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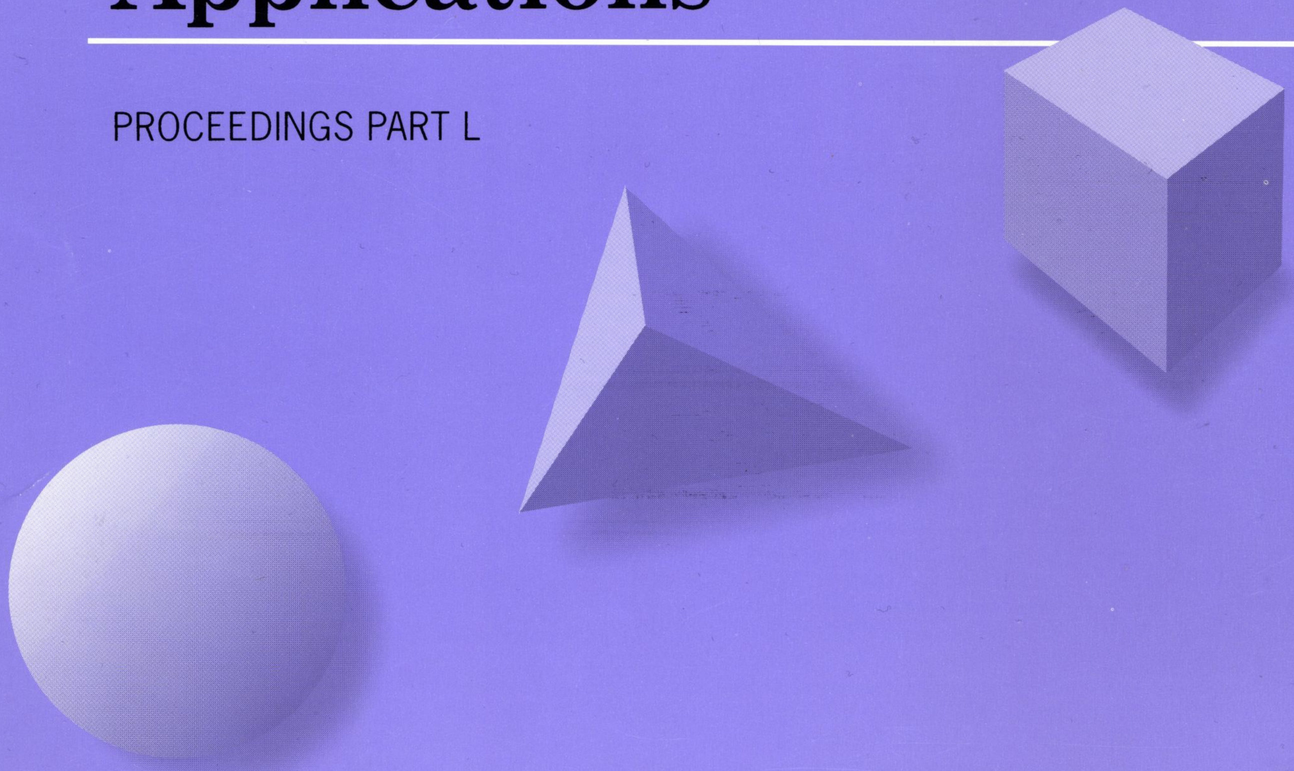

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Mechanical properties of some Swedish hard wood species

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Abstract: A large part of Sweden is located within the Taiga Area and hence most of the wood species growing there are included in the division of Coniferales. This has also led to major research activities on the needle-leaved types in the Pinaceae family. There are, however, many broad-leaved trees, but because of their relatively low economic importance only a few researchers have had the opportunity to study such woods. For certain branches of the Swedish wood manufacturing industry the Angiosperms are of vital importance, e.g. the furniture factories. In this paper the mechanical properties of two Swedish hard wood genera, namely *Betula* and *Alnus*, are revealed. These findings are also compared with those found in the literature.

Keywords: wood, material constants, solid mechanics, birch, alder, Young's modulus, bending properties

1 INTRODUCTION

In some recent papers the finite element method (FEM) has been used in calculating the necessary cross-sectional areas of members in chairs (see, for example, reference [**1**] or [**2**]). A real chair has also been tested using the same design as that used in the FEM calculations and it was found that for some of the chair members severe discrepancies occurred between calculated and monitored strains, which in turn led to an examination of why this had happened. One possible reason for this is the fact that the material constants used in solid mechanics calculations differ greatly from one tree to another and also differ within the same tree. Most of the tests referred to in the literature were finished more than 60 years ago (see, for example, reference [**3**], p. 295), where values for birch were presented. The problems related to solid mechanics for wood, especially for broad-leaved species, may therefore frequently be forgotten or neglected.

