Allocation of thermally treated structural beech timber to the European strength- classes and relevant grading and quality control procedures

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ABSTRACT

In this paper the evaluation of strength and stiffness properties for thermally modified beech (*fagus sylvatica*) structural timber (TMTB) is described. On base of test results the possibilities and limits for relevant grading and factory production control of TMTB are shown and discussed.
Within the EC-FP6 funded and still ongoing project HOLIWOOD it is intended to use TMTB for load bearing members. The relevant static calculations shall be based on the requirements of the appropriate European standards, e.g. Eurocode 5 and EN 338. The knowledge of characteristic strength and stiffness values is indispensable for the static design and therefore the determination of these values is a key task within the project. The respective tests were executed with TMTB "Buche forte" produced by Mitteramskogler GmbH in Austria. Results of preliminary tests showed, that the standard procedure – determination of bending strength, MOE and density followed by a calculation of the remaining properties using given conversion equations – cannot be used for TMTB. In consequence all properties have to be determined by tests.
The tests confirmed the known behaviour of TMTB: a significant reduction of most strength properties and a more or less unchanged stiffness compared to untreated beech timber. These premises also influence possible set-ups for grading and factory production control procedures. Therefore several parameters for machine grading were investigated and the current status is presented.
The paper shows the difficulties in introducing TMTB - which has to be regarded as a completely new material, rather than just a slight modification of a known wood species - into the European strength class system (EN 338).

INTRODUCTION

In recent years products made of thermally modified timber (TMT) are being used increasingly in a wide field of application. For outdoor use its superior durability and dimensional stability makes TMT being a good substitute for tropical hardwoods or impregnated softwoods. For indoor uses the wide range of possible colours of TMT made it competitive to naturally dark coloured tropical hardwoods.
The EC-funded FP6 project *Holiwood* aims at widening the field of application for TMT made of European hardwoods – here in particular beech (*fagus sylvatica*) - to structural applications in an outdoor environment, e.g. noise barrier elements.
It is known that a downside of TMT is its reduced strength compared to untreated timber (Hill 2006). For a given thermal treatment hardwoods show even higher strength losses than

softwoods. Therefore an extensive test program has been set up to determine the strength and stiffness parameters of thermally modified beech timber (TMTB) and to assess its suitability for structural use.

In order to be used for structural purposes TMTB has to be strength graded and assigned to a strength class, e.g. according to EN 338. Following the procedures of EN 384 it is possible to determine only bending strength and stiffness as well as density by tests for the assignation of a batch of timber to an EN 338 strength class. All other strength and stiffness values can be calculated on base of these data using relations given in EN 384. As preliminary tests indicated that the relation between several strength/stiffness parameters could differ significantly from respective specifications given in EN 384, the tests had to cover all parameters that are needed to assign TMTB to strength classes according to EN 338.

In the following bending, density, tension and compression tests on TMTB specimens are presented as first results of the still ongoing test program. Additionally selected data are chosen and analyzed in such a way that the feasibility of a machine grading for this material can be judged. This is an important factor regarding the acceptance on the market. Besides the knowledge of the structural behaviour of TMTB the end user, engineers at the planning stage as well as carpenters at the construction stage, will also regard reliability and economic performance of this material which is strongly related to grading.

EXPERIMENTAL

Raw Material

The beech wood was taken from three different stands in Austria. It was bought appearance graded and not strength graded. The visual strength grading took place with the already heat treated specimens before testing.

All specimens met the requirements for (visual) grading class LS13 according to DIN 4074-5 which would allow an assignment of the untreated timber to strength class D35 according to EN 1912.The specimens were free of major defects like big knots and also did not show significant twist or bow deformations. However, cup deformations existed in almost all beams but did not exceed the limit of 2% for grading class LS13. Slope of grain is difficult to determine on beech and thus was disregarded as grading criteria. The effective quality of the untreated timber in particular regarding knots implies a much greater potential for these wood samples.

