Strength properties for Swedish oak and beech

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Abstract

Because of economic impact most research on wood in Sweden is aimed at our needle-leaved species, pine and spruce. Saw-mills and other industrial enterprises using these conifers are also in vast majority, both in number of employees and number of companies. However, there is a viable industrial branch, e.g. furniture companies, in Sweden dealing with broad-leaved species such as oak, birch and alder. Such industries often import all the wood they use even if the same type of wood grows in the vicinity. In order to make Swedish broad-leaved trees more interesting for the wood manufacturing sector we have examined the strength properties for some common Swedish woods, viz. oak and beech. The result shows that our oak specimens had a modulus of elasticity of 12,243 MPa measured by using four point bending. The so called Young´s modulus was 11,761 MPa for tension and 15,610 MPa for compression in the fiber direction, i.e. a very high difference. The stress just before rupture was measured to 85 MPa for tension and 76 MPa for compression, i.e. a surprisingly small difference. For beech, our corresponding values were 13,017 MPa for four point bending, Young´s modulus during tension 13,954 MPa and 130.4 MPa in maximum stress, while they were 13,101 MPa and 84 MPa under compression.

Keywords:

Wood, testing, oak, beech, MOE, MOR, Young´s modulus

Introduction

Sweden is a long and narrow country. The northern part reaches far beyond the polar circle while the southern-most peak is located some 15 latitude degrees below on the Earth surface. Our country is therefore spanning several growth regions. Most of the country is covered by forests with needle-leaved species, especially pine and spruce. The utilization of these trees in the form of timber and paper has significant importance for the standard of living in Sweden. Broad-leaved species, such as birches, alder and oaks more seldomly create forests by their own, but instead such trees are scattered within the conifer wood lands. Saw-mills for such hard woods are hard to find, and if you find them they are usually old fashioned and have only a very small-scaled business even if there are one or two exceptions. Many of these companies are likely to die and disappear when the now ageing owners and workers retire. In order to reduce this risk, much more emphasis must be put on the fact that Sweden has interesting resources of broad-leaved species, and also that timber from these trees can be interesting alternatives to conifers for a number of different applications. As a designer of wooden constructions you must be aware of the physical properties for the wood. For conifer constructions there are building codes, rules and regulations showing the designer the values of allowed strain and stress that are accepted for different building parts but such recommendations are lacking for gymnosperms, or hard woods. This is unfortunate because many of the broad-leaved types are much stronger than the needle-leaved ditto. This can, for example be found in [1] where some species have been examined. Another example can be found in a report on birch, alder and aspen which was published not long ago, see Reference [2].

You also have to use the values from the experiments and reference [3] shows some Finite Element Method, FEM, calculations for one of the strongest hard-woods available in Sweden viz. ash, *Fraxinus excelcior*. Fortunately, it seems as a growing interest in FEM, and by this the examining of such hard-woods, has emerged. A number of studies have been published dealing with FEM analysis, see e.g. [4], [5] and [6], during recent years. New FEM programs are developed all the time but in spite of the rapid growth of computer programs for solving even very complex structures, see e.g. [7] for a 3-d study with wood composites, it must be stressed that there still is a need for thorough testing under reality-like conditions. There are some studies dealing with this for example [8] and [9]. Testing under such conditions is however a time-consuming and expensive activity, why FEM still has a role to play when designing furniture. Such calculations also makes it important to study the solid mechanics of the material itself.

Testing solid mechanical properties

Wood is a very special material due to its anisotropic and heterogeneous structure. If you apply forces in the same direction as the fiber orientation, i.e. acting so the wood is tensed along the fibers, it is surprisingly strong. If the forces are applied in the opposite direction, and hence the wood is compressed, only half of the strength is found, due to the literature. Even lower values are found if you apply the forces perpendicular to the fiber direction. Bending strength, for example, as is a form of mixture between tension and compression, will therefore probably be located between those corresponding values. In Reference [10] page 292 a graph is shown of this behavior. A suitable way to start our tests is therefore to see how much stress our specimens can endure in tension.