Traditionally, three different moduli were examined, viz. Young's moduli for tension and compression and the bending modulus. As wood is built up from cylindrical layers it has an anisotropic behaviour, but if a small cube is studied, three axes of symmetry emerge, i.e. the longitudinal, tangential and radial directions. In theory, this leads to nine different elastic constants which must be known if the deformation of a wooden sample is to be closely predicted as a result of an applied force (see reference [**3**], p. 293). Some of these elastic constants influence the deformation of a structure only to a very small degree, at least if restrictions on the applied forces occur. Consider, for example, the case where a rod is tensed in the axial, or longitudinal, direction. Because of this, the rod is not only elongated but also contracted in two perpendicular directions, a behaviour that is often ignored. The relation between these contractions and the longitudinal prolongation is shown by Poisson's ratio, which is always less than 1 and often less than 0.1 as well. Three of the original nine elastic constants show the influence of shear stress, which also may be of little importance. Variation in the more important constants might therefore be of greater interest.

In the Nordic countries there is a certain 'testing code' which must be followed when wood is examined from a solid mechanical viewpoint (see reference [**4**]). All the tests that follow are therefore made in accordance with that code. Two wood species are presented in this paper, birch and alder. Even if there are nine constants to be examined only four different cases are shown here, tensile and compression tests along the grain and three- and four-point bending. One way to test the strength of construction is to use strain gaugemeters which monitor the contraction and elongation at a certain spot. In order to calculate this value the modulus of elasticity of the material is required. There is also a need to know how much tension and compression the material endures before the construction falls apart, i.e. the maximum stress before rupture. There are a number of different

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recommendations given in the literature on how to prepare suitable specimens for testing (see, for example, references [**5**], p. 425, and [**3**], p. 324, for tensile tests). In the Scandinavian code, Kucera [**4**] shows still another type. It is important to note, however, that the specimen is significantly thinner in the middle section where the rupture will be located. Compression test specimens and those for bending tests are much simpler to manufacture because they are made of rectangular beams.

2 BIRCH

The first tests show stress-strain diagrams for tension of birch wood along or parallel to the grain (see Figs 1 and 2). It is obvious that the differences between the tests are very large. The birch tensile test BT1 had a strength in tension of about 225 MPa while the BT7 test only endured 121 MPa. Test BT5 showed a maximum strain of 0.9 per cent while BT6 could be elongated by 1.5 per cent before the rupture occurred. These behaviours are also shown in Table 1. In Kollmann and Côté [**3**], p. 295, Young's modulus for birch equals 16 670 MPa and the average in Table 1 shows almost perfect agreement with that value. The strength of wood changes very much due to the moisture content and the density. These values have not been measured for all the specimens but only for those used in the compression tests. All specimen origins from the same batch of wood are tested under 'identical' conditions and hence a density of about 0.65 g/cm^3 and 4.7 per cent moisture apply (see below).

Figures 1 and 2, however, show a problem when the modulus of elasticity is to be evaluated. Young's modulus is calculated as the slope of the curve where the conditions are purely elastic, i.e. in the lower part of the diagrams. The slopes in the stress–strain graphs are, however, not straight lines but have steeper slopes at lower loads. In the testing equipment computer this is dealt with by using only the initial part of the curve in the calculation of the modulus. When an attempt was made to verify the present experiments, with the strain gauges applied on the real construction, the load on the chair was of a disastrous magnitude, i.e. normal values of Young's moduli were perhaps not applicable. It must also be noted that an extensometer was used when elongation of the specimen was to be recorded. This device has a gauge length of 25 mm and therefore it is of vital importance in that the elongation measured really takes place where the extensometer is located. This is less important for lower loads but if the elasticity closer to rupture is to be examined it might be of interest. In some of the present tests (see, for example, BT1 and BT2 in Fig. 1) the rupture took place outside of that region and the device therefore registered a shortening of the specimen when this rupture had occurred and perhaps also a shorter strain before rupture. This did not, however, happen for test BT3. Perhaps an extensometer with a wider gauge length would reduce this problem.

