Relevance of wind-induced compression failures regarding bending strength and stiffness of Spruce structural timber

Martin Arnold, René Steiger

Empa, Swiss Federal Laboratories for Materials Testing and Research

Wood Laboratory

CH-8600 Dübendorf, Switzerland

martin.arnold@empa.ch rene.steiger@empa.ch

Keywords: compression failures, grading, storm damage, structural timber, strength class

ABSTRACT

Compression failures (CF) are a well-known phenomenon mainly in lower density softwood trees exposed to frequent and/or strong winds. They are induced by large stem deflections, which cause a buckling of the wood fibres on the leeward side of the stems after exceeding the axial compressive strength of the wood. The distorted fibres are weak points in the wood structure, which can lead to brittle fractures already at a relatively low stress level in bending or tension. According to many grading rules, CF are therefore not permitted in construction timber.

In an extensive research project started after the violent winter storm 'Lothar' (1999), open questions regarding the extent and location, the causes, the detection and the consequences of compression failures have been studied. 30 blown-down, broken or standing mature spruce (Picea abies) trees were harvested from a heavily storm damaged stand and converted into construction timber. During the visual grading procedures acc. to the Swiss standard SIA 265/1 the sawn timber was scrutinized for compression failures. Afterwards MOE and MOR of 563 beams (2200mm x 110mm x 95mm) were determined in bending tests acc. to EN 408. A statistically significant reduction of the moduli of rupture and elasticity in bending was found. The characteristic values of the mechanical properties however still exceeded the limits for the strength classes of visually graded timber (acc. to SIA 265/1). Since posing a severe safety risk because of the very brittle fracture behaviour it is nevertheless recommended not to use timber with detected CF in load bearing structures especially when members are subjected to tension or bending stresses.

INTRODUCTION

Defects in the wood structure in the form of buckled cell walls of the wood fibres are a well-known 'natural' phenomenon and are observed quite frequently in lower density softwoods such as spruce *(Picea abies)* [4, 9, 11, 19, 20]. These co-called compression failures (CF) may be wind-induced in the standing trees, if the stems are bent so much by frequent or strong winds that the proportionality limit of the wood in axial compression is locally exceeded on the inward (leeward) side of the bow. The size of CF may range from small deformations in the cell wall to wide bands of several millimetres in width, which can affect more than half of the stem's cross-section. The geometric structures of CF are complex, have more or less fuzzy boundaries and appear in a broad range of intensities. CF are usually difficult to detect, particularly in rough sawn timber. This poses a problem regarding processing and grading of such timber.

The distorted and damaged fibres can lead to brittle fractures in structural timber already at a relatively low stress in bending or tension. CF therefore are regarded as unwanted structural defects and particularly after heavy storm damages in the forests, questions regarding their influence on the mechanical properties of timber from the salvaged trees arise anew.

A reduction of the mechanical properties (mainly in bending and tension) at the fibre level [18] and in small clear wood specimens is generally acknowledged [9, 15], but the effect is less clear with structural timber. There the effect of CF may be confounded by the presence of other defects such as knots or grain deviations [7, 8]. However, because of their potential safety risk, many grading standards explicitly [14] or implicitly ('mechanical damages') exclude CF from timber elements in load bearing structures. The presented work is part of an extensive research project in Switzerland started after the violent winter storm 'Lothar' in December 1999, aiming to collect more information regarding the extent and location, the causes, the detection, and the consequences of wind-induced CF [2].

MATERIALS AND METHODS [1]

Sample material

The sample material was taken from 30 fully-grown spruce *(Picea abies)* trees of heights between 35 and 43 m and diameter at breast height between 39 and 72 cm, which were harvested from a mature, even-aged, heavily storm-damaged forest stand near Zurich, Switzerland. 3 to 5 logs of 5 m length were cut from each tree, graded and visually inspected for CF after partial debarking. All logs were sawn into boards of 100 mm or 55 mm thickness, acc. to a systematic sawing pattern adjusted to the previously marked main wind direction of the storm. Subsequently the sawn boards were cut into full-size structural timber as well as small clear specimens for the assessment of various mechanical properties in bending, tension and compression. This paper is focusing only on the bending tests of structural timber. Results of the tests with small clear specimens from the same sample material have been published already earlier [15].