Tension and compression tests

In Sweden, as we are a part of Scandinavia, certain testing regulations for wood apply, see Reference [11]. Other countries have other ways for testing wood and this goes especially for the recommended design of the test specimens. See e.g. References [10], page 324, and [12], page 84 and 85, for different types of design. In order to find the mechanical properties we must use machinery where we can apply known forces on our specimens and also monitor how much longer the specimens become due to these applied forces. All specimens for tensile tests have a marked waist of about 0.1 m. This is so because we want the specimens to achieve most of its prolongation in this waist section. Normal practice is also to monitor the prolongation with a so called extensometer with a monitoring gap, L, of 0.025 m. Because of the waist we want our specimens to break in this specific section and also be able to monitor the added length within the extensometer gap. The machinery is connected to a computer which registers both the applied forces and the prolongation in a fast pace, here set to 10 times each second. Each resulting data file therefore contains hundreds, or even thousands, of values. Even if we actually measure the extension, δL and the force, F, we are more interested in the stress, σ and strain, ϵ. These values are calculated as:

$$\sigma = \frac{F}{A} \quad \text{and} \quad \epsilon = \frac{\delta L}{L}$$

By using the formula:

$$E = \frac{\sigma}{\epsilon}$$

for the first interval of 200 values we have calculated the so called Young´s modulus. This modulus can also be depicted as the slope of the curve in a so called $\sigma\epsilon$ graph.

Bending tests

Because wood, many times, shows so large differences in strength for tension compared to compression, bending tests are important. Another fact is that most parts in wooden constructions are not under "clean" axial tension or compression but instead part of constructions that bend. For furniture and other small structures, axial forces can often be neglected without any hazards because the internal stress in each member will be very small compared to the strength of the material. Note that compression along the axis of slender wooden parts might lead to so called buckling where the structure might collapse without any warning at all, see [13] for a study on this. However, a beam that is bent is actually tensed on one side of the neutral layer and compressed on the other. A bending test, therefore, should give us an average value of the strength. Most larger real structures in buildings, bridges, scaffolds and other such common artefacts use wooden beams under bending.

A very straightforward test is called 3-point bending because a beam is then supported in each end and a force is applied in the middle of the beam, see Figure 1.

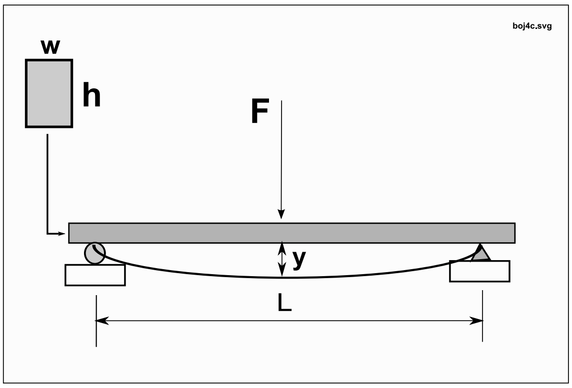

Figure 1: Three point bending tests. Experimental setup.

The things actually measured are the force and the deflection of the beam under the applied force. In this type of test so called shear stress is introduced which results in a too large a value for the deflection and hence 3-point bending is mostly used just for monitoring the so called Modulus of Rupture, MOR which is the largest tension/compression achieved when the beam is cracked. See e.g. [10] p. 300 and [14] p. 184. Because of this fact only so called 4-point bending tests have been used in our study, see Figure 2.

