Effects of Compression Failure on the Mechanical Properties of *Pinus* Wood in an Experimental Planting in North of Iran

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Introduction

Compression failure describes the buckling of fibres which often occurs on the lee side of the wind-exposed tree. Since the compression strength parallel to the fibre is only half the tensile strength, some parts of the lee side of the tree, where the highest compression strength is found, overload under major bending, resulting in the formation of compression failures. These failures can be very small and only visible through a microscope, or several millimeters wide already be detected with the naked eye. Previous investigations on the influence of compression failure on the strength of wood were in some cases contradictory. Trendelenburg (1940), testing clear wood specimens of spruce, stated that tensile strength and impact strength were already reduced by very small, microscopically fine compression failures, whereas compression strength and bending strength were reduced only by larger compression failures. Glos and Henrici (1993) noticed in tests of timber that bending strength was not reduced significantly, but that tensile strength was reduced by 22%. Koch (1999), in contrast, observed a 16% reduction in bending strength in tests of scantlings. In order to obtain a clearer picture on the impact of compression failure on the strength of spruce wood, as part of a comprehensive project investigating the quality and use of storm-damaged wood, tests on small clear wood samples were carried out.

Material and methods

Specimens. Thirty Pinus Brutia grown in 17 kilometers North of Dr. bahramnia experimental plantation in south-western of gorgan, Iran (36° 45′ N 54° 24′ E, 300 m altitude). From each tree, 3 to 5 consecutive 5-metre trunk sections (128 in total) were cut to a fixed pattern. The specimens used for this particular project were taken from 10-cm-thick heart planks cut from the lower two metres of each trunk section. These heart planks ran parallel to the wind direction. For bending, impact-bending and tensile tests, 50-cm-long blocks were cut from the heart planks. Wherever possible, one piece without compression failure and one or two pieces with macroscopically visible compression failure were cut from each heart plank, making sure that the compression failure was in the middle in each case.

Methods. Bending strength according to ASTM 52186 of specimens stored in a normal climate (20_C/65% relative humidity) and stored under water (average moisture content 89.7%), tensile strength according to ASTM 52188, and impact bending strength according to ASTM 52189 were tested. In addition, a number of non-destructive methods for the early detection of compression failure and its influence on wood strength were tested, in some cases on the same specimens used for the strength tests: sound velocity and eigenfrequency were measured for the specimens subsequently used in the bending test, and in addition, sound velocity was measured for specimens subsequently used in the impact-bending test. Accordingly, the MOE was calculated on the basis of sound velocity and eigenfrequency and compared with the MOE according to ASTM (Niemz (1993) for the formula used to calculate the MOE on the basis of sound velocity, and cf. G_rlacher (1984) for the calculation on the basis of eigenfrequency). In addition, the ability of computer tomography and scanner technology to detect compression failure was tested. Tests. For the bending tests on specimens stored in a normal climate, 1112 specimens without compression failure and 241 specimens with compression failure were tested.

Results

3.1 Bending test on normal climate specimens

The specimens with compression failure showed an average reduction in MOR of over 20% compared with the specimens without compression failure Table 1). Further, the MOR was strongly dependent on the width of the compression failure (Fig. 1). While the MOR for specimens with compression failures with a width of _0.1 mm revealed an average reduction of only 10% compared with the specimens without compression failure, MOR for specimens with compression failures of 1.5 mm and more in width decreased about 58% to an average MOR of 37.5 N/mm2.

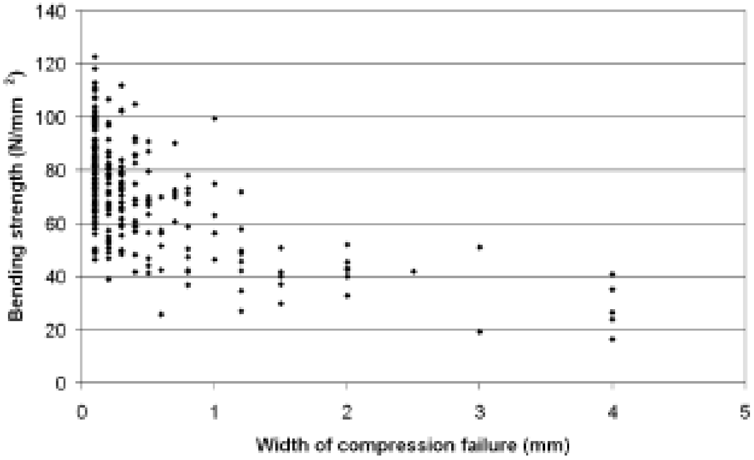


Figure 1**. Bending strength versus width of compression failure (normal climate**

