

# Thermally Modified Beech as a Structural Material: Allocation to European Strength- Classes and Relevant Grading Procedures

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**Keywords:** Beech, grading, strength class, structural timber, thermally modified timber

## ABSTRACT

In this paper the evaluation of strength and stiffness properties of 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. All properties have to be determined by tests, whereof density, bending and compression tests are discussed in this paper. 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. On the basis of good stiffness properties but weak strength properties of TMTB 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. Because 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 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 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 and to a quality controlled heat treatment process.

## 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) strength 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 strength 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 (Mitteramskogler 2009). This thermal treatment has to be considered as being an intensive modification. Detailed data for the respective treatment are confidential and thus not published. The used combination of modification temperature and time is selected in such a way that durability class 3 can be reached according to preliminary tests. Mitteramskogler also offers beech wood that underwent a stronger thermal modification under the brand "Buche forte exterior" and guarantees durability class 1 (Mitteramskogler 2009).

### *Specimens*

There were  $n = 100$  square-cut TMTB specimens per sample available for testing. The nominal specimen 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 length of 2565mm, 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 as given in EN 408 and the size of the specimens for the compression tests parallel to grain was:  $\ell \cdot b \cdot h = 180 \cdot 30 \cdot 30 \text{ mm}^3$  and are therefore classified as tests with small clear specimens.

### **Moisture content**

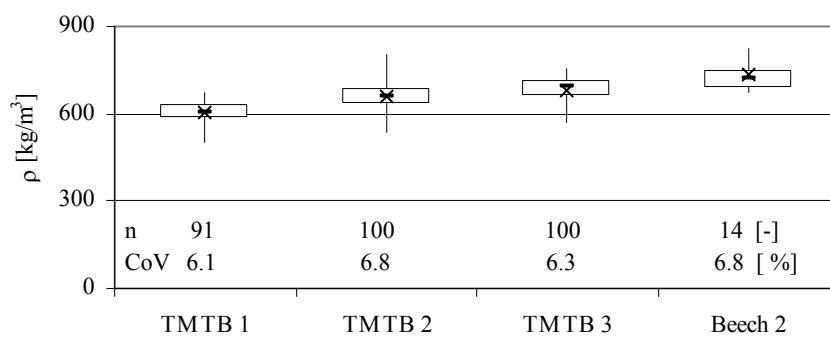
Apart from the bending specimens all other specimens were conditioned in standard climate and the effective moisture content was determined by the oven-dry method (EN 13183-1). Under identical climatic conditions TMTB shows significantly lower moisture content than untreated beech. At standard climate ( $20^\circ\text{C}$ , 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. This could be verified on base of tests with small clear specimens. In consequence the tested strength and stiffness values were not adapted to a reference moisture content.

### **Procedures**

The characteristic density was determined from mass of the entire bending specimens divided by their volume prior to testing. Before the bending tests were executed, the dynamic MOE  $E_{\text{dyn}}$  was determined in order to verify the possibilities for future machine grading of TMTB. The ultrasonic device "Sylvatest" was used to determine the longitudinal speed of sound  $v$  within each specimen. Together with the density  $\rho$  measured at the same time it was possible to determine  $E_{\text{dyn}}$  using the following equation:  $E_{\text{dyn}} = \rho \cdot v^2$  (Goens 1931). The bending and compression tests were executed according to EN 408. The characteristic strength and stiffness parameters were calculated according to EN384.

## **RESULTS AND DISCUSSION**

### **Density $\rho$**



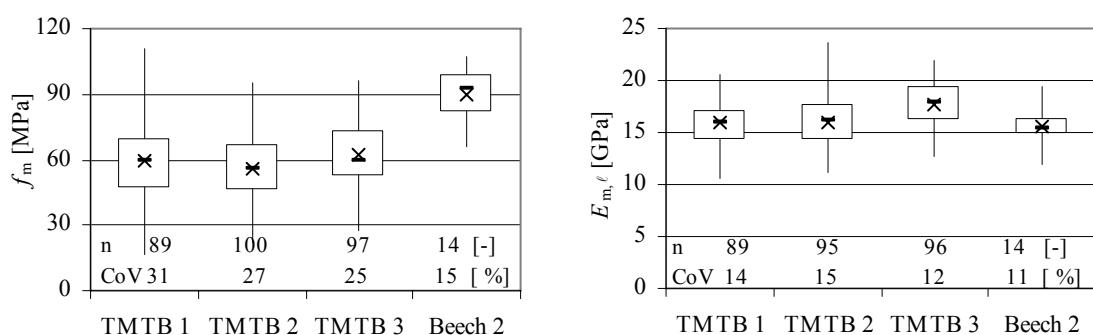
**Figure 1:** Density of three TMTB samples and one untreated beech sample. The mean moisture content of the TMTB samples varied between 5.5% and 6.5%, in the untreated beech sample the mean moisture added up to 13.2%.