Thermal modification

The specimens were thermally treated by Mitteramskogler GmbH (Gaflenz, Austria). This company uses the THA thermal treatment process where the respective modification is executed under a gas atmosphere. According to the desired end-use of the material, the heating temperature can vary between 160°C and 250°C with treatment times from 2h to 16h. For all tests TMTB with the brand "Buche forte" was used. Detailed data for the respective treatment are confidential and thus not published. However, the used combination of modification temperature and time is selected in such a way that durability class 1 can be guaranteed according to the manufacturer (Mitteramskogler 2008). This stated durability has been verified by tests in the meantime. The respective thermal treatment has to be considered as being an intensive modification.

Specimens

There were n = 100 square-cut TMTB beams and boards per sample available for testing. The nominal beam dimensions were $\ell \cdot b \cdot h = 3000 \cdot 50 \cdot 180 \text{mm}^3$. Width and depth varied slightly from specimen to specimen which resulted from drying and thermal treatment processes.
The specimens for bending and compression tests were cut from the same square-cut timber. As cross-sections for the bending tests square-cut timbers with a depth of 135mm and a nominal width of 50mm were selected. All specimens were planed in thickness.
For the compression tests perpendicular to grain the dimensions of the specimens were taken like given in EN 408 and the size of the specimens for the compression tests parallel to grain was: $\ell\ b \cdot h = 180 \cdot 30 \cdot 30 \text{mm}^3$. This means that the compression tests parallel to grain have to be regarded as tests with small clear specimens.
Tension tests were executed on boards with $\ell \cdot b \cdot h = 2800 \cdot 135 \cdot 30 \text{mm}^3$.

Moisture content

Apart from the bending specimens all other specimens were conditioned in standard climate and the effective moisture content was determined by the oven-dry method (EN 13183-1). Under identical climatic conditions TMTB shows significantly lower moisture content than untreated beech. At standard climate (20°C, 65%r.h.) the moisture content varied between 5% and 6.5% compared to around 12% expected for untreated beech. Therefore the effect of moisture content on strength and stiffness parameters within service-classes 1 to 3 can be assumed to be less pronounced than for untreated wood. In consequence the tested strength and stiffness were not adapted to reference moisture contents.

Procedures

The characteristic density was determined from mass of the entire specimens divided by their volume prior to testing.
Before the bending tests were executed, the dynamic MOE E_{dyn} was determined in order to verify the possibilities for future machine grading of TMTB. The ultrasonic device "Sylva Test" was used to determine the speed of sound v within each specimen. Together with the density ρ measured at the same time it was possible to determine E_{dyn} using the following equation:

$$E_{\text{dyn}} = \rho \cdot v^2 \tag{1}$$

The bending, tension and compression tests were executed according to EN 408.

RESULTS AND DISCUSSION

Density ρ

The boxplots shown in Fig. 1 represent the density of the beams that were used for the bending tests. The decrease in density due to the "forte" heat treatment can be estimated on base of the samples TMTB2 and Beech 2 and added up to about 12% at the mean level. For the determination of the characteristic density no adjustments for moisture content and size were made. The characteristic density was calculated to be: $\rho_k = \underline{580 \text{ kg/m}^3}$. This allows a classification of TMTB into strength class D35 whereas the mean density of 650 kg/m^3 only permits to assign TMTB to strength class D30.

