	3	21	23	25	72
			ρ_k	***356.1***	***334.8***	***388.7***	***355.0***	***358.3***
			ρ_{mean}	***385.2***	***408.4***	***430.8***	***406.7***	***416.7***
11	90	250	n.	0	30	13	27	71
			ρ_k	*[-]*	***372.3***	***369.4***	***368.0***	***369.6***
			ρ_{mean}		***405.1***	***404.3***	***413.2***	***408.2***
12	60	150	n.	10	17	16	5	48
			ρ_k	***374.0***	***380.7***	***374.8***	***362.6***	***376.3***
			ρ_{mean}	***422.8***	***422.7***	***424.5***	***409.6***	***422.9***

1) Data given differs slightly for those presented by Ceccotti et al. [1994]. The difference is caused by the fact that here the basic data is reported wheras Ceccotti et al. reported the data of 192 beams that failed inside the loading points. Differences however are small and do not affect the conclusions drawn here.

Annex B. Local Modulus of elasticity for subsamples 1 to 12.

Sample				S1	S2	S3	Reject	Whole
No.	width	depth						
1	90	150	n.	67	117	28	1	215
			E_{mean}	***12064***	***10733***	***9410***	***[-]***	***10976***
			sd.	***1395***	***1764***	***1509***		***1843***
2	45	70	n.	10	17	11	7	45
			E_{mean}	***10727***	***12465***	***12687***	***7324***	***11333***
			sd.	***2872***	***1954***	***2263***	***2671***	***2968***
3	45	70	n.	10	11	24	5	50
			E_{mean}	***10703***	***9007***	***8726***	***6275***	***8943***
			sd.	***2251***	***1771***	***2073***	***1422***	***2270***
4	70	110	n.	15	20	6	4	45
			E_{mean}	***10955***	***9907***	***9534***	***8048***	***10041***
			sd.	***1492***	***1474***	***1621***	***2082***	***1762***
5	85	150	n.	15	24	4	2	45
			E_{mean}	***10235***	***8760***	***7604***	***[-]***	***9189***
			sd.	***1530***	***1240***	***697***		***1520***
6	90	150	n.	9	26	9	0	44
			E_{mean}	***11175***	***10847***	***9733***	***[-]***	***10690***
			sd.	***2062***	***1543***	***1951***		***1767***
7	90	145	n.	3	25	17	0	45
			E_{mean}	***8877***	***8066***	***7750***	***[-]***	***8001***
			sd.	***639***	***1722***	***1273***		***1519***
8	90	145	n.	8	14	15	0	37
			E_{mean}	***10342***	***9412***	***8770***	***[-]***	***9347***
			sd.	***2660***	***1893***	***1770***		***2217***
9	120	260	n.	4	12	4	3	23
			E_{mean}	***11322***	***9893***	***8142***	***8645***	***9743***
			sd.	***880***	***2320***	***1096***	***2508***	***2138***
10	75	200	n.	3	21	23	25	72
			E_{mean}	***11045***	***10621***	***10739***	***10278***	***10709***
			sd.	***1180***	***1827***	***1706***	***1666***	***1746***
11	90	250	n.	0	30	13	27	71
			E_{mean}	***[-]***	***9976***	***8678***	***9408***	***9512***
			sd.		***1407***	***1020***	***1970***	***1654***
12	60	150	n.	10	17	16	5	48
			E_{mean}	***10675***	***10061***	***9258***	***7754***	***9681***
			sd.	***2217***	***2232***	***2354***	***322***	***2266***

Annex C. Bending strength values for subsamples 1 to 12.

Sample				S1	S2	S3	Reject	Whole
No.	width	depth						
1	90	150	n.	67	117	28	1	215
			f_{mean}	***53.7***	***42.3***	***35.3***	***[-]***	***44.5***
			sd.	***8.6***	***8.6***	***7.7***		***10.6***
2	45	70	n.	10	17	11	7	45
			f_{mean}	***57.91***	***58.26***	***50.85***	***30.89***	***52.11***
			sd.	***17.71***	***13.42***	***17.69***	***9.84***	***17.56***
3	45	70	n.	10	11	24	5	50
			f_{mean}	***53.09***	***42.88***	***39.38***	***28.51***	***41.85***
			sd.	***11.41***	***10.39***	***11.20***	***7.97***	***12.56***
4	70	110	n.	15	20	6	4	45
			f_{mean}	***48.88***	***42.92***	***34.01***	***32.75***	***42.81***
			sd.	***11.21***	***10.55***	***9.92***	***13.35***	***11.98***
5	85	150	n.	15	24	4	2	45
			f_{mean}	***39.37***	***32.89***	***25.55***	***[-]***	***34.74***
			sd.	***9.48***	***9.04***	***7.03***		***9.90***
6	90	150	n.	9	26	9	0	44
			f_{mean}	***41.78***	***37.58***	***32.84***	***[-]***	***37.47***
			sd.	***11.29***	***7.58***	***7.01***		***8.62***
7	90	145	n.	3	25	17	0	45
			f_{mean}	***41.47***	***28.17***	***24.30***	***[-]***	***27.59***
			sd.	***2.92***	***7.78***	***6.55***		***8.16***
8	90	145	n.	8	14	15	0	37
			f_{mean}	***37.86***	***32.32***	***27.71***	***[-]***	***31.21***
			sd.	***7.88***	***9.04***	***8.26***		***9.12***
9	120	260	n.	4	12	4	3	23
			f_{mean}	***35.75***	***30.55***	***22.56***	***23.50***	***29.42***
			sd.	***7.57***	***8.07***	***7.08***	***5.69***	***8.52***
10	75	200	n.	3	21	23	25	72
			f_{mean}	***45.67***	***39.43***	***40.33***	***37.02***	***39.86***
			sd.	***11.96***	***12.82***	***8.97***	***9.82***	***10.98***
11	90	250	n.	0	30	13	27	71
			f_{mean}	***[-]***	***33.56***	***24.27***	***28.83***	***29.98***
			sd.		***8.85***	***7.85***	***8.30***	***9.03***
12	60	150	n.	10	17	16	5	48
			f_{mean}	***51.38***	***36.45***	***31.97***	***36.63***	***37.95***
			sd.	***10.78***	***8.36***	***12.45***	***13.43***	***13.17***