

COMPRESSION FAILURES IN WIND-DAMAGED SPRUCE TREES

Martin Arnold

Swiss Federal Laboratories for Materials Testing and Research (EMPA), Wood Laboratory
CH-8600 Duebendorf, Switzerland

(✉ martin.arnold@empa.ch)

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 deflexions and the resulting exceeding of the axial compressive strength of the wood. In an extensive research project started after the hurricane 'Lothar' (1999), open questions regarding the extent and location, the causes, the detection and the consequences of CF are being studied. 30 blown-down, broken or standing spruce (*Picea abies*) trees were harvested from a heavily storm-damaged, even-aged mature stand. In a first step the stems and the sawn timber were scrutinised for CF. Further steps in this project are the assessment of the mechanical wood properties and the underlying damage mechanisms.

The focus of this paper is on the frequency and distribution of the compression failures in the investigated trees. Almost 1000 CF of various size were identified in 29 of the trees. In one single tree no CF was found. The macroscopically visible CF were concentrated mainly on the leeward side of the stems within 10 to 60% of the tree height. No difference in the intensity of CF was found between blown-down, broken and standing trees.

Introduction

Frequent or strong winds can bend the stems of trees so much, that the axial compressive strength of the wood on the inward side of the bow will locally be exceeded. This will cause a buckling of the wood fibres in different intensities, which are known under various terms. This paper is dealing mainly with the macroscopically visible phenomenon, for which the term 'compression failures' (CF) is being used (Fig. 1).



Fig. 1: Massive CF on the girth of a debarked log (left) and in a planed board (right). More than half of the stem cross-section can be affected by such particularly large CF.

The distorted fibres of CF are weak points in the wood structure, which can lead to characteristic brittle fractures already at a relatively low stress in bending or tension. The main reason for the development of CF lies in the fact that the axial compressive strength of wood is only about 50% of its tensile strength. Therefore compressive rather than tensile stresses are the limiting factors for many loading situations with wood. Trees try to counteract this weakness by building up tensile growth stresses in the peripheral parts of the stems, but despite of this natural strategy, some of our lower density native softwoods such as spruce (*Picea abies*) are known to be especially prone to CF.

The consequences of CF have two main aspects. The first one is of biological nature, since CF may impair the stability of the affected trees. A tree may survive a storm with many CF and will try to locally strengthen the wood structure by callus swellings ('Wulstholz') and reaction wood. But the CF will remain as weak and potential failure points in the stem. The second aspect is concerning the utilisation of wind-damaged timber. Because CF are a potential safety risk, such defects must be excluded with a reasonable certainty particularly in construction timber. Thus CF may impose serious restrictions on the utilisation of wind-damaged timber and require additional effort regarding grading and quality control. Moreover, the reaction of surviving trees to the instability caused by the CF (callus swellings and reaction wood) has a profound negative impact on the overall wood quality.

The phenomenon of CF in connection to storm damages has been addressed already in several earlier studies (Trendelenburg 1940, Delorme 1974, Kunz 1961, Glos et al 1993, Bäucker et al 1996, Bues et al 1999, Koch 1999, Leenen 2001). CF are complex three-dimensional geometric structures with more or less fuzzy boundaries and are not always well defined (Kisser et al 1950, Frey-Wissling 1953, Keith et al 1968, Delorme et al 1975). Their size can range from minute 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.

Although compression failures are not a new phenomenon, there are still many open questions. Particularly the early detection of compression failures in logs and rough-sawn timber is very difficult and more knowledge on the frequency and the location of compression failures is needed for more effective detection strategies. In this context it is of particular interest, if there is a difference in intensity of CF in blown-down, broken and standing trees, which could be used as a grading indicator.

An extensive, still ongoing research project started after the hurricane 'Lothar' in December 1999 aims to collect more information regarding the extent (frequency, distribution), the causes and development, the detection and the consequences of CF, with the main focus on the utilisation of storm-damaged timber in constructions. In this paper some first results on the location and the intensity of CF within individual trees and the stand will be reported.