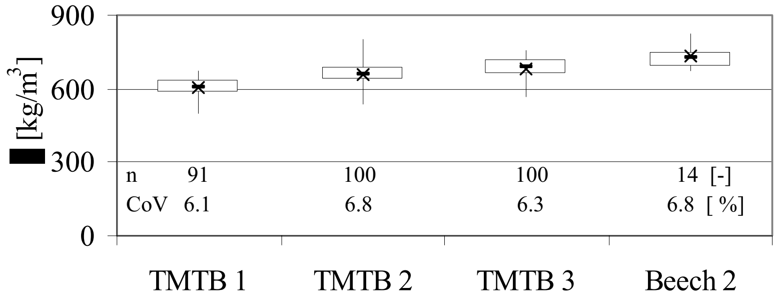


Figure 1: Density of three TMTB samples and an untreated beech sample. The mean moisture content of the TMTB samples varied between 5.5% and 6.5%, in the untreated beach sample the mean moisture added up to 13.2%

Bending strength f_m

The TMTB square-cut beams showed a brittle failure mode. A lot of the specimens failed almost explosively accompanied by the development of a small wood dust cloud and several small sized timber particles emitting from the beam. The ten specimens per sample that showed the lowest bending strength were analysed visually in order to obtain information about possible reasons for the low strength values. General or local significantly increased angles of grain at the failure area could be observed on several of these specimens, however no visual indicators for the low strength of other beams could be found.

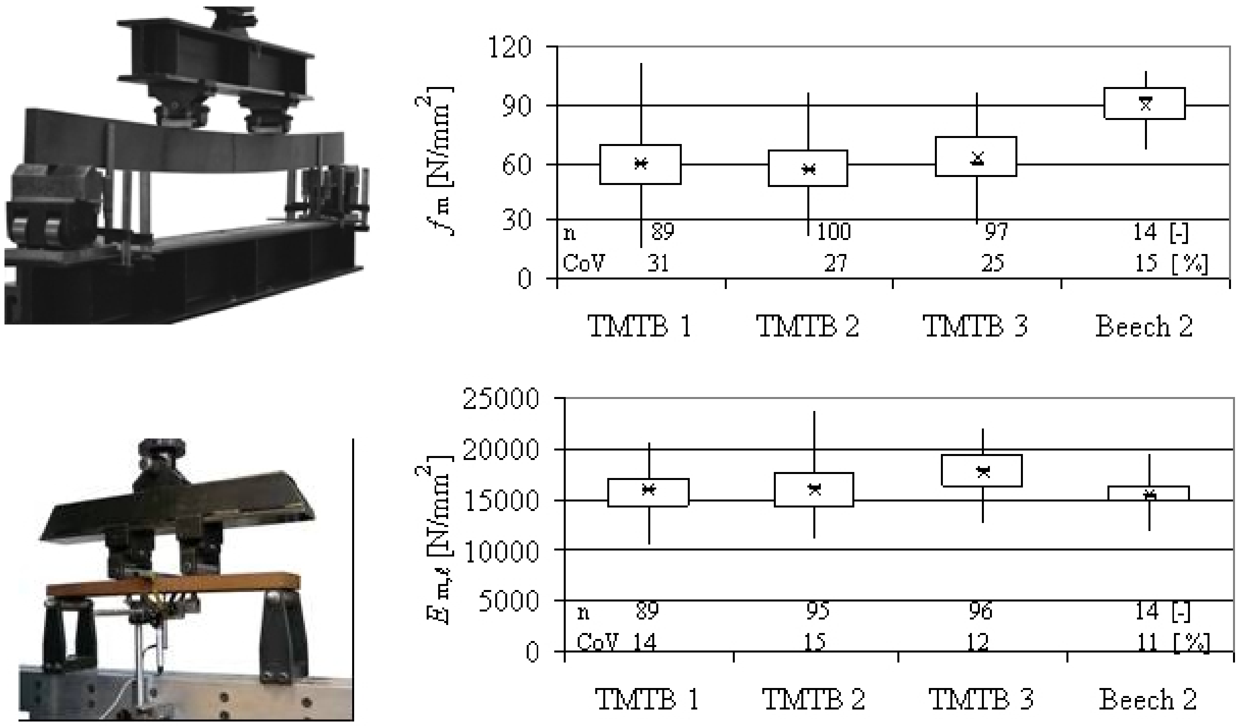


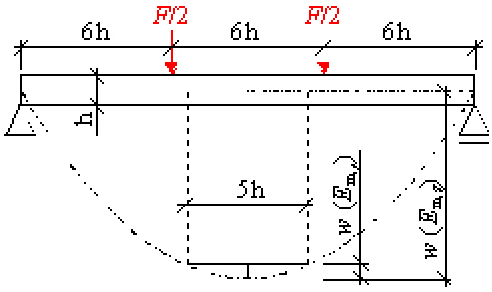
Figure 2: Bending strength f_m and bending MOE $E_{m,\ell}$ of three TMTB sample and one untreated beech sample