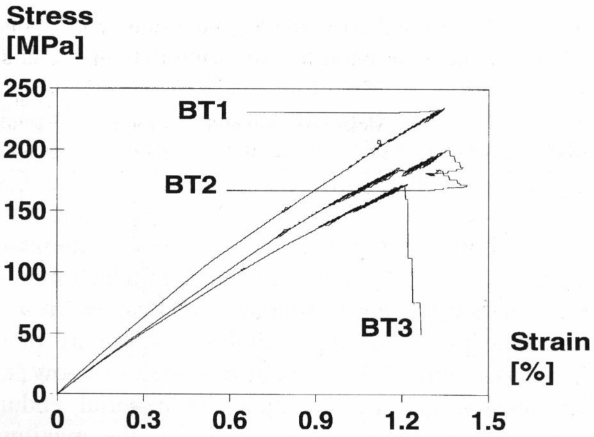

Fig. 1 Tensile test for birch along the grain

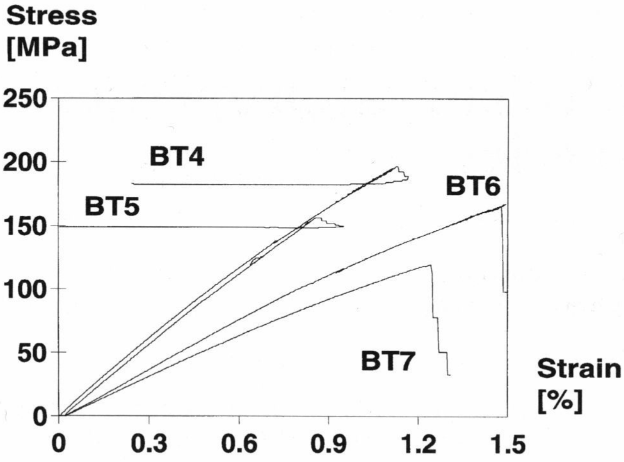

Fig. 2 Tensile test for birch along the grain

Compression tests along the grain for birch have also been conducted. Unfortunately, these tests could not be accomplished in complete accordance with the testing code. The code states that specimens with a square area of 0.02 × 0.02 m must be used. The load cell in the present equipment could not, however, be used for the high forces that had to be applied in order to compress the

Table 1 Strength and strain just before rupture and Young's modulus for birch, with tension along the grain

Test number	Strength (MPa)	Strain (%)	Young's modulus (GPa)
BT1	225	1.35	19.1
BT2	211	1.36	17.9
BT3	164	1.22	14.9
BT4	193	1.14	19.1
BT5	166	0.87	20.6
BT6	168	1.48	13.2
BT7	121	1.23	11.2
Average	178	1.24	16.5

specimens until rupture. Therefore, smaller specimens with a square area of about 0.015 m × 0.015 m had to be used. This can sometimes lead to problems, such as instability because of misalignment, and some of the tests had to be excluded because of that. Nonetheless, the results are shown in Figs 3 and 4 and Table 2.

When Figs 3 and 4 are examined it is obvious that some of the tests are not reliable. Tests BC5 and BC9 even showed negative values for the stress, i.e. tension instead of compression. A closer look at the data set, however, showed that these values have a rather small absolute magnitude, only about 0.01 MPa, and that they emanate from noise in the electrical signal from the load cell. Also, the BC2 graph looks suspicious because the slope of the curve seems to be almost vertical at the beginning of the test. In that case there were problems in aligning the test specimen absolutely vertically and the force could therefore not be applied parallel to the centreline. In Table 2 Young's moduli for those data sets are excluded.

If Tables 1 and 2 are compared it is also obvious that the strength in compression is less than half the value found for tension, 78 compared to 178 MPa. Both values are higher than those found in the literature (see, for example, reference [**6**], p. 164, where the values are 50 and 134 MPa). In part this might be explained by the moisture content, which is relatively low in the present specimens, with an average of 4.7 per cent. The ratio between compression and tension strengths is also somewhat higher in these tests compared to the ones in the reference, 0.44 and 0.37 respectively. For tension, the average Young's modulus was about 16.6 GPa, while it was about 15.0 GPa for compression. It is not possible from these few tests to confirm that there really is a difference in Young's modulus if tension or compression are considered. In the literature, such as that of Kollmann and Côté [**3**], these measurements are often supposed to be equal, but the authors mentioned that this is not always the case (see p. 361 of reference [**3**]). Tsuomis [**6**], for example, mentions only the modulus of elasticity (MOE) for bending, which for birch is said to be 16 170 MPa. The MOE must have a value between Young's modulus for tension and compression, and the present tests show that this is the case.