Table 1. Influence of compression failure on bending strength,MOE for specimens stored in a normal climate The means of allspecimens (total) and of the specimens without compression wood(clear) are specified. Coefficient of variation in brackets. The percentages refer to the specimens without compression failure

	Without compression failure		With compression failure		With compression f ailure		With compression failure	
			≤0.1 mm		>0.1 mm		All specimens	
	Total	Clear	Total	Clear	Total	Clear	Total	Clear
Number of specimens	1112	687	89	23	152	39	241	62
Density at normal climate (kg/m^3)	**484** (12.80) 100%	472 (10.79) 100%	**513** (12.67) 106.0%	482 (12.07) 102.1%	532 (10.47) 109.9%	504 (9.83) 106.8%	**525** (11.41) 108.5%	496 (10.77) 105.1%
Bending strength (N/mm^2)	**90.29** (16.27) 100%	92.66 (14.95) 100%	**82.75** (19.81) 91.6%	82.79 (17.03) 89.3%	**63.94** (29.92) 70.8%	66.13 (29.02) 71.4%	**70.89** (28.62) 78.5%	72.21 (26.55) 77.9%
MOE according to DIN (N/mm^2)	**13,167** (20.80) 100%	14,101 (16.25) 100%	**13,272** (20.42) 100.8%	13597 (18.26) 96.4%	**12,429** (23.87) 94.4%	13,281 (22.97) 94.2%	**12,740** (22.75) 96.8%	13,396 (21.20) 95.0%
$E_{b.ef}$ (N/mm^2)	**13,282** (19.97) 100%	14,160 (15.77) 100%	**13,605** (18.65) 102.4%	13,748 (17.92) 97.0%	**13,517** (18.68) 102.2%	14,399 (17.24) 101.7%	**13,584** (18.59) 102.3%	14,161 (17.48) 100.0%
$E_{b.sound}$ (N/mm^2)	**15,932** (18.51) 100%	16,609 (15.59) 100%	**17,019** (17.26) 106.8%	17,179 (17.55) 103.4%	**17,247** (15.96) 108.3%	17,680 (14.69) 106.4%	**17,163** (16.42) 107.7%	17,498 (15.68) 105.4%

The influence of compression failure on the MOE according to ASTM was low. The average MOE for specimens with compression failure was reduced to only 5% compared with specimens without compression failure (Table 2). Further, the coefficient of determination between the MOR and the MOE was small (R2=0.35) for the specimens with compression failure, whereas the specimens without compression failure had a coefficient of determination of R2=0.76 (Fig. 2).

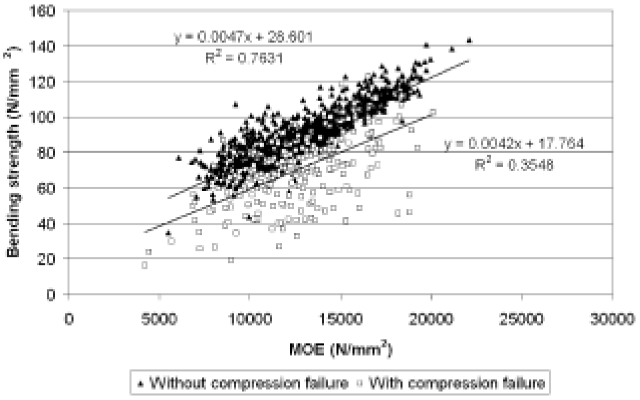


Figure 2. Bending strength versus MOE according to DIN (normal climate)

On the MOE calculated on the basis of non-destructive methods—eigenfrequency (Eb.ef) and sound velocity (Eb.sound)—the influence of compression failure was even lower than on the MOE according to ASTM. While Eb.ef remained more or less constant over all measurements, Eb.sound increased slightly for the specimens with compression failure in line with their higher density. According to this the coefficient of determination between the MOR and Eb.ef for the specimens with compression failure was very low at R2=0.21. At R2=0.08, there was practically no correlation at all between the MOR and Eb.sound (Figs. 3 and 4).