The mean bending strength of TMTB with the mentioned heat treatment reaches only about 65% of the mean bending strength of untreated beech (Fig. 2). It has to be kept in mind that the shown reference sample (so far) consisted of only 14 tested specimens, however preliminary tests with

small sized defect free specimens showed a similar drop in mean bending strength. Decisive for structural applications are 5-percentile values and at this level the drop exceeding 50% is even much more pronounced. This goes in line with much higher strength variations within the treated samples compared to the untreated sample.
Following the identification of the 5-percentile bending strength of each sample with the application of the relevant factors k_h and k_ℓ (EN 384) the overall characteristic bending strength was determined under the consideration of k_s and k_v factors (EN 384) to be: $f_{m,k}$ = 30.9N/mm². This bending strength refers to strength class D30 according to EN 338.

Bending stiffness E_0

The bending MOE was determined as global MOE $E_{m,g}$ and as local MOE $E_{m,\ell}$ according to EN 408. *Fig. 2* displays the local MOE results.The stiffness of treated and untreated beech (sample 2) do not show a significant difference. In EN384 the determination of the MOE parallel to grain E_0 is given as a function on base of a linear regression between $E_{m,g}$ and $E_{m,\ell}$ illustrated as dashed line in Fig. 3. The main reason for this procedure is that deflections which result in global MOE are easier to measure than deflections for the determination of the local MOE. Fig. 3 contains also the measured data and the respective linear regression (continuous line). A linear regression without offset (intercept = 0) fits the data similarly ($E_{m,\ell} = 1.15 \cdot E_{m,g}$, $R^2 = 0.896$) and demonstrates that the local MOE exceeds the global MOE by about 15%.



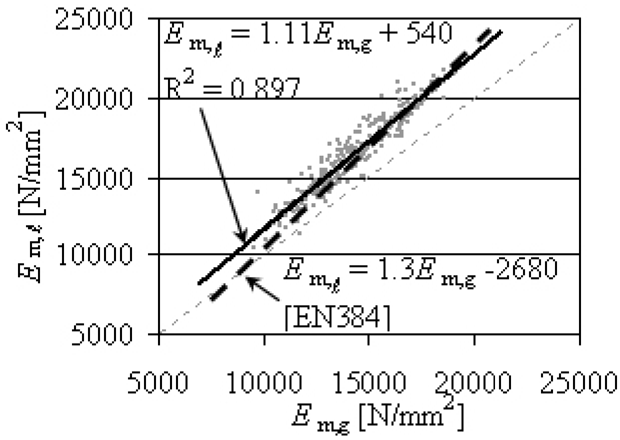


Figure 3: Measuring principle and correlated results for local ($E_{m,\ell}$) and global ($E_{m,g}$) bending MOE of all three TMTB samples

The data analyse was made according to EN 384 but adapted in so far as additionally the measured $E_{m,\ell}$ was taken to determine $E_{0,mean}$.

- On base of mean local MOE: $E_{0,mean} = \bar{E}_{m,\ell}$ = 16570 N/mm² (2)
- On base of mean global MOE (EN 384): $E_{0,mean} = 1.3\bar{E}_{m,g} - 2860$ = 15980 N/mm² (3)

These MOE refer to strength class D50 according to EN 338. The 5-percentile value of the local MOE added up to $E_{0,05} = E_{m,\ell,05}$ = 13150 N/mm² which also fits TMTB into strength class D50.