The boxplots shown in Figure 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  $\rho_k = 580 \text{ kg/m}^3$ . This allows a classification of TMTB into strength class D35 whereas the obtained mean density of  $650 \text{ kg/m}^3$  only refers to strength class D30.

### 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 samples 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 (Figure 2). It has to be kept in mind that the shown reference sample 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 which is indicated by the comparably high CoV's. Following the identification of the 5-percentile bending strength of each sample with the application of the relevant factors  $k_h$  and  $k_\ell$  (EN 384) the overall characteristic bending strength was determined under the consideration of  $k_s$  and  $k_v$  factors (EN 384) to be:  $f_{m,k} = 30.9 \text{ MPa}$ . This bending strength refers to strength class D30 according to EN 338. It has to be remarked, that within the sample 1 the minimum observed bending strength added up to only 16.2 MPa.

### 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. Figure 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  $E_{m,\ell}$  as follows:  $E_0 = 1.3E_{m,g} - 2.68 \text{ [GPa]}$ . Our data fitted

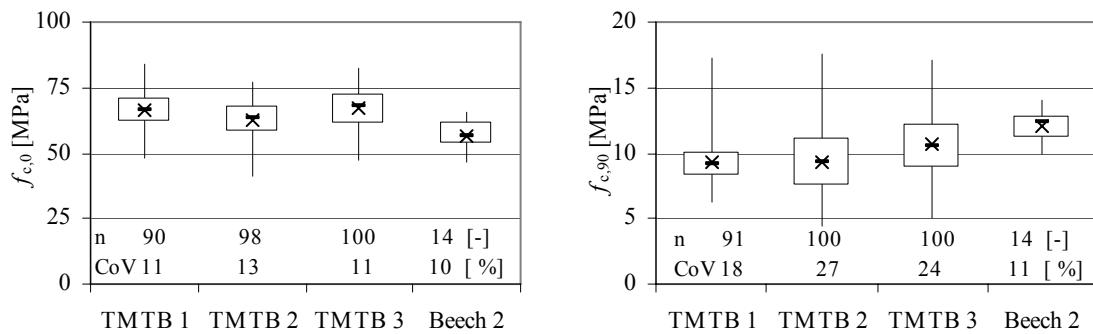
well ( $R^2 = 0.896$ ) to a linear regression without offset:  $E_{m,\ell} = 1.15 \cdot E_{m,g}$  and shows that the local MOE exceeds the global MOE by about 15%. The data analyse was made according to EN 384 but adapted in so far as additionally for comparison the measured  $E_{m,\ell}$  was taken to determine  $E_{0,mean}$ .

$$\begin{array}{lll} \text{On base of mean local MOE: } & E_{0,mean} = E_{m,\ell} & = 16.6 \text{ GPa} \\ \text{On base of mean global MOE (EN 384): } & E_{0,mean} = 1.3E_{m,g} - 2.86 & = 16.0 \text{ GPa} \end{array}$$

These MOE refer to strength class D50 according to EN 338. The 5-percentile value of the local MOE added up to  $E_{0,05} = E_{m,\ell,05} = 13.2 \text{ GPa}$  which also fits TMTB into strength class D50.

### **Compression strength parallel $f_{c,0}$ and perpendicular $f_{c,90}$ to grain**

In Figure 3 the results of the compression tests are shown. It can be observed, that the compression strength parallel to grain of the treated and untreated samples do not differ importantly as they do for other strength properties.

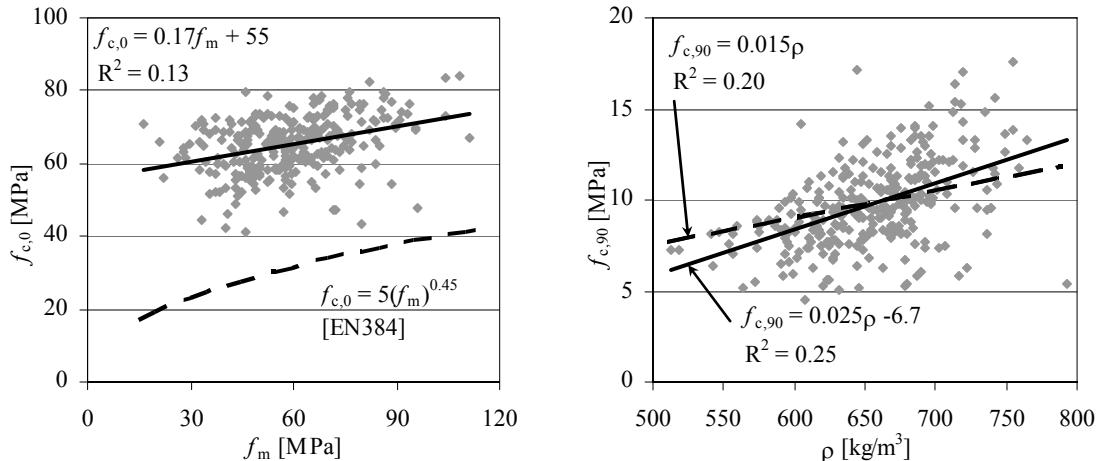


**Figure 3: Compression strength parallel  $f_{c,0}$  and perpendicular  $f_{c,90}$  to grain of three TMTB and one untreated beech sample sample.**