Material and methods

The heart piece of the project is an extensive case study of the extent of CF and their possible connection to the wood properties of 30 spruce (*Picea abies*) trees, which were harvested from an even-aged stand in the teaching forest of the Swiss Federal Institute of Technology on the Uetliberg near Zurich. This stand, with an area of about 2 hectares on a gentle slope towards NE, consisted mainly of mature spruce trees planted probably in 1880. It suffered extensive damage during the hurricane 'Lothar' in December 1999 (Fig. 2).



Fig. 2: Aerial view of the investigated storm-damaged spruce stand.

10 trees from each of the 'damage' categories 'Blown-down', 'Broken' and 'Standing' were selected for investigation in the untouched stand soon after the hurricane. Their position and situation in the stand was recorded and the main wind direction of the hurricane was marked on the stems according to the average direction of the wind-thrown trees. Diameter at breast height (DBH), tree height and the length of the crown were measured where possible. Several tree height values had to be estimated for broken trees or because of lost crowns. The stems were then cut to length into logs with a target length of 5 m (with some deviations because of stem breaks) and the lower 4 to 6 logs were removed from the stand for further investigations. A total of 139 logs with a volume of about 90 m³ were investigated.

The logs were carefully inspected for CF after partial debarking and planing on the leeward side of the stems and were afterwards sawn into thick boards with a nominal thickness of 110 or 55 mm according to a systematic sawing pattern adjusted to the marked wind direction (see Fig. 5). This direction was mostly identical with the largest stem eccentricity, which points to the usually westerly wind direction in this stand. The centre board was planed on its two radial surfaces and inspected for CF. The identified CF on the centre boards are the main basis for the presented analysis in this paper (see Fig. 3). The upper half of the centre boards and all of the side boards were then sawn into the maximum possible number of blanks for test pieces used in subsequent bending and tension tests (cross-sections of 110x95 mm² and 150x45 mm² respectively), planed and also inspected for CF. Data on the CF in the test pieces from the side boards were used to analyse the distribution of CF in the stem cross-sections (see Fig. 5). The remaining lower half of the centre boards was cut into small clear specimens for the determination of the wood density and various mechanical properties.

The location and the size of CF was assessed by the following concept: For practical reasons (assessments in the field and at different processing steps, high number of CF) the complex three-dimensional geometric structure of the CF was simplified to a one level plane defined by its distance from the stem base, its maximum axial thickness, its tangential extension (as seen on the girth of the logs) and its radial depth (as seen on the radial surfaces of the centre boards). On the test pieces for bending and tension the extension of the CF was measured as the visible length on their circumference.

The macroscopic visibility of the CF is determined mainly by their axial thickness (called 'width'). However, the light conditions, the angle of vision, the surface structure and the experience of the observer are very important factors for a reliable detection of CF. A complete detection of all CF is probably not possible with a justifiable expenditure. A wrong-

positive detection on the other hand is very rare. The registered CF are therefore to be considered as a minimum quantity.

The distance from the stem base as well as the tangential and radial extensions were measured as metric values. The width of the CF was assessed by a discrete classification system indicating their (maximum) thickness in the fibre direction in millimetres by a visual estimation (Table 1). This system allows not only a classification into width classes, but gives a semi-quantitative measure.

CF class	Max. (axial) width of CF	Definition	Remarks
1	0.1 mm	very fine CF; just visible with normal corrected vision	can be missed under unsuitable lighting
2	0.5 mm	fine, but perceptible CF; clearly visible with normal corrected vision	will normally be detected on careful visual inspection on planed surfaces
3	1.0 mm	distinct CF; clearly visible	
4	>1 mm (1.5, 2.0, ...)	large and significant CF	stated in intervals of 0.5 mm

Table 1: Classification system for the (axial) width of CF.

Results

The investigated trees were dominant, fully-grown and about 120 years old at the time of the hurricane. Diameter at breast height ranged from 39 to 72 cm with an average value of 54.6 cm and the tree height was in the quite narrow range from 35 to 43 m with an average value of 38.2 m (Table 2). The slenderness ratio (tree height / DBH) between 56 and 95 indicates a high to medium tree stability (Rottmann 1986).