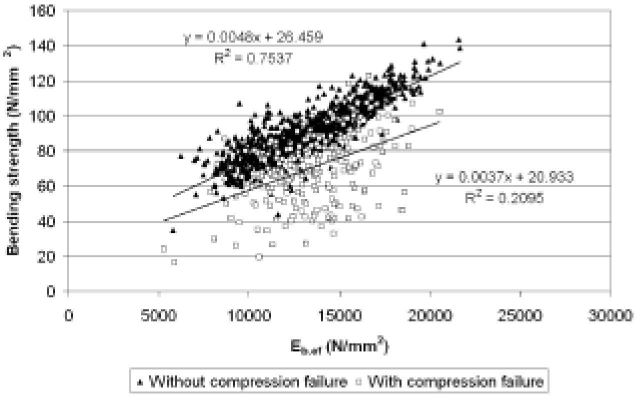


Figure 3. Bending strength versus MOE according to Eb.ef on normal climate

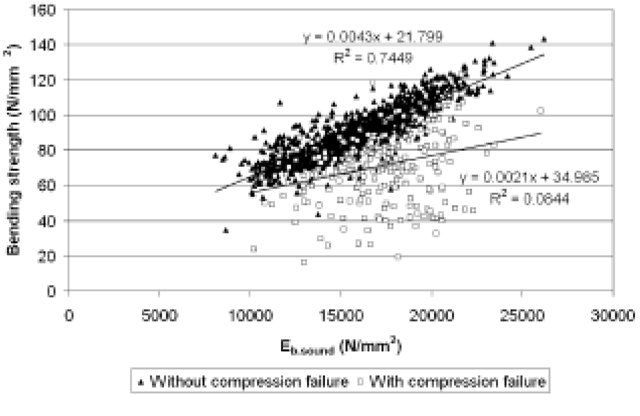


Figure 4. Bending strength versus MOE according to Eb.sound on normal climate

3.2 Bending test on specimens stored in water

As expected, the MOR of specimens stored in water was much lower (more than 40% lower on average) than that of specimens stored in a normal climate (cf. Niemz 1993). However, the effect of compression failure on waterstored and normal-climate specimens was similar (Table 2), with both types of specimen losing around 20% of their strength on average. However, the reduction in the strength of water-stored specimens with wider compression failure was less pronounced than for specimens of the same width stored in a normal climate (Fig. 5). For widths of 1.5 mm and more the mean reduction in strength was 43% compared with the specimens without compression failure (normal-climate specimens 58%, see above).

The bending MOE according to ASTM was significantly affected by compression failure (unlike the normal-climate specimens). This was reflected in a substantial 34% reduction in MOE for the specimens with compression failure compared with the specimens without compression failure (Table 2). Further, Fig. 6 (bending strength versus MOE according to ASTM) shows only a slightly lower regression line for the specimens with compression failure. However, the coefficient of determination was low, both for specimens without compression failure (R2=0.34) and those with compression failure (R2=0.32). As was the case with normal-climate specimens, MOE calculated on the basis of eigenfrequency and sound velocity displayed only minimal correlation with strength for the specimens with compression failure. While Eb.ef decreased slightly for specimens with compression failure, Eb.sound remained fairly constant. At R2=0.26, the coefficient of determination for Eb.ef was also very small, and R2=0.04 for Eb.sound indicates virtually no correlation with strength at all (Fig. 7, 8).

Table 2. Influence of compression failure on bending strength, MOE on the basis of eigenfrequency (Eb.ef) and sound velocity (Eb.sound) for specimens stored in water (average moisture content 89.7%). Represented are the mean and, in brackets, the coefficient of variation. The percentages refer to the specimens without compression failure

	Without compression failure	With compression failure	With compression failure	With compression failure
		≤0.1 mm	>0.1 mm	All specimens
Number of specimens	70	14	36	50
Density at normal climate 20°C/65% RH (kg/m³)	**488**	**477**	**510**	**501**
	(9.35)	(11.16)	(10.46)	(10.97)
	100%	97.7%	104.5%	102.7%
Bending strength (N/mm²)	**52.36**	**45.92**	**39.97**	**41.63**
	(12.61)	(16.02)	(25.28)	(23.36)
	100%	87.7%	76.3%	79.5%
MOE according to DIN (N/mm²)	**12,266**	**8,099**	**8,163**	**8,145**
	(15.74)	(11.38)	(30.59)	(26.56)
	100%	66.0%	66.5%	66.4%
$E_{b.ef}$ (N/mm²)	**10,782**	**9,711**	**10,404**	**10,210**
	(14.65)	(11.58)	(15.98)	(15.20)
	100%	90.1%	96.5%	94.7%
$E_{b.sound}$ (N/mm²)	**19,927**	**18,752**	**20,684**	**20,143**
	(12.74)	(8.73)	(10.37)	(10.84)
	100%	94.1%	103.8%	101.1%