In such tests the influence of shear stress could be neglected because of the constant moment in the middle of the beam and this type of test is therefore assumed to give us a more accurate value for the Modulus of Elasticity, MOE. Also in this test the force, F, and the deflection, y, are measured. Together with the hight of the beam, h, the width, w, and the length, L, this modulus is calculated as:

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

In tension and compression tests Young´s modulus is calculated based on the slope of the stress and strain graph. Each experiment gives us one graph, and one modulus. In bending tests one MOE can be calculated for each registered level of the force and deflection. This fact also makes it possible to test the MOE without destroying the test specimens. In the Scandinavian code for wood testing, see [11] p. 45 the procedure is described in detail. The basic idea is to calculate two moduli for very specified forces. These forces depend on the density of the wood, see the following under the corresponding part for each type of wood.

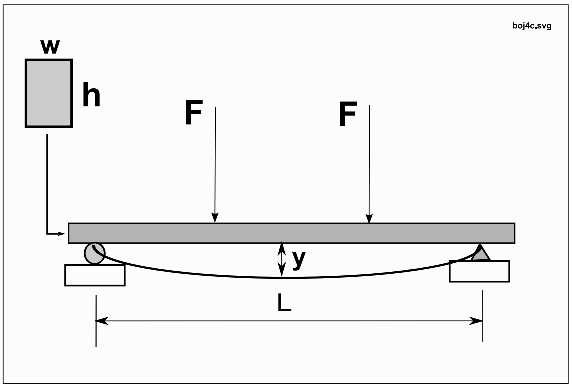

Figure 2: 4-point bending test.

Moisture content

The ability to withstand different forces from the outside depends to a large part on the density of the wood, but also on the moisture content, i.e. the ratio between the weight of the internal water amount to the weight of the wood itself, see e.g. [10] page 310 for a graph of this. When studying the solid mechanics properties for wood the measurement of the water content in the wood is therefore vital. A fool-proof way to measure this is to use a good scale and note the weight of each specimens before and after it has been in an oven for a day or two. All water in the wood will then be changed into steam which in turn is transported from the wood by diffusion.

Testing of oak, *Quercus robur*

Tension tests for oak

Just as an example of the testing we show a graph over our first five tensile tests, see Figure 3.

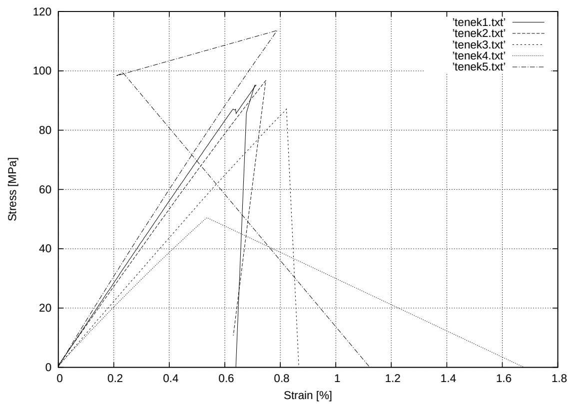

Figure 3: Five tensile tests for oak, *Quercus robur*.

Even if the number of tests are few it is possible to get a grasp of the strength in terms of endured stress and strain. Important is also to note that the traditional look, i.e. for metals, of a stress and strain graph does not apply when oak wood is tensed to rupture. For instance we cannot see any plastic region where the curve becomes non-linear. Instead it is an almost perfect linear relationship between strain and stress from the starting point of the graph to rupture. Study for instance our first test in Figure 3. The corresponding line is drawn by using a normal line in the graph, also identified as the second line to the right from the stress scale, i.e. the ordinate axis, at the level 60 MPa. It is obvious that the line starts almost in the point (0,0) and continues in a straight line up to (0.62, 85) where some rupture occurred. However, the specimens did not break in two parts until the stress became about 92 MPa.

These graphs show that both the endured strain and corresponding stress, and also the slope of each curve differs significantly between different specimens. By using the slope in the tensile $\sigma\epsilon$ graphs we have calculated Young´s modulus as found in Table 1. In this table we have also included the maximum stress for each specimen just before rupture.