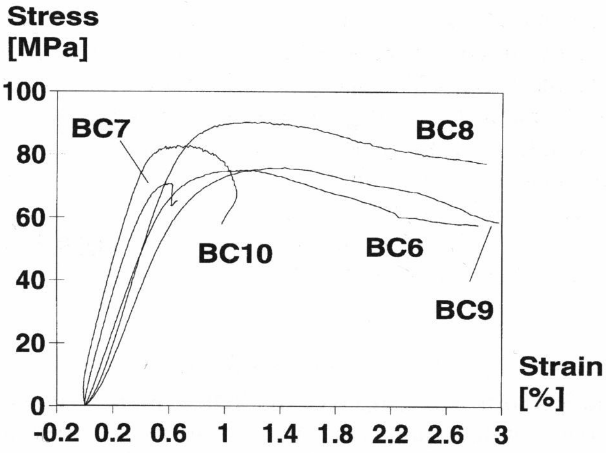

Fig. 4 Compression tests for birch along the grain

Tests by three-point bending have also been given for birch. This test differs from the others because the monitored values are the force applied on the specimen and the achieved deflection from that force. MOE3 must therefore be calculated according to

$$\mathrm{MOE3} = \frac{PL^3}{4ywh^3}$$

and the modulus of rupture (MOR) by

$$\mathrm{MOR} = \frac{3PL}{2wh^2}$$

where P is the force, y is the deflection, L is the span, w is the width and h is the depth (thickness) of the tested beam

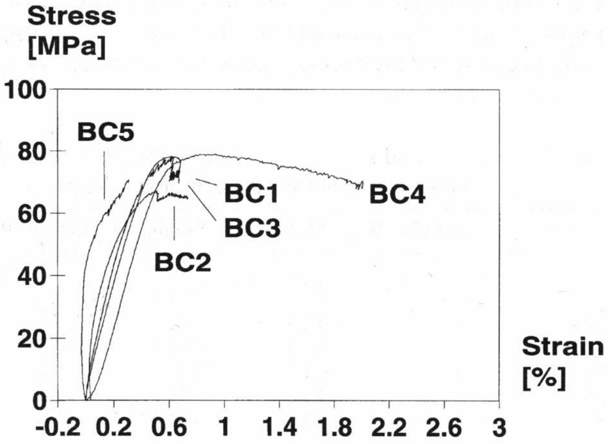

Fig. 3 Compression tests for birch along the grain

Table 2 Strength and strain just before rupture and Young's modulus for birch. Compression is along the grain

Test number	Density (g/cm^3)	Moisture (%)	Strength (MPa)	Strain (%)	Young's modulus (GPa)
BC1	0.60	4.6	78	0.62	17.0
BC2	0.64	4.5	66	0.51	—
BC3	0.68	4.7	77	0.62	19.2
BC4	0.65	4.7	79	0.93	15.8
BC5	0.70	5.0	71	0.30	—
BC6	0.61	4.5	75	1.11	12.8
BC7	0.64	4.7	71	0.59	—
BC8	0.70	4.8	90	1.27	14.1
BC9	0.62	4.7	75	1.43	11.1
BC10	0.66	4.8	81	0.75	—
Average	0.65	4.7	78	0.81	15.0

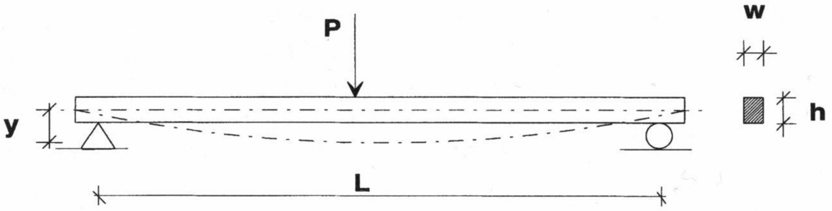

Fig. 5 Three-point bending test

(see Fig. 5). Kollmann and Côté (reference [**3**], pp. 300 and 364) or Bodig and Jayne (reference [**5**], p. 431) show variants of this equipment. MOR is only used for bending tests. A few such tests for birch are shown in Figs 6 and 7 and Table 3 and it is obvious that there are larger differences between the curves than before. MOR varies from about 80 up to about 150 MPa. Tsuomis [**6**] gives the MOR for birch wood as 144 MPa. Kucera [**4**] only uses the three-point bending tests to find the MOR, four-point bending being recommended instead to find the MOE. These values can be found in Table 3 (see MOE4).