Tension strength $f_{t,0}$ and stiffness $E_{t,0}$ parallel to the grain

The tension strength $f_{t,0}$ and stiffness $E_{t,0}$ parallel to grain were determined with preliminary tests on one TMTB sample consisting of 42 boards. One part of each board was used in tension, the other part for 4-point bending tests (flatwise) in order to be able to compare bending and tension strength of the specimens. About 40% of all tension failures appeared partly or completely within the clamping jaws of the tension machine which apparently affected the observed tension strength. Another important observation was the fact that more than 25% of all boards failed exactly at the spot where the strain gauges were fixed with (tiny) screws. These observations indicate that the used TMTB is very susceptible to stress concentrations and stresses perpendicular to grain which is likely to have a negative effect on the performance of joints in TMTB.

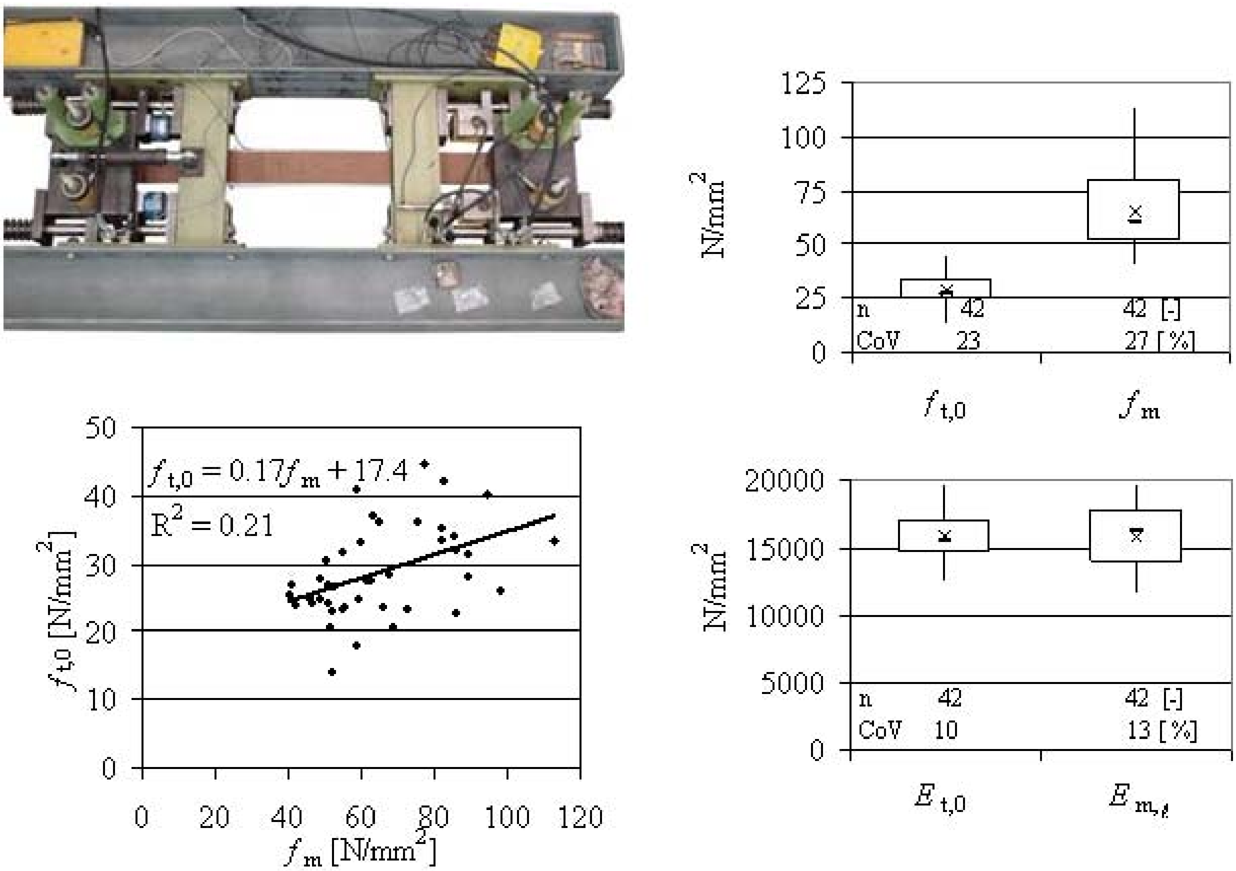


Figure 4: Tension strength $f_{t,0}$ and tension MOE $E_{t,0}$ parallel to the grain compared to (flatwise) bending strength f_m and MOE $E_{m,\ell}$ of one TMTB sample consisting of n = 42 boards

A comparison of the bending and tension properties showed that tension and bending strength correlate only marginal (R^2 = 0.21) for all boards and moderate (R^2 = 0.40) for the boards which did not fail within the clamps. The bending and tension MOE were at the same level and showed a good linear correlation (R^2 = 0.64). The European standard EN 384 states that for a given strength class the characteristic tension strength can be taken as 60 percent of the characteristic bending strength. Based on a comparison of the 5-percentiles found in our tests it can be seen that with:

$$f_{t,0,05} / f_{m,05,corr} = 18.1 / 29.7 = \underline{0.61} \tag{4}$$

the determination of the tension strength on base of the bending strength at the 5-percentile level can be confirmed.. For the comparison the bending strength $f_{m,05}$ was corrected to $f_{m,05,corr}$ with factor k_h acc. EN 384 to account for the reduced specimen depth in flatwise bending.
The observed 5-percentile tension strength $f_{t,0,05}$ = $\underline{18.1\ \text{N/mm}^2}$ implies a possible allocation of TMTB to strength class D30 which has to be confirmed by further tests however.

Compression strength perpendicular and parallel to grain

Table 1: Compression strength perpendicular $f_{c,90}$ and parallel $f_{c,0}$ to grain of the TMTB 1 sample

		$f_{c,90}$	$f_{c,0}$
ℓ x b x h	[mm]	70 x 45 x 90	180 x 30 x 30
n	[-]	91	90
Mean	[N/mm^2]	9.37	66.3
StDev	[N/mm^2]	1.72	7.2
CoV	[-]	0.18	0.11
Max	[N/mm^2]	17.2	83.9
Min	[N/mm^2]	6.33	47.7
q05	[N/mm^2]	7.03	54.5

According to EN 384 compression strength parallel to grain $f_{c,0}$ can be determined on base of the characteristic bending strength. An estimation was made using the 5-percentile bending strength of sample TMTB 1, $f_{m.05}$ = 30.4 N/mm^2. The characteristic compression strength parallel to grain should then be:

$$f_{c,0,05} = 5 \cdot (f_{m,05})^{0.45} = 5 \cdot 30.4^{0.45} = \underline{23.2\ \text{N/mm}^2} \qquad (5)$$