According to EN 384 compression strength parallel to grain  $f_{c,0}$  could be determined on base of the characteristic bending strength. With the observed  $f_{m,k} = 30.9 \text{ MPa}$  the characteristic compression strength parallel to grain should be:  

$$f_{c,0,k} = 5 \cdot (f_{m,k})^{0.45} = 5 \cdot 30.9^{0.45} = 23.4 \text{ MPa}$$

The observed compression strength parallel to grain of TMTB exceeded this by far (see Figure 3 and Figure 4, left). On base of the observed  $f_{c,0,k} = 44.3 \text{ MPa}$  TMTB would fit into the highest strength class D70. This high compression strength parallel to grain has to be attributed 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. The performance of TMTB regarding compression perpendicular to grain differed strongly from its good performance in compression parallel to grain. The observed compression strength  $f_{c,90,k} = 6.03 \text{ MPa}$  implies that TMTB cannot even be allocated to the lowest hardwood strength class D30 (EN384:  $f_{c,90,k} = 8.0 \text{ MPa}$ ) but on the other hand exceeds the compression strength of the highest softwood strength class C50.



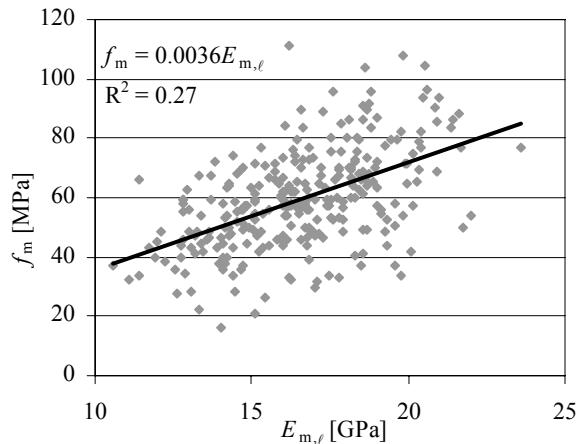
**Figure 4:** Compression strength parallel to grain  $f_{c,0}$  in relation to bending strength  $f_m$  (left) and compression strength perpendicular to grain  $f_{c,90}$  versus density  $\rho$  (right)

In general the 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 Figure 4, right. However, if this calculation is done discretely at the 5-percentile level the characteristic compression strength perpendicular to the grain  $f_{c,90,k}$  of TMTB would be overestimated:  $f_{c,90,k}/\rho_k = 6.03/580 = 0.010 < 0.015$ . Therefore at least this conversion given in EN384 cannot be used for TMTB.

### 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 (Figure 5, left).

$R^2$	$\rho$	$v$	$E_{dyn}$	$E_{m,g}$	$E_{m,\ell}$
$v$	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 5:** 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  $f_m$  ( $n = 280$ ) as an example for the difficulty to strength-grade TMTB.

The measured static MOE's  $E_{m,g}$  and  $E_{m,\ell}$  can be well predicted by  $E_{dyn}$ . Compared to each other the two single parameters speed of sound  $v$  and density  $\rho$  that influence the

dynamic MOE have a more or less similar importance for the prediction of the static MOE. 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 Figure 5. 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 Figure 5 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 on bending MOE the correlation will have been more pronounced under their presence. However it is likely that MOE and strength would come further down with knots. This was verified by results of preliminary tests. However, regarding the relatively low strength values of the tested samples it is questionable if TMTB with an even lower strength 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 be carried out twice: once before and once after the thermal modification process. It might be even required to apply proof-loading of TMTB members before their use in structures. 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.  $\gamma_M$  for solid timber according to EC5, can be applied unchanged for this material as well. On the other hand a rawmaterial 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 a strength class according to EN 338. The status of some parts of the tests have 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 to 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 significantly limit the structural use of TMTB.

- Conversion factors to determine unknown strength and stiffness properties as given in EN 384 for solid wood cannot 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.
- A strict quality management for the thermal modification process has to be installed in order to obtain a reliable quality of the structural TMTB products.

Overall it looks like the application of TMTB as a structural material in an important quantity will be difficult to realize. Good stiffness properties (that are often decisive for the design of a timber structure) face relatively low strength properties which in addition vary strongly. The brittleness of the material and its susceptibility to stress concentrations and multidimensional stresses are other important downsides that will come into play when it gets to the load-bearing behaviour of joints. Therefore it is suggested to use TMTB only for low loaded structural members.

## ACKNOWLEDGEMENTS

The presented work is financially supported by the European Commission under contract No. NMP2-CT-2005-011799 (HOLIWOOD project). The author would like to thank Mitteramskogler GmbH for the supply of the material and the technical staff of Empa Wood Laboratory for the support in test preparation and execution.

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