The sample material included a wide range of wood quality and growth ring orientations. All sawn pieces were kiln-dried to a wood moisture content of 15% and planed to their final dimension. Finally, a sample of 563 squared timber beams (2200·110·95 mm^3) was available for bending tests.

Grading and detection of CF

Each beam was visually graded into 4 strength classes (I, II, III, ungraded) according to the supplementary specifications of the Swiss standard for the design of timber structures SIA 265/1 [14]. These visual grades are linked to the EN 338 [5] strength classes C24 (I+II) and C20 (III). Due to practical reasons, visual grade I is currently assigned to C24 instead of the theoretically possible strength class C27. Deviating from the grading rules, beams with detected CF were not excluded. The wood density and the axial ultrasonic speed were measured additionally, but these parameters were not used to derive the strength classes (Table 1).

All beams were inspected for CF and the detected CF were marked. A reliable detection of CF is difficult and depends on the light conditions, the angle of observation, the surface structure, and the experience of the observer. All macroscopically visible CF on the longitudinal faces of the beams were assessed. Because the inspection was done on planed surfaces, even rather fine CF could be detected. For each beam the 'intensity' of CF was recorded as the total number of identified CF and the 'size' of the largest CF (Table 1). The 'size' was assessed by a system simplifying the complex geometric structure of the CF to a one level defect plane, defined by its maximum axial 'width' (CFMAX, Table 1) and the visible length on the circumference of the beam (CFLEN, Table 1). This procedure resulted in 2 sub-samples of beams without and with CF (CFIND, Table 1).

Table 1. Parameters recorded during grading and testing procedures

Parameter group	**Code**	**Parameter**	**Unit**	**Details**
Wood quality	**DENS**	wood density	[kg/m^3]	calculated from mass and volume of whole beam at 15% MC
	USMIN	axial ultrasonic speed	[m/s]	min. value of 2 measurements (device 'Sylvatest')
	KMAX	diameter of largest knot	[mm]	between loading heads (inner third of span)
	KCLU	size of largest knot cluster	[mm]	maximum sum of knot diameters (2 or more knots) within 150 mm length
	CW	compression wood	[%]	affected cross-section (0, 5, 10, 20, 30, …, 100%)
	FUNG	discolouring fungal attack in sapwood	[%]	affected cross-section by blue stain or red stripe (0, 5, 10, 20, 30, …, 100%)
	SCSIA	strength class		I, II, III, ungraded (i. e. unfit for structural purposes); by visual grading according to Swiss standard SIA 265/1 [14]
CF	**CFIND**	binary indicator variable for presence of CF		0 = without CF, 1 = with CF
	NCF	number of (single) detected CF		
	CFMAX	axial 'width' of largest CF	[mm]	Classes: 0.1 mm, 0.5 mm, 1.0 mm, > 1 mm
	CFLEN	circumferent. length of largest CF	[mm]	visible length on tension edge and side faces
Mechanical properties	**MOR**	modulus of rupture	[N/mm^2]	calculated for nominal cross section of 110·95 mm (h·b)
	MOE	modulus of elasticity	[N/mm^2]	
	DMAX	total deformation at max. load	[mm]	measured at neutral axis over 1980 mm span

Bending tests

Bending tests followed the procedure given in EN 408 [6] (4-point bending). The average time to failure was 210 s with 238 beams having times to failure shorter than 180 s due to particular brittle fracture behaviour with a small deformation at maximum load. Deformation was measured on both side faces at the neutral axis over the total span as well as within the central gauge length and averaged over the two faces. The critical section with the expected failure location (e.g. knots, CF) was positioned between the inner loading points. In order to reproduce the original loading situation in the tree, the beams from the leeward side of the stem were loaded in the wind-direction and vice-versa. Thus, present CF were positioned in the majority on the tension edge and thus the beams were loaded in their most critical orientation. Parameters modulus of rupture (MOR), modulus of elasticity (MOE) and total deformation at maximum load (DMAX) were recorded (Table 1).

Data analysis

In a first step the grading characteristics of the sample material was compiled. Then analysis of bending test results was carried out using two different approaches: (1) focusing on the statistical significance and (2) the practical relevance of the effect of CF on the mechanical properties. The effect of the 'size' of the CF and the fracture behaviour was regarded as well.