	All trees (n=30)			Damage categories (n=10 in each category)								
	Min	Mean	Max	Blown-down (A)			Broken (B)			Standing (C)		
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Diameter at breast height DBH [cm]	39.0	54.6	72.0	40.0	54.7	68.0	39.0	54.6	72.0	43.0	54.5	66.0
Diameter at 5m height [cm]	34.9	45.3	63.6	34.9	47.5	59.2	35.4	44.9	63.6	37.7	43.7	54.9
Tree height [m]	35.0	38.2	43.0	35.0	38.9	43.0	36.0	38.4	41.0	35.0	37.2	40.0
Crown length [m]	9.0	14.3	20.0	12.0	15.4	19.0	9.0	13.0	20.0	10.0	14.6	19.0
Rel. crown length [%]	23.7	37.5	51.4	31.6	39.6	51.4	23.7	33.7	48.8	26.3	39.3	50.0
Tree height / DBH ratio	55.9	71.4	95.0	60.3	72.9	95.0	55.9	72.2	94.9	56.5	69.2	81.4

Table 2: Stem characteristics of all the investigated trees and for the 3 damage categories separately.

In total 961 CF of various sizes were identified in 29 of the 30 investigated trees. In one single tree no CF was found at all. Considering the 713 m of investigated stem length, on average 1.35 CF were found per meter. About 50% of the identified CF were induced during the hurricane 'Lothar', the other 50% were related to earlier storms as far back as 1930 as dated by the formed callus swellings and the sudden appearance of reaction wood.

The great variety of patterns of the vertical distribution of the CF in the stems is illustrated with 5 examples in Fig. 3. In tree B07 only few CF are spread over the whole length of the trunk. Tree C08 exhibits a concentration of the CF in about mid-height and trees B10, A04 and C09 have many and rather large CF.