The reason for this can be found in Kollman and Côté (reference [**3**], p. 303), where it is noted that the deflection in three-point bending is also caused by the longitudinal shear stress. The phenomenon is present for beams with a length–height ratio (*L/h* in Fig. 5) $\leqslant 20$. In the present case this ratio was 15 and, hence, the shear could not be neglected. The beam is therefore deflected more than would be expected if only the MOE3 expression above is considered. For these beams the difference should be about 10 per cent. Note that the specimens are not loaded up to rupture in the MOE4 test and therefore the same beams could be used also in the MOE3 experiments. The modulus of elasticity for four-point bending is calculated as (see reference [**4**], p. 45)

$$\mathrm{MOE4} = \frac{FL^3}{36wh^3y}$$

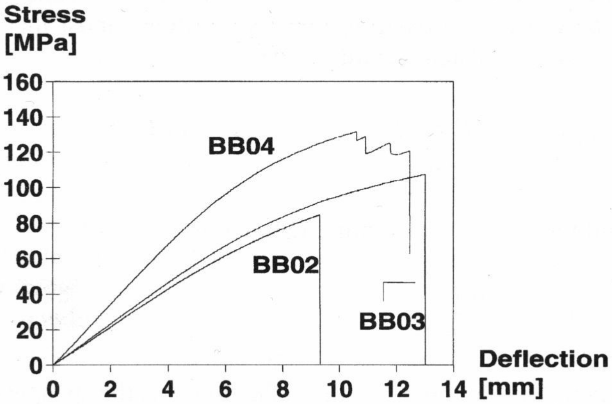

Fig. 6 Three-point bending tests for birch

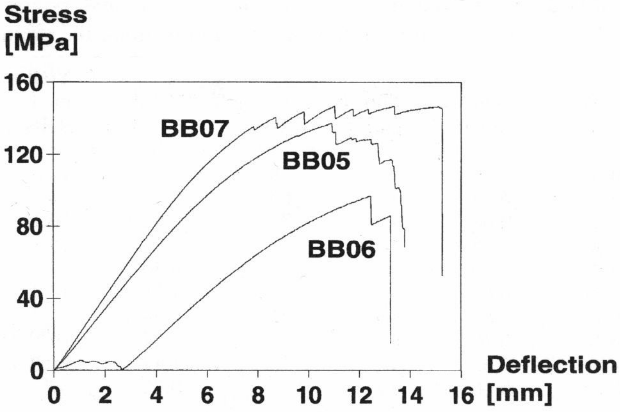

Fig. 7 Three-point bending tests for birch

From Table 3 it is obvious that the MOE4 method yields a higher modulus than MOE3, with a ratio of about 1.3, and they are closer in magnitude to the tension and compression tests in Tables 1 and 2. The moment is uniform between the inner load points in four-point bending and no transverse shear is present. The deflection is therefore lower and the MOE4 will be higher than MOE3. The moisture content has been calculated to be 5.4 per cent and the density is 0.62 g/cm^3. The average values in Table 3 for MOE3, MOE4 and MOR are lower than those found in Tsuomis [**6**], which are 16 170 for MOE and 144 for MOR. Unfortunately, Tsoumis does not mention whether MOE3 or MOE4 apply. Table 3 also presents values that are lower than both the present tensile and compression tests. According to classic theory this should not happen.

Table 3 Bending tests for birch

Test number	MOE3 (GPa)	MOE4 (GPa)	MOR (MPa)	Deflection (mm)
BB02	8.1	13.2	84.8	9.3
BB03	8.7	12.5	107.3	13.0
BB04	12.8	17.6	131.4	10.6
BB05	12.8	14.7	137.3	10.9
BB06	9.6	11.8	97.0	12.4
BB07	15.4	19.4	146.6	11.0
Average	11.2	14.9	117.4	11.2