The statistical significance of the effect of CF on the mechanical properties was assessed with a multiple regression approach. The same main factor model without interaction terms was used for both dependent variables MOR and MOE as defined in formulas 1 and 2, thus allowing a comparison of the respective influence of the same factors in both models:

$$MOR = a_0 + a_1 \cdot DENS + a_2 \cdot USMIN + a_3 \cdot KMAX + a_4 \cdot KCLU + a_5 \cdot CW + a_6 \cdot FUNG + a_7 \cdot CFIND + \varepsilon_1 \quad (1)$$

$$MOE = b_0 + b_1 \cdot DENS + b_2 \cdot USMIN + b_3 \cdot KMAX + b_4 \cdot KCLU + b_5 \cdot CW + b_6 \cdot FUNG + b_7 \cdot CFIND + \varepsilon_2 \quad (2)$$

a_0-a_7 and b_0-b_7 are regression coefficients and ε_1 and ε_2 are error terms in the models 1 and 2 respectively. The abbreviation codes for the regression variables are listed in Table 1. Interaction terms were not included in the models because they were not significant at the 5% level in most cases. All 563 tested beams have been included in this analysis.

The practical relevance of CF regarding the mechanical properties was assessed by comparing the characteristic values of the visually strength graded beams (including both beams without and with CF) as determined according to prEN 384 [12] with the limits of the given strength classes according to SIA 265 [13] and EN 338 [5]. 'Ungraded' beams were not included in this analysis.

RESULTS AND DISCUSSION

Properties of sample material

Only very few beams (24) were visually graded as strength class I, 145 and 197 beams were graded as strength class II and III respectively and a rather high number of beams (197) were graded unfit for structural timber ('ungraded') (Table 2). Big knots and severe compression wood (CW > 20% in 127 of the beams) were the most frequent reasons for downgrading. 200 (36%) of the 563 tested beams contained CF in various 'intensities'. The proportion of beams containing CF increased in the lower strength classes. More information on sample material properties is given in [1].

Table 2. Number of tested beams grouped by presence of CF (CFIND) and strength class (SCSIA)

Frequency [%]	**Strength class SCSIA**				**Total**
CFIND	**I (C24)** [1)]	**II (C24)**	**III (C20)**	**ungraded**	
0	23 (4.1%)	114 (20.3%)	120 (21.3%)	106 (18.8%)	363 (64.5%)
1	1 (0.2%)	31 (5.5%)	77 (13.7%)	91 (16.2%)	200 (35.5%)
Total	24 (4.3%)	145 (25.8%)	197 (35.0%)	197 (35.0%)	**563 (100%)**
Note: [1)] According to SIA 265/1 [14] visual grade I is assigned to C24 (see 2.2)					

For the interpretation of the results it must be noted that the sample material consisted of timber from a heavily storm-damaged forest stand. Compared to earlier studies with structural timber [7, 8], we have tested a notably larger number of specimens with CF and with a higher 'intensity' of CF.

Effect of CF on mechanical properties

In Table 3 selected sample statistics for wood density (DENS), modulus of elasticity (MOE), modulus of rupture (MOR) and total deformation at maximum load (DMAX) are given. MOR and MOE are in the usual range observed for spruce timber in Switzerland [16], but somewhat higher than in other recent studies [7, 8]. Variability within the sub-samples without and with CF is very similar. The mean values of MOR and DMAX are distinctly lower in beams with CF, MOE differs only slightly (Fig. 1).

Table 3. Sample statistics for bending test results grouped by presence of CF (CFIND)

	CFIND	n	Mean	Std	Min	Max
DENS	**0**	363	472	34	367	570
[kg/m^3]	**1**	200	506	38	424	602
MOR	**0**	363	53.0	9.9	23.1	76.3
[N/mm^2]	**1**	200	45.8	11.4	12.2	71.6
MOE	**0**	363	12451	2149	4550	16877
[N/mm^2]	**1**	200	12200	1971	6863	18041
DMAX	**0**	363	55.7	17.6	19.9	106.4
[mm]	**1**	200	39.3	14.7	12.4	81.5