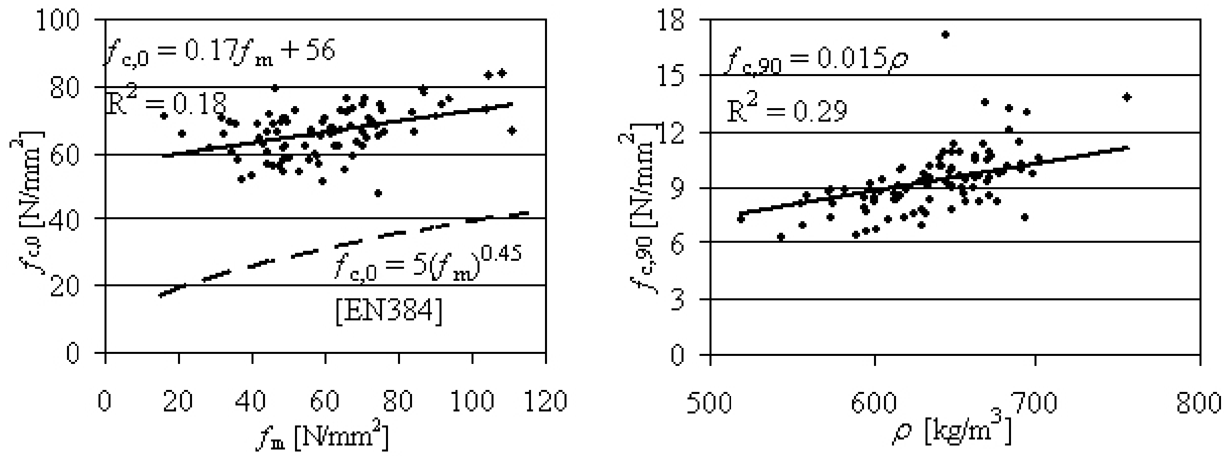


Figure 5: Compression strength parallel to grain $f_{c,0}$ in relation to bending strength f_m (left) and compression strength perpendicular to grain $f_{c,90}$ versus density ρ (right)

The observed compression strength parallel to grain of TMTB sample 1 exceeded this by far (see Table 1 and Fig. 5, left). On base of the 5-percentile strength $f_{c,0,05}$ = 54.5 N/mm^2 TMTB would fit into the highest strength class D70. This high compression strength parallel to grain has to be attributed mainly to the fact, that small clear specimens were used. The use of small clear specimens is permitted for hardwoods according to EN 384, however it is proposed not to use these high values for respective structural calculations. It is planned to set-up a test program for the determination of $f_{c,0}$ on full cross sections.

The performance of TMTB regarding compression perpendicular to grain differed strongly from its good performance in compression parallel to grain. The observed 5-percentile compression strength $f_{c,90,05}$ = 7.03 N/mm^2 implies that TMTB cannot even be allocated to the lowest hardwood strength class D30 (EN384: $f_{c,90,k}$ = 8.0 N/mm^2).
A linear regression (with intercept = 0) of the correlated compression strength perpendicular to grain and density corresponds well with the standard (EN 338: $f_{c,90,k} = 0.015\rho_k$) as can be seen in Fig. 5, right. However, based on a calculation of the 5-percentile of the sample density ρ_{05}, the 5-percentile of the sample compression strength perpendicular to the grain $f_{c,90,05}$ of TMTB would be overestimated:

$$f_{c,90,05}/\rho_{05} = 7.03/566 = \underline{0.012 < 0.015} \qquad (6)$$

Grading

As mentioned in the material section, the timber was graded visually. The timber was of a superior visual quality in particular regarding knots. However, the bending strength showed high variations and there was no clear evidence for the low strength values of certain specimens. Therefore the possibility of machine grading was evaluated. The bending strength was correlated to data that are often used for machine grading: stiffness, density and ultrasonic speed of sound.

R^2	ρ	v	E_{dyn}	$E_{m,g}$	$E_{m,\ell}$
v	0.07				
E_{dyn}	0.60	0.66			
$E_{m,g}$	0.60	0.52	0.88		
$E_{m,\ell}$	0.45	0.65	0.87	0.90	
f_m	0.06	0.23	0.22	0.25	0.27

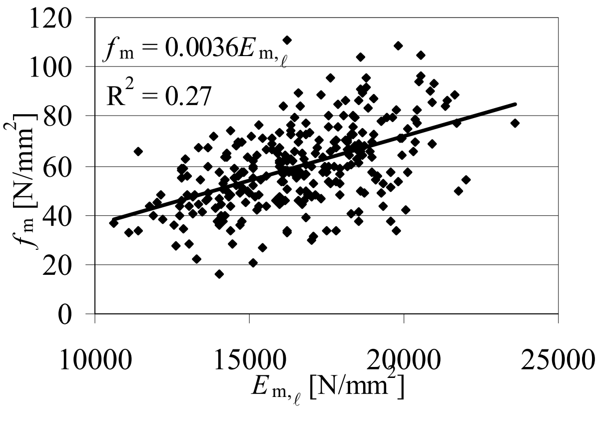


Figure 6: Matrix of coefficients of correlation R^2 of several possible parameters to grade TMTB and a graph showing the linear correlation of measured local MOE $E_{m,\ell}$ and bending strength f_m as an example