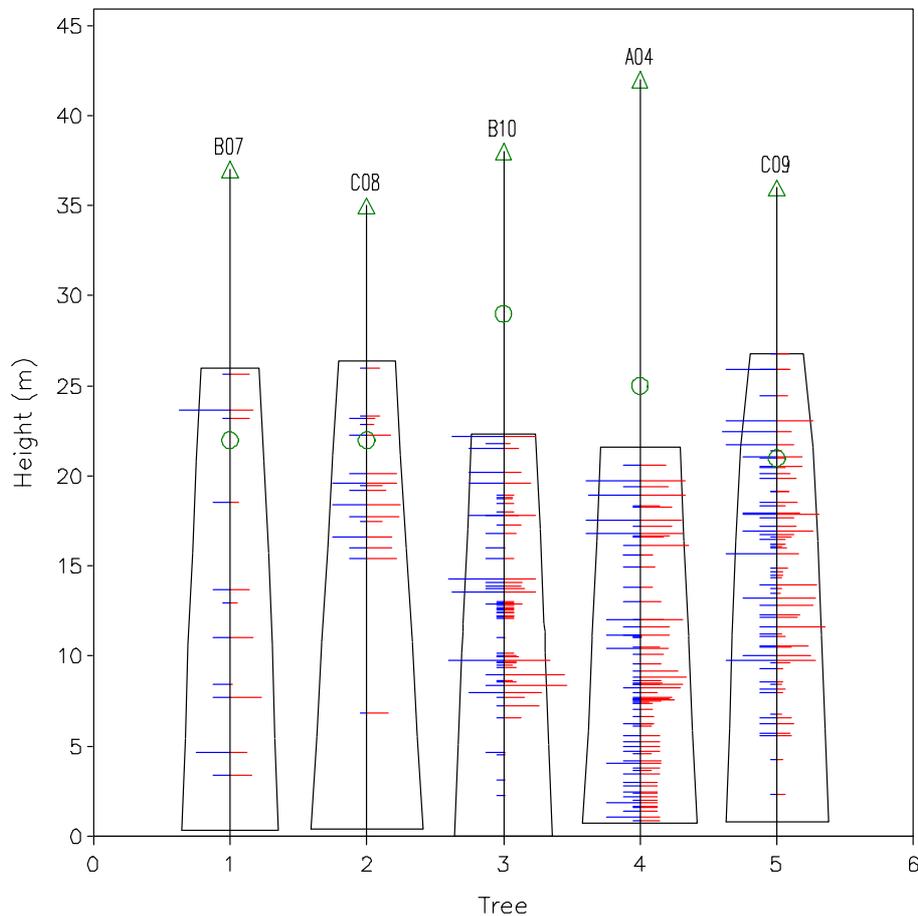


Fig. 3: Vertical distribution and size of CF in the stems of five selected trees as recorded on the centre boards of the sawn logs. The trapezoids show the investigated parts of the stems. The triangles indicate the height of the trees and the circles the beginning of the crown. The rays extending from the centre line to the left are indicating the width of the CF, the rays extending to the right are proportional to their radial depth.

50% of the CF are located between 19 and 47% of the relative tree height with a distinct decreasing frequency towards the higher parts of the stem (Fig. 4, left). CF were found starting at a height of only 0.89 m (2% relative tree height) up to 28.08 m (74.6%).

The distance between two neighbouring CF is in the wide range between a few centimetres to several metres and shows a highly skewed frequency distribution (Fig. 4, left). Regardless of the size of the CF, 50% are between 0.17 and 0.63 m apart with a median value of 0.35 m. The median value of the distance between the CF is increasing to 0.55 m if only CF with a width of 0.5 mm and above are considered, to 0.91 m for CF with a width of 1 mm and above and to 1.12 m for the largest CF with a width more than 1 mm.

The distribution of the CF in the cross-section of the trees is illustrated in Fig. 5 with the same five spruce trees as in Fig. 3. The CF were found almost exclusively on the leeward side of the stems.

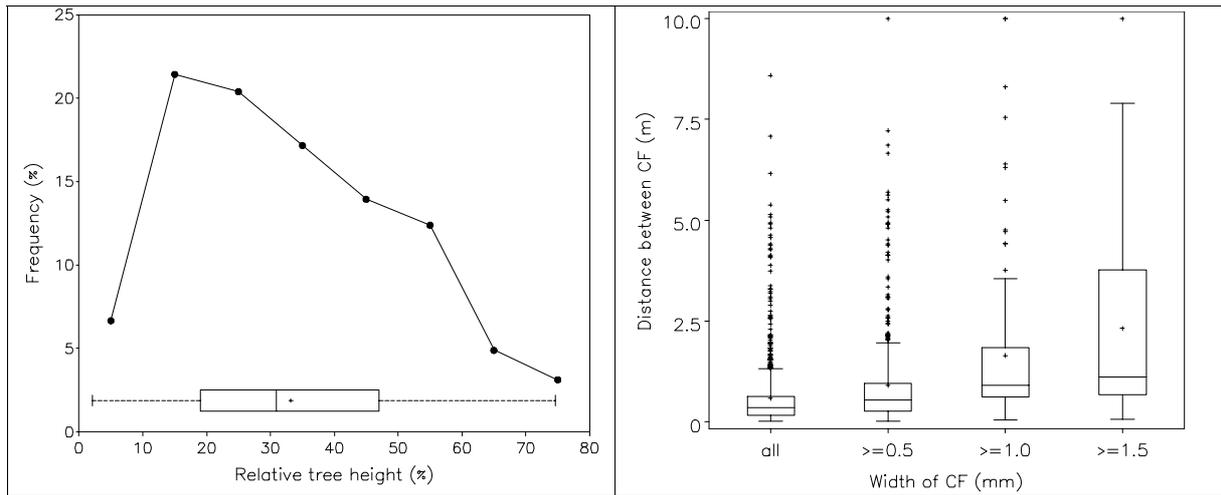


Fig. 4: Intensity of CF along the relative tree height (frequency polygon for all identified CF in 10% intervals and corresponding boxplot) (left) and frequency distribution of the distance between two neighbouring CF for different width categories (right). The boxes in the boxplots enclose 50% of the values and the whiskers extend to the extreme values within 3.5 times the interquartile range. Values outside the whiskers are marked with a plus sign. To improve the scaling of the right hand boxplots the maximum distance between two CF was limited to 10 m.