The standard deviation for Young´s modulus has been calculated to 1,874 MPa while it is 18.1 for the maximum stress.

Interesting is now to find out if other researchers have found similar results. In [10], page 295, a value of 58,100 kp/cm^2, i.e. $\approx$ 57 MPa, is shown but the authors write that this value, probably is too low. Instead 130,000 kp/cm^2 should apply. Noteworthy is that the value is monitored in 1935, more than 70 years ago. Another value can be found in [14] page 164 and here a value of maximum tension stress is found to be 109 MPa. No value of Young´s modulus for tension is presented. From the figures in Table 1 it is obvious that the values differ very much between different specimens and also that they are lower than some corresponding values found in literature.

Above we mentioned that the moisture content had a significant influence on the strength. Dryer specimens are stronger than those containing more water. In Table 2 we show the result from our measurements for our oak specimens.

In [14] the author mentions that the shown values are calculated for specimens in air-dry condition but it is not exactly clear what moisture content this would imply. The cited references in [14] are published in Romania and in Germany and

Specimen number	Young´s modulus [MPa]	Maximum stress [MPa]
1	13,922.9	95.17
2	13,113.4	96.68
3	10,776.2	91.02
4	9,339.0	50.48
5	14,821.4	108.01
6	12,045.1	98.68
7	10,395.8	94.47
8	12,985.6	79.53
9	10,043.2	66.20
10	10,171.3	67.87
Average	11,761.4	84.81
Stand. dev.	1,874.5	18.12

Table 1: Young´s modulus and maximum stress in tension for ten specimens of oak, *Quercus robur*.

Specimen no.	M.C. in %	Specimen no.	M.C. in %
1	5.46	6	5.58
2	5.44	7	5.52
3	5.53	8	5.53
4	5.60	9	5.59
5	5.50	10	5.60

Table 2: Moisture content, M.C. in % for the oak, *Quercus robur*, tensile test specimens.

hence the M.C. was probably higher than for our own specimens. Due to the fact that strength should grow when the moisture content gets lower it is a little disappointing that our test showed lower values even if we had dryer samples. However, this was the result of the test.

Compression tests for oak

We have also tested a number of oak specimen under compression. The tests are supposed, due to Reference [11] page 28, to be made with small rectangular pieces but with quadratic cross sectional areas. Each side is supposed to be 0.02 m while the length is set to be 0.06 m. Unfortunately, we did not have such samples but instead we used specimens of the size 0.015 $\times$ 0.015 $\times$ 0.045 m. Table 3 shows the moisture content for the specimens.

Spec. no.	Density [g/cm^3]	M.C.[%]	Spec. no.	Density [g/cm^3]	M.C. [%]
1	0.734	6.66	6	0.745	4.62
2	0.655	5.18	7	0.757	5.05
3	0.741	5.10	8	0.680	5.18
4	0.645	5.19	9	0.727	5.05
5	0.749	5.25	10	0.760	5.36
Average				0.719	5.26

Table 3: Density in g/cm^3, and moisture content, M.C., in % for the oak, *Quercus robur*, compression test specimens.

When a piece of wood is compressed to the level of rupture the inner structure is crushed. Normally the piece does not break into two parts but instead it only becomes shorter and shorter. The graph for a compression test therefore looks significantly different from the corresponding graphs for tensile tests, see Figure 4. Also different is the very start of the testing. As can be found in the graphs the stress did not increase when the test started but instead the curves are located a little bit to the right. This is probably so because of small gaps between the testing equipment and the specimens. These gaps must be closed before the stress gets higher, i.e. when the force is actually increasing.

One of our tests were completed for a strain of about 0.6 % while another went on up to over 4 %. The strain for maximum stress was found to be between values 0.57 % and 1.44%, see Table 4. Also found in the table is that one of the specimens had a significantly higher Young´s modulus, i.e. number 10, than the others.