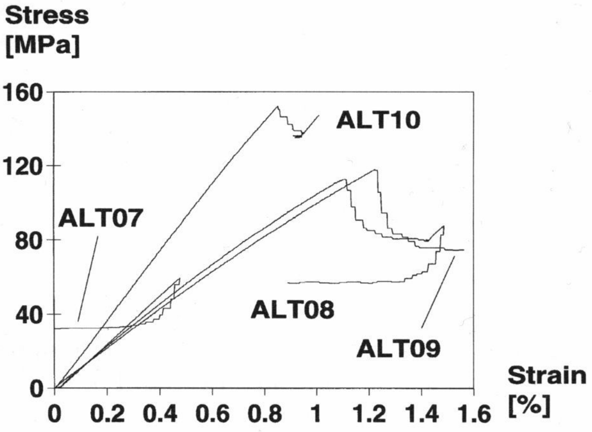

Fig. 8 Tensile tests for alder along the grain

3 ALDER

The second species that was of interest in this paper was alder, *Alnus glutinosa*. In Fig. 8 and Table 4 the results are shown for the tensile tests along the grain. It is obvious that the variations between different specimens are large. The ALT10 test shows Young's modulus of about 19 GPa while the same modulus for test ALT09 was only 10 GPa. The strength before rupture varied between 154 and 108 MPa.

Tsuomis [**6**] states that the strength is 92 MPa, but the present tests showed, on average, somewhat larger values. Also for these tests an extensometer was used. The high modulus and low strain values for test ALT10 might be explained by this because the elongation might have exceeded the range of the metering device. One test, ALT107, had to be stopped before rupture and the result is therefore excluded from Table 4. According to these tests, alder has a strength in compression of about 56 MPa, which is significantly lower than that for birch. This value corresponds well with the one found by Tsuomis [**6**], where 54 MPa is mentioned. Kollmann and Côté [**3**] do not give any values for alder but Boutelje and Rydell [**7**] mention an interval of 39–52 MPa, which is somewhat lower than the values found in both Tsuomis and in the present tests. Compression tests along the grain were made on 15 different specimens of alder. Test ALC04, however, had to be excluded from the set. The results are shown in Figs 9, 10 and 11 and Table 5.

Table 4 Strength and strain just before rupture and Young's modulus for alder. Tension along the grain

Test number	Strength (MPa)	Strain (%)	Young's modulus (GPa)
ALT06	108	0.61	17.7
ALT07	—	—	—
ALT08	112	1.09	11.3
ALT09	119	1.23	10.5
ALT10	154	0.86	19.1
Average	123	0.95	14.6

In Table 5 an average value for Young's modulus in compression is presented, of about 11.0 GPa. This is significantly lower than the value found for birch but unfortunately no reference for alder is found in the available literature. Tsuomis [**6**] shows an MOE of