The correlation matrix in Fig. 6 leads to the following conclusion:
The measured static MOE's $E_{m,g}$ and $E_{m,\ell}$ can be well predicted by the dynamic MOE E_{dyn}. Compared to each other the two single parameters speed of sound v and density ρ that influence the dynamic MOE have a more or less similar importance for the prediction of the static MOE but correlate less good with static MOE than if they are combined in E_{dyn}. None of the measured parameters allows a satisfying estimation of the bending strength f_m as it is indicated by the low coefficients of determination in the bottom line of the matrix in Fig. 6. Ultrasonic speed of sound, static and dynamic MOE correlate with bending strength on a similar low level compared to each other whereas density is found to have no influence on the bending strength of TMTB. As an example the graph in Fig. 6 shows the dependence of f_m on $E_{m,\ell}$. An important factor for the low linear correlations might be the good wood quality and in particular the absence of knots. As knots would have a strong influence on bending strength as well as bending MOE the correlation might have been more pronounced under their presence. However it is likely that MOE and strength would come further down with knots. Regarding the relatively low strength values of the tested samples it is questionable if TMTB with even lower strengths would be an interesting product on the market for structural timber.
Another aspect of timber quality and grading has to be addressed. The thermal treatment of the wood is one more important parameter that must be added to the existing visual and possible machine grading parameters. The great variations of the strength values might also be partly attributed to a more or less inhomogeneous treatment of the specimens within one batch. This however is difficult to verify and therefore it is proposed that grading has to take place twice: once before and once after the thermal modification process.
For the end user, e.g. an engineer or carpenter, the quality of TMTB and its big variations in strength have several consequences. On the one hand the big variations of strength question if the known partial factors, e.g. γ_M according to EC5, can be applied unchanged for this material as well. On the other hand a material of a superior quality has to be used – and to be paid for– in order to achieve only average strength values. With the tested grading procedures it is not possible to distinguish between low and high strength TMTB which would have been a great contribution for an economical use of this material.

CONCLUSIONS

Several samples of TMTB have undergone standard tests in order to investigate their structural behaviour and to assign this timber to one ore more strength classes according to EN 338. The status of the biggest part of the tests has to be regarded as preliminary because not all of the samples as well as not all structural parameters have been tested yet. From the tests executed so far it can be concluded that:

- The stiffness values of TMTB are similar or slightly exceed those of untreated beech timber and thus could lead to a classification of TMTB into high strength classes, e.g. D50.
- The strength values of TMTB are lower than those of untreated beech timber and thus could lead to a classification of TMTB into low strength classes, e.g. D30.
- The conclusions mentioned above suggest not to assign TMTB to existing EN 338 strength classes but to state discrete properties for its structural use.

- The brittle behaviour of the material and the big variation of the test values is the main problem regarding its strength properties. Poor rigidity parallel to grain and great sensitivity to stress concentrations are likely to limit the structural use of TMTB.
- Conversion factors to determine unknown strength and stiffness properties as given in e.g. EN 384 can not be used for TMTB.
- The TMTB tested up to now was of a high visual grade. It can be assumed, that in particular the strength properties of TMTB of a lower visual grade (timber containing knots and other defects) might further decrease compared to the material tested so far.
- The prediction of the static MOE of TMTB by ultrasonic together with density measurements works well. However, the possibility of (bending) strength prediction is only limited. In consequence the application of machine grading of TMTB might be difficult.

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