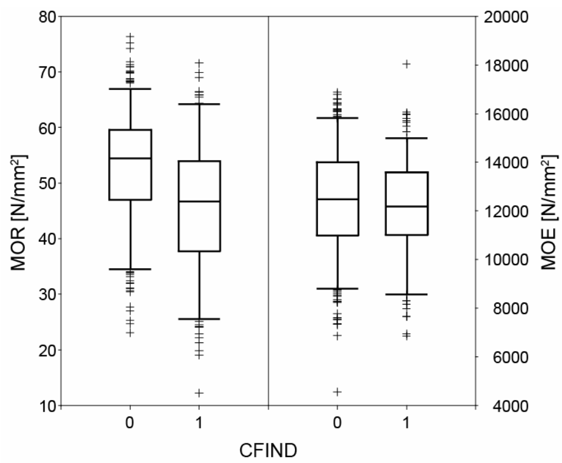

Figure 1. Effect of the presence of CF (CFIND) on MOR and MOE. Box plots for sub-samples without and with CF. (Boxes show the median together with 25th and 75th percentiles, whiskers extend to 5th and 95th percentiles.)

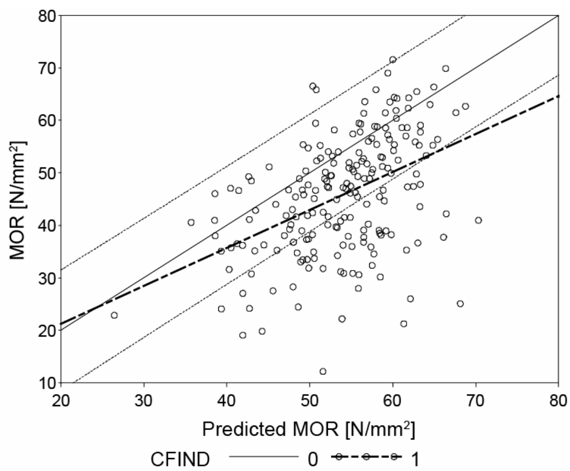

Figure 2. Relationship between predicted and observed MOR for the beams with CF. (The thin solid and dotted lines are the linear regression line and the 90% confidence bands for individual predicted values respectively of the regression model built on the sub-sample of the beams without CF. The thick dotted line is the linear regression line for the beams with CF.)

Both multiple regression models corresponding to formulas 1 and 2 (see above) show a high overall statistical significance with a coefficient of determination (R^2) of 0.45 for MOR and 0.69 for MOE. Except for compression wood (CW) in the MOR model, all included factors are significant at the 5% error level. The diameter of the largest knot (KMAX) and the presence of CF (CFIND) are the most important factors in the MOR model, while wood density (DENS) and axial ultrasonic speed (USMIN) are particularly dominant in the MOE model. A negative effect of CF on both MOR and MOE could statistically be proven. For MOR the presence of CF reduces the bending strength 'on average' by 8.1 N/mm^2 (95%-confidence limits: 9.7 and 6.5 N/mm^2). Related to the mean value of the beams without CF this corresponds to an average reduction of MOR by 15%. The estimate for the effect on MOE is -526 N/mm^2, which is a 4% reduction related to the mean value of the beams without CF. The identified more dominant effect of CF on MOR compared to MOE agrees well with earlier studies [8, 15]. As expected, the reduction of the mechanical properties of structural timber is slightly lower than with small clear specimens [15].

In an alternative approach, a multiple regression model (formula 1 without the indicator variable CFIND), was built on the sub-sample of beams without CF. The resulting regression coefficients were then used to calculate predicted MOR values for the beams with CF (without explicitly taking the visually detected CF into account), thus simulating a specifically calibrated machine stress grading system. An analysis of the deviations of the predicted and the observed MOR values is shown in Fig. 2. This approach disregarding the visually detected CF clearly predicts too high MOR values for many beams containing CF. A practical conclusion of this result is, that CF will not reliably be detected by machine stress grading relying on the dynamic or static assessment of the MOE, as reported already in earlier studies [3, 15, 17]. Machine stress grading of timber containing CF without an additional visual inspection may therefore lead to an overestimation of expected MOR and wrong strength grades.

Characteristic values for MOR, MOE and DENS are listed in Table 4. The sub-samples of beams without and with CF were combined, but stratified by strength classes. The characteristic values all exceed the limits in the given strength classes C20 and C24. This means that in spite of the general and statistically significant reduction of the mechanical properties, visually graded structural timber even with CF meets the requirements with an adequate safety margin. (During the usual visual grading process in sawmills, some of the beams with CF would have been detected and probably discarded.)