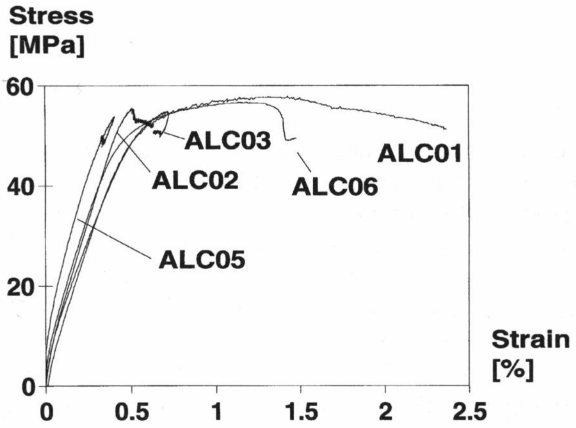

Fig. 9 Compression tests of alder along the grain

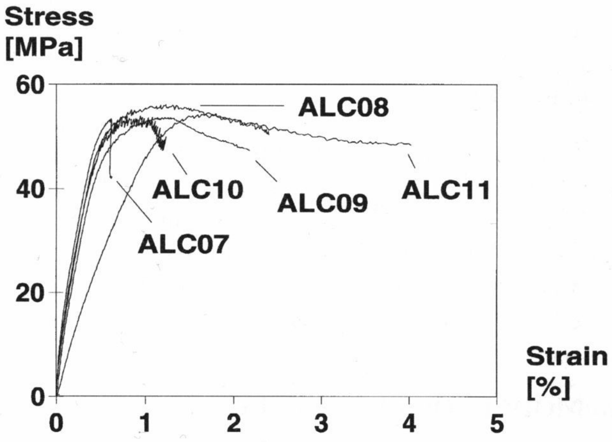

Fig. 10 Compression tests of alder along the grain

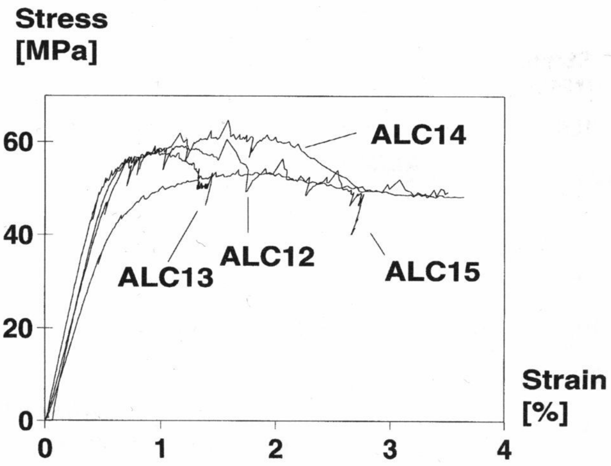

Fig. 11 Compression tests of alder along the grain

Table 5 Compression tests of alder along the grain

Test number	Density (g/cm^3)	Moisture (%)	Strength (MPa)	Strain (%)	Young's modulus (GPa)
ALC01	0.513	4.02	57.90	1.43	10.9
ALC02	0.506	3.97	55.18	0.51	12.0
ALC03	0.510	3.81	54.73	0.72	11.7
ALC04	0.519	3.98	—	—	—
ALC05	0.510	3.99	53.16	0.41	—
ALC06	0.509	3.98	56.41	1.18	12.2
ALC07	0.488	3.86	52.67	0.62	12.7
ALC08	0.506	3.47	53.06	1.28	10.4
ALC09	0.502	3.66	55.37	1.23	11.0
ALC10	0.509	3.80	52.79	0.8	11.0
ALC11	0.498	4.18	55.46	1.67	—
ALC12	0.488	4.49	60.18	1.57	11.0
ALC13	0.488	4.67	58.64	0.95	11.4
ALC14	0.503	4.25	63.79	1.59	9.6
ALC15	0.501	4.48	56.98	2.06	8.1
Average	0.503	4.04	56.16	1.14	11.0

11 470 MPa, which is close to the present value for Young's modulus. An interval of 9000–12 000 is given by Boutelje and Rydell [**7**], but they do not say anything about how this interval is achieved.

For alder, it is obvious that the MOE4 tests yield higher moduli compared to the MOE3 tests and the ratio is likewise about 1.3, which therefore is somewhat higher than the 1.1 which was expected. The MOE4 values are also higher than those mentioned by Tsuomis [**6**], 11.5 GPa, and so are all the MOR values compared to that of Tsuomis, which is 83 MPa. The moisture content in the present specimens was 5.4 per cent and the density was 0.52 g/cm^3. MOE3 and MOE4 tests were also made for alder (see Figs 12 and 13 and Table 6).

4 MODULI OF ELASTICITY

The tests on birch and alder showed that theory and practice do not always totally correspond. According to classic theory (see, for example, reference [**3**], p. 360), the MOE must be located between or be equal to the values of Young's moduli for tension or compression. In these tests this is true for MOE4 but not for MOE3, even when the influence of shear stress is considered.