If Tables 4 and 1 are compared it is obvious that the maximum stress under compression is lower than those values found for tension. However, the difference is small compared to the one expected. In [14] p. 164, oak is expected to have a tension strength along the fibers of about 108 N/mm^2 while the compression strength is about 42 N/mm^2. In our tests the corresponding average values are 85 and 76 N/mm^2. The Young´s modulus for test number 10 is surprisingly high, about 29,000 MPa compared to the other values, about 15,000 MPa. Even if the modulus is high the stress before rupture was approximately the same as for the other specimens. If number 10 is excluded from the average we still get a Young´s modulus under compression of about 14,000 MPa. It must be noted here that we have used software provided by the manufacturer of the testing equipment, an Instron 5582, in order to test our specimens. Each compression test has been made with a sample rate of 10 "points" per second and with a so called cross-head speed of one mm per minute. The test is stopped when the force gets lower than a preset value or when the number of registrations becomes too large. Hence, during each test a different number of points have been registered. Just as examples, in test number 1, 2,536 lines are present in the data file while 2,296 are present for test number 10.

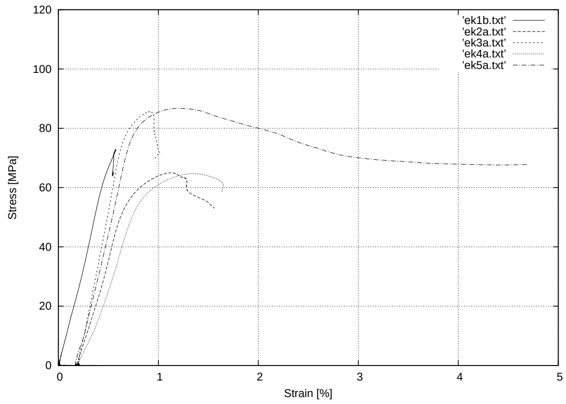

Figure 4: The first five compression tests for oak, *Quercus robur*.

Specimen Number	Max. Load kN	Stress at Max.Load MPa	Strain at Max.Load %	Young´s Modulus MPa
1	15.74	72.69	0.5728	15,720
2	13.94	65.01	1.1180	13,840
3	18.37	85.61	0.9145	18,100
4	13.90	64.75	1.3430	11,400
5	18.66	86.76	1.2190	15,070
6	18.59	86.27	1.1200	15,810
7	18.54	86.04	1.1060	14,730
8	13.94	64.69	1.1740	10,570
9	16.25	75.29	1.4410	11,610
10	15.68	73.12	0.6860	29,220
Average:	16.36	76.02	1.0690	15,610
Stand. dev.:	2.04	9.48	0.2729	5,320

Table 4: Ten compression tests in the fiber direction for oak, *Quercus robur*.

Bending tests for oak

Above was described the procedure for four point bending tests. These tests are made using different forces. In order to find them it is necessary to calculate the density of the specimen. In our case the length was measured to 341 mm the width and height to 20 mm which gave us a volume of 136.4 cm^3. The weight was found to be 91.62 g and hence the density was calculated to 671.7 g/cm^3. Actually three forces are used. From a table in [11] p. 44 we found these three forces $F_1 = 288.3$ N, $F_2 = 720.7$ and $F_a = 201.5$ N. The specimen was now to be loaded with the F_2 force, however, split on the two forces shown in Figure 2. After this the load was reduced to the F_a level. This was done twice. The beam was now to be reloaded again up to the F_1 level. The force and the deflection were monitored ten times each 0.1 second. This gave us an average value on the lower force of 290 N while the average deflection was 0.092 mm, i.e. we tried to set it to zero. The force was now increased to the F_2 level, i.e. 720 N. Also now the actual force and the deflection were measured each 0.1 second giving us ten new values for force and deflection. The average was calculated to, by coincidence, 720 N and the deflection 0.26 mm. The difference between the average forces, 430 N, and the average deflections, 0.17 mm, was now used to calculate the MOE. The result was, without the approximations:

$$MOE = \frac{430 \times 0.300^3}{36 \times 0.020^4 \times 0.00017} = 11,873MPa.$$

Four measurements were to be made for each specimen resulting in three more values, 12,164, 12,249 and 12,130 MPa. The lead us to a new average which was calculated to 12,104 MPa. In all we had ten specimens and each resulted in four calculated MOEs. Averages for each specimen are shown in Table 5.