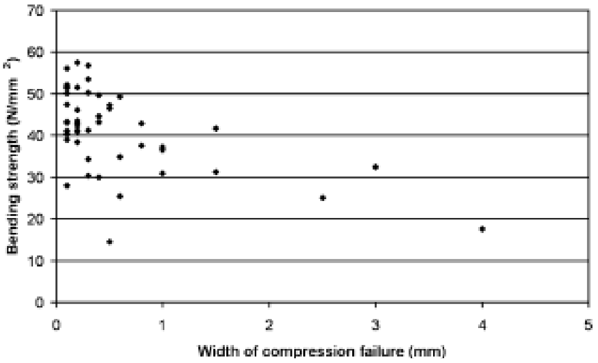


Figure 5. Bending strength versus width of compression failure (water stored)

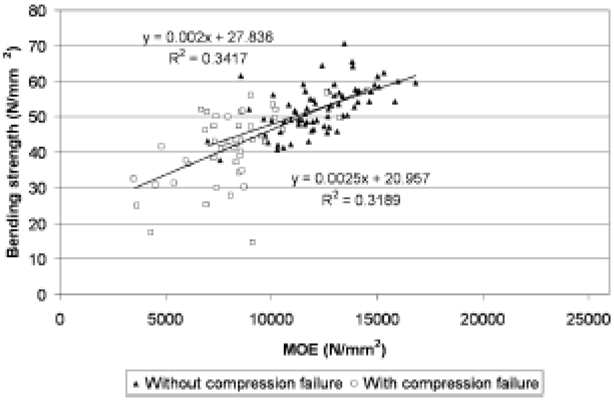


Figure 6. Bending strength versus MOE according to DIN (water stored)

3.3 Tensile test

The tensile strength of the specimens with compression failure was around 23% lower than for those without compression failure. The tensile MOE according to ASTM displayed no influence to compression failure, but increased with higher density and decreased with lower density (Table 3). This is also reflected in Fig. 9 in the lower coefficient of determination between tensile strength and MOE for the specimens with compression failure (R2=0.35) than for specimens without compression failure (R2=0.53).

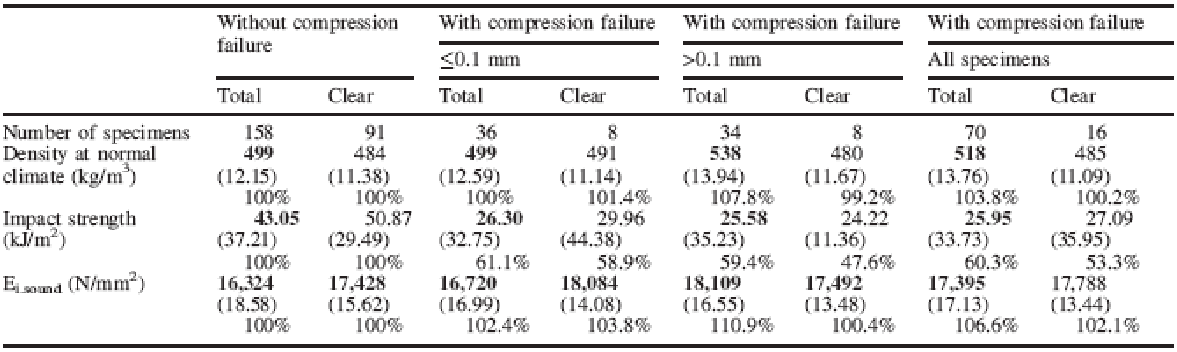
Table 3. Influence of compression failure on tensile strength and tensile MOE of specimens stored in a normal climate (20_C/65% RH). Represented are the mean and, in brackets, the coefficient of variation. The percentages refer to the specimens without compression failure