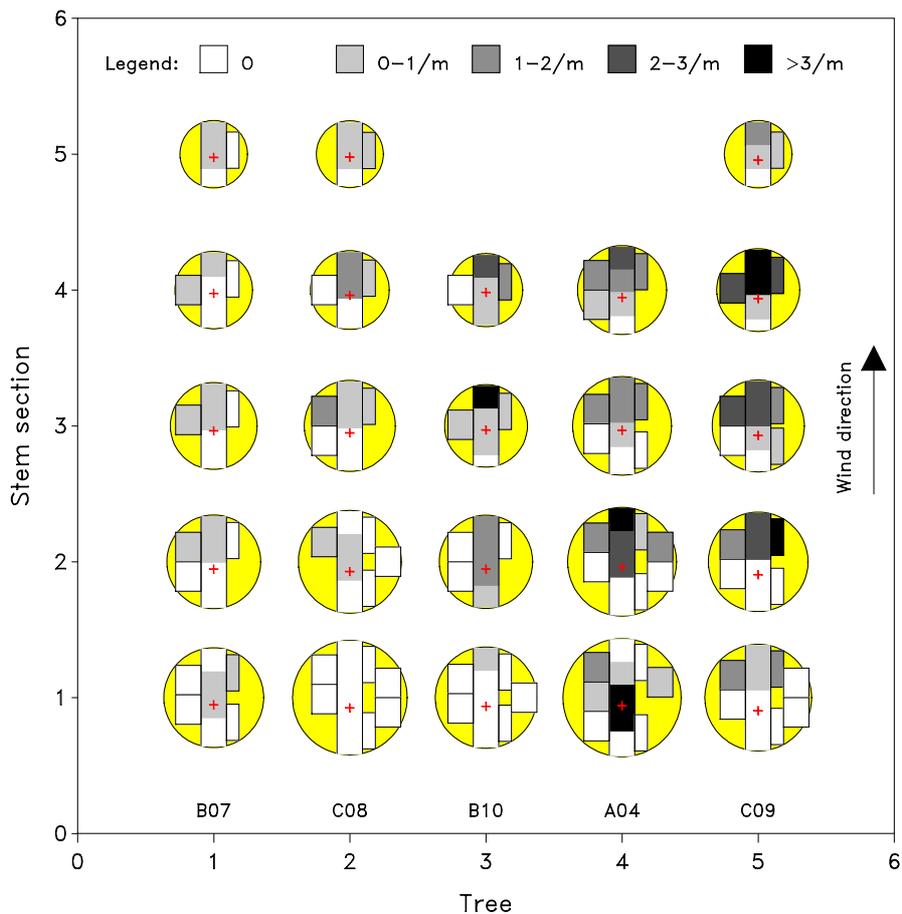


Fig. 5: Occurrence and intensity of CF in the stem cross-sections at different tree heights (approx. 5 m intervals) of the same five spruce trees as in Fig. 3. The cross-sections are idealised as (slightly shaded) circles with the approximate position of the pith marked with a '+' sign. The drawn rectangles show the number and the position of the sawn test pieces. The intensity of CF (number of CF per meter in 5 m stem sections) is indicated by different grey levels.

As in Fig. 3, the rather low intensity of CF in tree B07 is apparent. In tree C08 section 1 shows no CF, but an increasing intensity towards sections 3 and 4. Tree B10 is an example of the rare occurrence of CF on the windward side of the stem and trees A04 and C09 again show the high intensity of CF in the whole trunk. With the sawn timber, 258 (37%) of the 696 blanks of 5 m length for the bending and tension tests contained CF.

No significant difference was found between the 3 'damage' categories 'Blown-down', 'Broken' and 'Standing' trees neither regarding the tree characteristics (Table 2) nor regarding the number and average width of the CF (Fig. 6, left). The same is true regarding the frequency of the different width classes of the CF, with about 50% of the CF being in the smallest class of 0.1 mm width (Fig. 6, right). Therefore, the damage categories do not seem to be suitable indicators for the intensity of CF within the stem of a tree.