Test number	MOE_4 [MPa]	Test number	MOE_4 [MPa]
1	12,104	6	12,125
2	11,916	7	13,464
3	8,992	8	12,630
4	13,315	9	12,021
5	13,634	10	12,231
		Average:	12,243
		Stand. dev.:	1,311.6

Table 5: Average MOE_4 and standard deviation values for oak, *Quercus robur*.

Our findings are now to be compared to values found in literature. In [14] page 164 the MOE for white English oak is said to be 12,250 MPa, while red oak is slightly "weaker", 11,560 MPa. The writers to [15] give us the values 10,000 to 13,000 MPa. Hence, it seems as our oak is well in the vicinity of the values found from other examinations.

Testing of beech, *Fagus sylvatica.*

Tensile strength tests, beech

The method dealt with was exactly the same as before. The specimen was equipped with an extensometer with a gap of 25 mm and the load in kN was registered each 0.1 second until the specimen broke into two pieces.

As for the oak tests the properties differed between different specimens. We can also see that our beech wood is significantly stronger than the oak ditto, see Table 6. After testing the tensile strength each piece of the the specimen is dried in an oven in order to evaporate all water. Using the weight before drying, and after drying, the moisture content can be calculated. Table 6 also shows these conditions.

Specimen no.	M.C. [%]	Young´s modulus [MPa]	Maximum stress [MPa]
1	5.73	12,464.1	128.8
2	5.65	15,795.2	150.9
3	5.61	14,324.1	132.3
4	5.60	15,741.2	135.5
5	4.29	13,653.3	126.1
6	5.68	13,757.6	122.4
7	5.57	13,899.0	112.3
8	5.50	12,103.1	129.5
9	5.62	14,240.0	143.8
10	5.58	13,564.9	122.3
Average:		13,954.3	130.4
Stand. dev:		1,189.4	11.09

Table 6: Young´s modulus and maximum stress in tension for ten specimens of beech, *Fagus sylvatica.*

The average of all specimens were calculated to 130.4 MPa, which value correspond to the one found in [14] page 164 which is 130 MPa. Further, it is said to be 135 MPa in [15], page 70. Unfortunately, Young´s modulus is not presented neither in [14] nor in [15], but the E_y value for red beech in [10] page 295 is said to be 144,100 kp/cm^2 which equals 14,100 MPa. The values in Table 6 seem to correspond very well with the values found in literature. It is also obvious that beech wood has a higher Young´s modulus compared to the oak ditto.

Also in this case our specimens contain less water, about 5.5 %, than those mentioned in literature, between 12 to 15 %. Hence, our tensile strength values should perhaps be even higher, even if the Young´s modulus is the least sensitive of the strength properties to changes in the moisture content, see [10], page 310.

Compression tests for beech

As for oak we have studied strength in compression for 10 specimens of beech.

From graphs, not presented here, it is shown that the tests went on for a longer period of time, i.e. the samples were compressed to a higher level than the oak ditto. There were also less problems precisely in the beginning of the tests and the stress, i.e. actually the force, was increasing at the very moment when the machine cross-bar started to move. The differences between the Young´s moduli seems also to be slightly less than before but that depends to some part on different scaling. These graphs also show that the samples can endure significant load even if the maximum crushing strength has been passed. Further, these experiments showed a closer relationship with traditional tests of the Young´s modulus because the maximum load was found well to the right of the linear sections of the graphs. We have also put together our findings in Table 7.