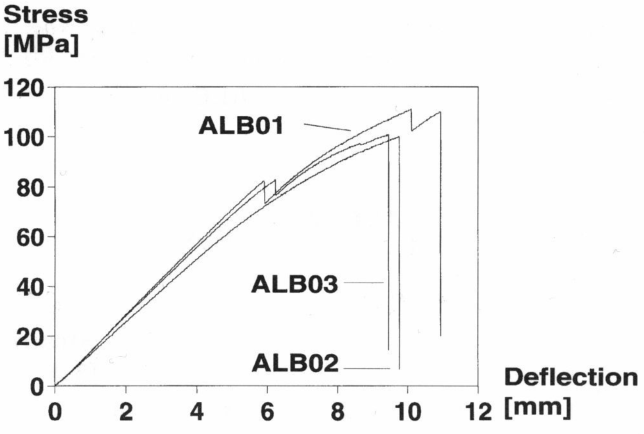

Fig. 12 Three-point bending tests for alder

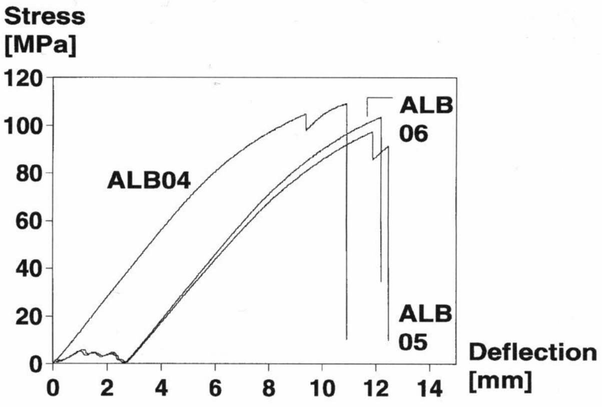

Fig. 13 Three-point bending tests for alder

The MOE3 values are, of course, lower than the modulus found for tension, but very close to the one found for compression. This could be the result of weak parts in the specimens used in the bending tests. In order to find out whether this is so, tests must be conducted with a greater number of specimens in order to obtain statistically viable results. Another reason for this could be that the deflection registrations, which in turn are used for the MOE3 calculations, are located too high in the stress region for the material to behave in an elastic way. As can be found in the bending stress versus deflection graphs, the relation cannot be depicted by a straight line but instead the tests show a high MOE3 for low stress while the MOE3 becomes lower and lower when the stress increases. Another reason is, of course, the influence of shear. In Fig. 14 the MOE3 values in GPa are plotted as a function of the stress calculated from the registered values in the ALB01 test. Figure 14 shows that the MOE3 values for a very low stress are unpredictable. They range from about 9 up to 27 GPa (see the leftmost part of the diagram). As the test proceeds the MOE3 values show very stable values of about 10 GPa up to, say, 85 MPa, where a minor rupture occurred. After this the MOE3 values are about 9 GPa but decrease to

Table 6 Bending tests for alder

Test number	MOE3 (GPa)	MOE4 (GPa)	MOR (MPa)	Deflection (mm)
ALB01	11.0	13.2	111.0	10.0
ALB02	9.6	11.0	99.9	9.7
ALB03	10.6	11.9	100.7	9.4
ALB04	10.7	15.3	109.2	10.8
ALB05	9.9	12.9	97.3	9.2
ALB06	10.3	16.5	103.7	9.5
Average	10.3	13.5	103.6	9.8

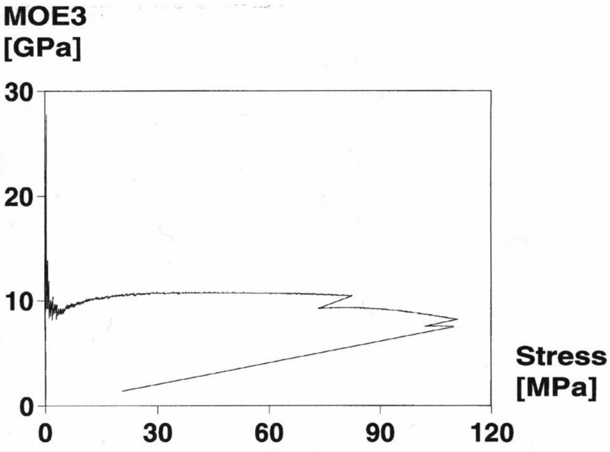

Fig. 14 Moduli of elasticity from three-point bending tests of alder versus calculated stress values

Table 7 Moduli of elasticity for birch and alder in GPa

	Young's moduli		Bending moduli	
Species	Tension	Compression	MOE3	MOE4
Birch	16.5	15.0	11.2	14.9
Alder	14.6	11.0	10.3	13.5

7.5 GPa just before the total rupture. It can be seen that the straight line below about 7 GPa in Fig. 14 emanates from only one registered value after rupture. In the present tests the MOE3 values were never higher than about 10.7 GPa if the few initial values are excluded. Even if an extra 10 per cent is added, it is obvious that the three-point bending test shows moduli that are too low compared to the four-point bending test and the tensile and compression tests.

5 CONCLUSIONS

Two species of Swedish hard woods were tested, birch and alder. Young's moduli have been calculated both from tension and compression and, further, three- and four-point bending tests have been elaborated. The results are presented in Table 7.

The three-point bending moduli are lower than Young's modulus for compression for birch and very close for alder, even if the expected influence of shear is considered. This should not be the case according to classic theory. Four-point bending yields values of about 1.3, which should be 1.2 according to the theory, and are larger compared to the three-point bending test. The values are therefore inside the Young's moduli interval for alder but not for birch. The result, however, is achieved from only a very limited number of tests and should probably not be used as a general rule.

ACKNOWLEDGEMENTS

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