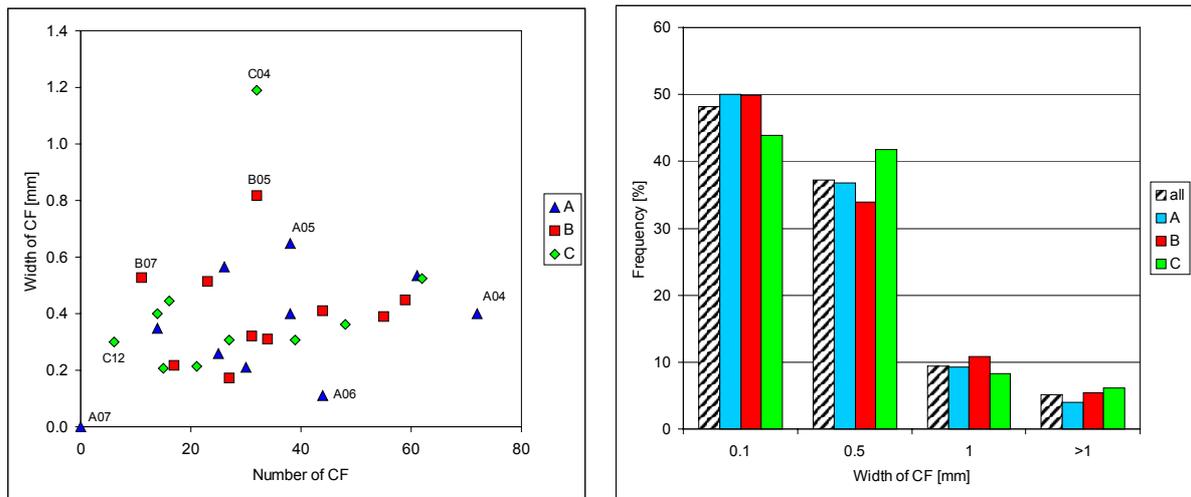


Fig. 4: Scatterplot of average width against total number of CF in the 30 investigated trees (left) and frequency distribution of the width of CF (right) by the different damage categories Blown-down (A), Broken (B) and Standing (C) trees.

The intensity of the CF seems to be more or less evenly distributed over the whole stand and no apparent local concentrations can be detected (Fig. 7). This observation is supported by the fact that the tree with no CF stood close to trees with a rather high intensity of CF.

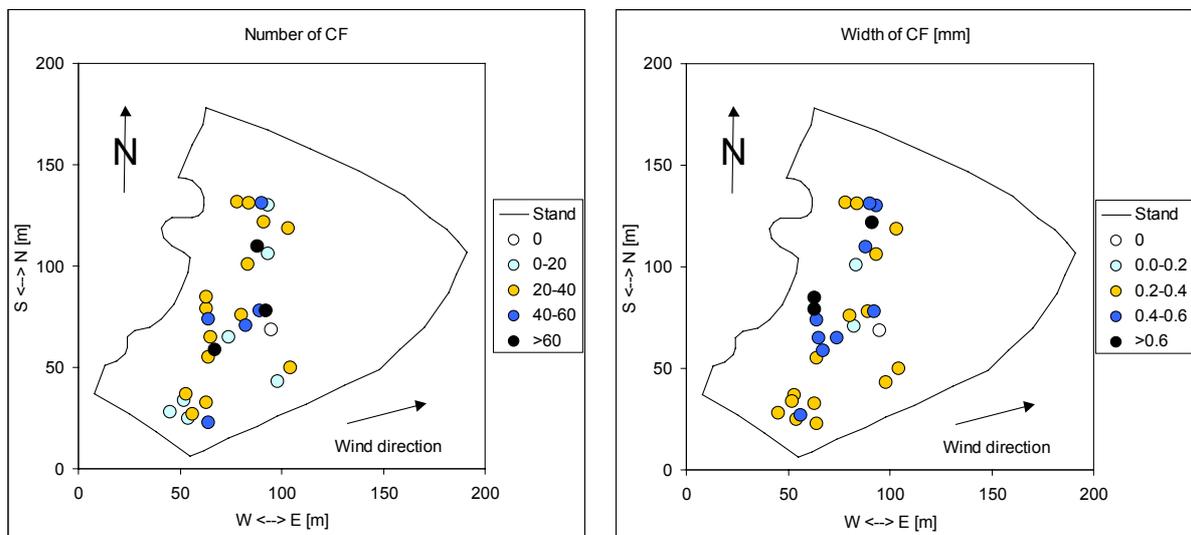


Fig. 5: Distribution of number (left) and average width (right) of CF per tree in the stand. Darker colours indicate a higher intensity of CF.