The compression values in Table 7 also show that beech is a stronger type of wood compared to oak, see the Maximum stress column in Table 4. If looking at the Young´s modulus oak seems to be somewhat less elastic than beech, i.e. oak has a higher modulus. This is a little surprising because the same fact seems not to be valid under tension, compare Tables 6 and 1.

We have, of course also, measured the moisture content of our beech specimens and they were slightly less dryer than the oak ditto. The M.C was about 6 % with one exception, sample number 2. Perhaps this is due to some measuring error.

Four point bending tests for beech

The method used is exactly the same as for the oak tests. First we had to find the density and we we measured it to 771.0 g/cm^3. If we compare this density with the one found for our oak specimens it is obvious that beech is a denser type of wood. This will also lead to a higher strength. However, the measured density value gave us the input in order to get the higher force level, F_2, equaling 827.9 N, the lower level F_1 = 331.1 N and F_a = 231.5 N. As before these values were found in [11]. The monitored MOE_4 values are shown in Table 8.

The modulus of elasticity for beech is said to be 13,130 in [14] and between 10,000 to 16,000 MPa in [15]. Both references therefore applies to our measured value. Also here we find that the species beech is stronger than oak even if the difference is smaller than expected, MOE_4 for beech was found to be 13,017 compared to 12,243 MPa for oak.

Spec. no.	Density [g/cm^3]	M.C. [%]	Young´s m. [MPa]	Max. stress [MPa]
1	792.56	6.45	16,426.1	93.8
2	789.45	12.81	15,130.3	84.6
3	763.98	6.13	11,867.7	81.4
4	748.86	6.07	13,141.6	85.5
5	745.13	6.35	11,503.4	77.9
6	802.43	6.42	12,334.6	90.7
7	765.84	6.11	12,047.1	83.7
8	761.63	6.15	13,362.6	81.9
9	771.59	6.08	13,410.9	87.5
10	748.66	6.14	11,788.2	76.2
		Average:	13,101.3	84.3
		Stand. dev.:	1,592.9	5.41

Table 7: Density, moisture content, Young´s modulus and maximum stress in compression for ten specimens of beech, *Fagus sylvatica.*

Test number	MOE_4 [MPa]	Test number	MOE_4 [MPa]
1	10,557	6	14,912
2	14,222	7	11,011
3	10,828	8	11,640
4	16,068	9	12,431
5	13,880	10	14,621
		Average:	13,017
		Stand. dev:	1,965

Table 8: Average MOE_4 values for beech, *Fagus sylvatica.*

Conclusions

In this paper we have tested about 60 specimens made of oak, *Quercus robur*, and beech, *Fagus sylvatica.* Due to the higher density of our beech specimens, 771 compared to 671 g/cm^3 for the oak ditto it was assumed that beech was the stronger type of wood. This was also the case except for the Young´s modulus in compression. Oak had a higher value, 15,610 MPa than beech with 13,101 MPa. Why this is so has not been possible to find out. Interesting to note is also that Young´s modulus for tension differs from the one in compression even if the differences are rather small, at least for for beech with 13,954 for tension and 13,101 for compression. Corresponding values for oak were 11,761 and 15,610 MPa. At least for oak these differences might have significance when using such moduli in FEM calculations and we have not, as yet, seen computer programs that can take such discrepancies into consideration. It must be noted again that our number of specimens was rather small. It might be necessary to test several hundred, or even thousand, specimens made from the same board and the same location within the tree in order to ascertain that there are in fact differences with significant implications. The bending tests were used in the form of four point bending, a method assumed to give use better values than the three point ditto. For oak we calculated an average modulus as 12,243 MPa while it was 13,017 for beech. The breaking strength during tension was higher than that under compression but for oak this difference was surprisingly small, 76 MPa for compression and 84 MPa for tension. The corresponding values for beech were 84 and 128 MPa.

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