	Without compression failure	With compression failure	With compression failure	With compression failure
		≤0.1 mm	>0.1 mm	All specimens
Number of specimens	79	13	10	23
Density at normal climate (kg/m³)	**451** (12.23) 100%	**424** (11.70) 94.0%	**476** (11.82) 105.5%	**447** (12.92) 99.1%
Tensile strength (N/mm²)	**95.22** (20.88) 100%	**76.75** (25.46) 80.6%	**69.64** (34.86) 73.1%	**73.66** (29.19) 77.4%
MOE according to DIN (N/mm²)	**14,514** (30.27) 100%	**13,423** (25.10) 92.5%	**16,412** (24.95) 113.1%	**14,723** (26.61) 101.4%

3.4 Impact-bending test

In Table 5, if all specimens tested are compared, the impact bending of specimens with compression failure is around 40% lower than for those without compression failure. The difference is even higher for clear specimens (almost 47%). The reduction is already around 40% for specimens with compression failure of a width of 0.1 mm or less, and not much more for wider compression failure. Comparing impact-bending strength with the MOE calculated on the basis of sound velocity gives only a low correlation (R2=0.33 for specimens without compression failure, R2=0.15 for those with compression failure.

Table 4. Influence of compression failure on impact strength and MOE calculated on the basis of sound velocity (Ei.sound) for specimens stored in a normal climate. The means of all specimens (total) and of the specimens without compression wood (clear) are specified. Coefficient of variation in brackets. The percentages refer to the specimens without compression failure



	Without compression failure		With compression failure		With compression failure		With compression failure	
			≤0.1 mm		>0.1 mm		All specimens	
	Total	Clear	Total	Clear	Total	Clear	Total	Clear
Number of specimens	158	91	36	8	34	8	70	16
Density at normal climate (kg/m^3)	**499** (12.15) 100%	484 (11.38) 100%	**499** (12.59) 100%	491 (11.14) 101.4%	**538** (13.94) 107.8%	480 (11.67) 99.2%	**518** (13.76) 103.8%	485 (11.09) 100.2%
Impact strength (kJ/m^2)	**43.05** (37.21) 100%	50.87 (29.49) 100%	**26.30** (32.75) 61.1%	29.96 (44.38) 58.9%	**25.58** (35.23) 59.4%	24.22 (11.36) 47.6%	**25.95** (33.73) 60.3%	27.09 (35.95) 53.3%
$E_{i.sound}$ (N/mm^2)	**16,324** (18.58) 100%	**17,428** (15.62) 100%	**16,720** (16.99) 102.4%	**18,084** (14.08) 103.8%	**18,109** (16.55) 110.9%	**17,492** (13.48) 100.4%	**17,395** (17.13) 106.6%	17,788 (13.44) 102.1%

Discussion

Compared to all the types of strength investigated, impact- bending strength is the most strongly affected by compression failure, with a mean reduction in strength of between 40% and 47%. This tallies with the findings of Koch (1999), who even observed a mean reduction in strength of over 60%, albeit on fibre-saturated specimens (cf. also Koch 1996). Impact-bending strength and tensile strength decrease sharply even with compression failure of a width of 0.1 mm or less (around 40% and 20% respectively), and in both cases the reduction in strength is not much more pronounced for compression failure of more than 0.1 mm. However, bending strength decreases only minimally, between 8% and 12%, for compression failure less than or equal to 0.1 mm wide, but decreases around 60% when there is wide compression failure (cf. Fig. 1). This tallies with the observations of Trendelenburg (1940), who detected tensile strength, but not in bending strength, even with compression failure of microscopic width. Unlike Glos and Henrici (1993) testing timber, the present investigation of clear wood specimens observed a sharp decline in the bending strength (around 20% on average) of specimens with compression failure stored both in a normal climate and in water.

According to Glos and Henrici (1993) and Koch (1999), no significant reduction in MOE according to DIN was observed in bending tests (normal climate) or tensile strength tests for specimens with compression failure. One exception were bending test specimens stored in water, where MOE decreased even more than MOR. It is interesting that there is a substantial reduction in MOE even in cases where only fine compression failure occur. Trendelenburg (1940) also observed a significant reduction in the bending MOE of specimens with compression failure. However, the data give no indication of whether the specimens were tested in a fibre-saturated or normal-climate state.

As far as using non-destructive methods—eigenfrequency and sound velocity—to assess the strength of specimens with compression failure is concerned, bending tests and impact-bending tests (sound velocity only) demonstrated only a minimal correlation, or no correlation at all, between the MOE calculated on the basis of eigenfrequency and sound velocity and the bending or impactbending strength. This shows that detecting compression failure and its influence on bending and impact-bending strength is not possible using the two non-destructive methods investigated, eigenfrequency and sound velocity.

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