Outlook

The presented results are the basis for all the subsequent parts of this project. The next steps will be the analysis of a possible relationship between the development of CF and the mechanical wood properties and the exploration of the three-dimensional patterns of CF in the trees by numerical modelling methods, integrating factors such as tree size, wind forces and wood properties. Also the consequences of the CF on the stiffness and strength of the wood and the possibilities of their reliable detection will be investigated. The results of this project will help to make conclusions and recommendations regarding the grading and the save utilisation of wind-damaged timber.

Acknowledgements

This project was funded partly by the Swiss Forest Agency within the framework of the 'Lothar Evaluations- und Grundlagenprojekte' and executed in co-operation with the institutes of Silviculture, Wood Science and Structural Engineering of the Swiss Federal Institute of Technology Zurich and the Structural Engineering Research Laboratory of EMPA.

References

- Bäucker, E., Bemmann, A., Bues, C.T., Nuys, G.-J., 1996:** Stammbrüche an Fichten mit atypisch stumpfen Bruchbildern, AFZ/Der Wald Nr. 12, pp. 686-688
- Bues, C.T., Stein, A., 1999:** Faserstauchungen und Faserbrüche im Holz von Fichten, AFZ/Der Wald Nr. 15, pp. 796-797
- Delorme, A., 1974:** Über das Auftreten von Faserstauchungen in Fichtensturmholz, Forstarchiv 45 (7), pp. 121-128
- Delorme, A., Verhoff, S., 1975:** Zellwanddeformationen in sturmgeschädigtem Fichtenholz unter dem Rasterelektronenmikroskop, Holz als Roh- und Werkstoff 33, pp 456-460
- Frey-Wyssling, A., 1953:** Über den Feinbau der Stauchlinien im überbeanspruchten Holz, Holz als Roh- und Werkstoff 11 (7), pp. 283-288
- Glos, P., Henrici, D., 1993:** Festigkeitseigenschaften von Bauschnittholz aus Fichtensturmholz, Abschlussbericht 90504/5 an die Bayerische Forstliche Versuchs- und Forschungsanstalt (FVA) über das Projekt "X 17", Institut für Holzforschung der Universität München
- Keith, C.T., Cote, W.A., 1968:** Microscopic Characterization of Slip Lines and Compression Failures in Wood Cell Walls, Forest Products J. (18)3, pp. 67-74
- Kisser, J., Frenzel, H., 1950:** Mikroskopische Veränderungen der Holzstruktur bei mechanischer Überbeanspruchung von Holz in der Faserrichtung, Schriftenreihe Österr. Ges. Holzforschung, Heft 2, pp. 7-31
- 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
- Kunz, R.G., 1961:** Über die Verwertung von Holz aus sommerlichem Sturmschaden, Mitteilungen der Bundesforschungsanstalt für Forst- und Holzwirtschaft, Hamburg, Nr. 49
- Leenen, M., 2001:** Untersuchungen von Rund- und Schnittholz aus unterschiedlich sturmbelasteten Fichten (*Picea abies* (L.) Karst.) hinsichtlich Faserstauchungen und Festigkeitseigenschaften, Diplomarbeit an der Forstwissenschaftlichen Fakultät der Albert-Ludwig-Universität Freiburg
- Rottmann, M., 1986:** Wind- und Sturmschäden im Wald, Beiträge zur Beurteilung der Bruchgefährdung, zur Schadensvorbeugung und zur Behandlung sturmgeschädigter Nadelholzbestände, J. D. Sauerländer's Verlag, Frankfurt a. M.
- Trendelenburg, R., 1940:** Über Faserstauchungen in Holz und ihre Überwallung durch den Baum, Holz als Roh- und Werkstoff 3 (7/8), pp. 209-221