Table 4. Verification of characteristic values of strength classes according to prEN 384 [12]

Strength class [1)]	Test results [2)]					Adjustment to reference conditions [3)]			Characteristic values [4)]		
	n	Mean	Std	Min	5%-P	k_{MC} (Factor)	k_h (Divisor)	adjusted values	k_s (Factor)	**char. value**	limit
	MOR [N/mm²]										
I+II / C24	169	56.6	9.0	22.2	**39.1**	–	1.064	36.8	0.89	**32.7**	24
III / C20	197	48.7	10.6	12.2	**30.1**			28.2	0.90	**25.5**	20
	MOE [N/mm²]										
I+II / C24	169	**13464**	1683	8608	10397	1.060	–	14272	–	**14272**	11000
III / C20	197	**12432**	1839	7362	9279			13178		**13178**	9500
	Density [kg/m³]										
I+II / C24	169	475	33	367	**422**	0.985	–	468 / 33	–	**414**	350
III / C20	197	480	35	395	**427**			473 / 34		**416**	330

1) Strength class based on visual grading (without considering the presence of CF) according to the Swiss standard SIA 265/1 [14]

2) Abbreviations of sample statistics: **n** = sample size, **Mean** = arithmetic mean, **Std** = standard deviation, **Min** = minimum value, **5% P** = empirical 5th percentile. The input values for the calculation of the characteristic values are printed in bold.

3) Conversion to reference conditions according to prEN 384: $\mathbf{k_{MC}}$: Correction factor wood moisture content 15 → 12%, $\mathbf{k_h}$: Correction factor timber size / height of beam (150/110)0.2, **adjusted values**: property values at reference conditions. No adjustments to a pure bending MOE were made, which leads to a more conservative estimation of the characteristic values of MOE. Also no adjustments were made for the density as determined from mass and volume of the whole beams.

4) Verification of characteristic values: $\mathbf{k_S}$: correction factor for sample size, **char. value**: characteristic value calculated from tested sample, **limit**: expected characteristic value according to EN 338 [5] for the given strength classes

Effect of the size of CF

Multiple regression analysis failed to show evidence for an improvement of the model fit by the inclusion of the recorded CF 'intensity' variables NCF, CFMAX and CFLEN instead of the binary indicator variable for the presence of CF (CFIND). This is interpreted as a general difficulty to describe the 'damaging' dimensions of CF. The correlation between the 'size' variables of CF and MOE is even lower. Based on these findings, the use of allowable 'size' limits for CF in grading procedures seems neither safe nor practical. This result is in contrast to some earlier reports, where such limits have been proposed [7, 8].

Fracture behaviour

If CF were involved in the mode of failure, frequently abnormally brittle and short-fibred fractures have been observed. Fracture occurred often suddenly and without any prior indications. In some cases the beams were broken completely over the whole cross-section. The low-strain failure mode is also apparent in the total deflection at maximum load. Average total deflection at maximum load was only 39 mm in beams with CF compared to 56 mm in beams without CF, which corresponds to a reduction of 30% (Table 3). The beams with the lowest MOR all contained CF and exhibited very low deformations. This brittle fracture behaviour has been observed already in earlier studies [8, 9, 20]. Moreover, CF have been reported to be particularly sensitive to impact loads (e.g. impact bending tests), which showed a high strength reduction by CF [9, 15].

CONCLUSIONS

The following conclusions regarding the influence of wind-induced CF on the mechanical properties of spruce structural timber can be drawn from the results of the study:

- Bending MOR and MOE of squared timber beams containing CF are statistically significantly lower compared to beams without visible CF. (MOR more pronounced than MOE)
- Despite the general reduction of strength and elasticity, the limits for the characteristic values of the strength classes C20 and C24 of visually graded structural timber (acc. to the Swiss standard SIA 265/1 [14]) are still exceeded. Considering the decreasing influence of other structural defects, this may however not be the case in the higher strength grades.
- Because the MOE is only slightly affected by the presence of CF, machine stress grading methods relying on the dynamic or (low stress level) static assessment of the MOE are not able to reliably detect CF. Machine stress grading of timber containing CF without an additional visual inspection may therefore lead to an overestimation of expected MOR and wrong strength grades.
- The macroscopically visible appearance ('size') of the CF is only a weak indicator for the potential reduction of MOR and MOE. It is therefore impossible to distinguish between 'benign' and 'malignant' CF and to define allowable 'size' limits for CF for visual grading procedures. Only a strict exclusion of CF seems practical.
- Timber containing CF frequently fails abnormally brittle with low-strain, short-fibred fractures.
- Because of the potential safety risk and the difficult prediction of their strength reduction, detected CF should be excluded from load bearing structural elements stressed in tension or bending and explicitly addressed in the relevant grading standards. Timber containing CF should only be used in compression loaded or not load-critical applications.

ACKNOLEDGMENTS

The presented work was funded partly by the Swiss Forest Agency.

REFERENCES

[1] Arnold M., Steiger R. 2007. The influence of wind-induced compression failures on the mechanical properties of spruce structural timber. Materials and Structures 40:57-68.

[2] Arnold M. 2003. Compression Failures in wind-damaged Spruce Trees. In: Proceedings International Conference 'Wind Effects on Trees', 16. – 18. September 2003, University of Karlsruhe, Germany, (Ed. B. Ruck et al., Karlsruhe), 253-260.

[3] Bernasconi A., Boström L., Schacht B. 1999. Detection of severe timber defects by machine grading. Proceedings CIB-W18, 32. meeting, Graz, Austria, Paper 32-5-2.

[4] Delorme A. 1974. Über das Auftreten von Faserstauchungen in Fichtensturmholz. Forstarchiv 45(7):121-128.

[5] EN 338:2003. Structural timber – Strength classes.

[6] EN 408:1995. Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties.

[7] Glos P., Denzler J.K. 2004. Einfluss von Faserstauchungen auf die Festigkeit von Fichtenbauholz. Schweiz. Z. Forstwes. 155(12):528-532.

[8] Hoffmeyer P. 2003. Mechanical properties of timber from wind damaged Norway spruce. In: Proceedings of the 'Second International Conference of the European Society for Wood Mechanics', Stockholm, Sweden, 25.-28. May 2003 (ESWM, Ed. L. Salmén, 2003).

[9] Koch G. 1999. Sekundäre Veränderungen im Holz dynamisch beanspruchter Fichten (Picea abies [L.] Karst.) aus immissionsbelasteten und windexponierten Hochlagenbeständen. Mitteilungen der Bundesforschungsanstalt für Forst- und Holzwirtschaft, Hamburg, Nr. 192.

[10] Kucera L.J., Bariska M. 1982. On the fracture morphology in wood. Part 1: A SEM-study of deformations in wood of spruce and aspen upon ultimate axial compression load. Wood Sci. Technol. 16:241-259.

[11] Mergen F., Winer H.I. 1952. Compression failures in the boles of living conifers. Journal of Forestry 50:677-679.

[12] prEN 384:2000. Structural timber – Determination of characteristic values of mechanical properties.

[13] SIA 265:2003. Holzbau. Schweizerischer Ingenieur- und Architektenverein, Zürich.

[14] SIA 265/1:2003. Holzbau – Ergänzende Festlegungen. Schweizerischer Ingenieur- und Architektenverein, Zürich.

[15] Sonderegger W., Niemz P. 2004. The influence of compression failure on the bending, impact bending and tensile strength of spruce wood and the evaluation of non-destructive methods for early detection. Holz als Roh- und Werkstoff 62(5):335-342.

[16] Steiger R. 1995. Biege-, Zug- und Druckversuche an Schweizer Fichtenholz. Forschungsbericht ETH/IBK Nr. 207, Birkhäuser, Basel.

[17] Steiger R. 1996. Mechanische Eigenschaften von Schweizer Fichten-Bauholz bei Biege-, Zug-, Druck- und kombinierter M/N-Beanspruchung; Sortierung von Rund- und Schnittholz mittels Ultraschall. Forschungsbericht ETH/IBK Nr. 221, Birkhäuser, Basel.

[18] Terziev N., Geoffrey D., Marklund A. 2005. Dislocations in Norway spruce fibres and their effect on properties of pulp and paper. Holzforschung 59:163-169.

[19] Timell T.E. 1986. Compression Wood in Gymnosperms, Volume 3, Chapter 15.2.1.5, Springer, Berlin.

[20] Trendelenburg R. 1940. Über Faserstauchungen in Holz und ihre Überwallung durch den Baum. Holz als Roh- und Werkstoff 3(7/8):209-221.

[21] Wilkins A.P. 1986. The nomenclature of cell wall deformations. Wood Sci. Technol. 20:97-109.