1998:327

LULEÅ TEKNISKA UNIVERSITET

MASTER'S THESIS

Non-destructive testing of particleboard with ultra sound and eigen frequency methods

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Civilingenjörsprogrammet

1998:327 • ISSN: 1402-1617 • ISRN: LTU-EX--98/327--SE

1998:327CIV

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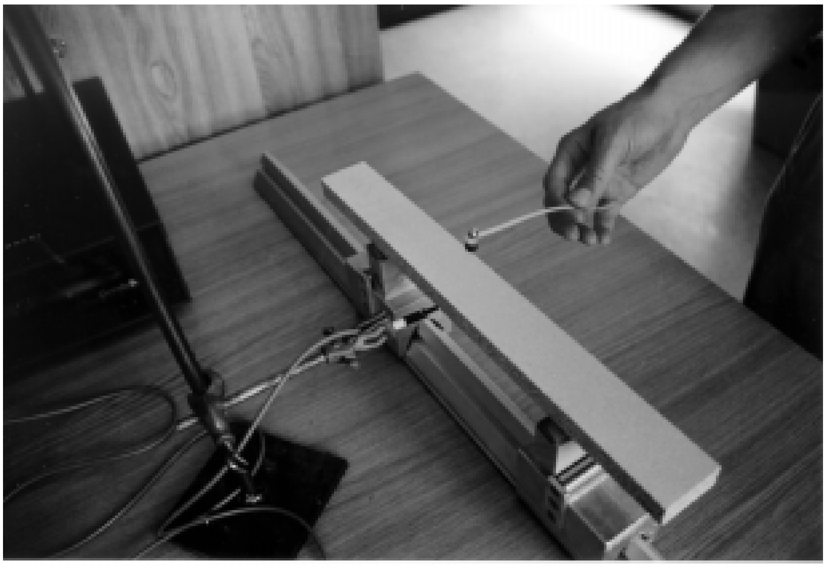

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1998:327CIV • ISSN: 1402 - 1617 • ISRN: LTU - EX--1998/327--SE

Preface

This master’s thesis is the final moment in the Mechanical Engineering program specialising in wood technology, at Luleå University of Technology. The theme for this work was provided by ”Professur für Holzwissenschaften, ETH Zurich” and covers non-destructive testing of the elastic and fracture properties of particleboard with ultrasound- and eigen frequency methods.

To all those who have made this work possible, I would like to place a warm "Thank you!". This especially to Prof. L.J. Kucera and Dr. Peter Niemz at ETH who arranged the theme, and to Thomas Lott for his help in the practical matters. Others that deserve to be mentioned here are Magnus Berglund for housing during the writing of this thesis, and Johan Oja and Olle Hagman for their help with models, theory and corrections. Beyond those already listed I would also like to thank Nicholas Zeuggin for helping me into Switzerland and lending me time, friendship and, occasionally, his car.

Skellefteå, November 1998

Fredrik Grundström

Abstract

In the production of particleboard, different properties of the board have to be measured in order to keep the board quality within required limits. Non-destructive methods for this purpose include ultra-sonic testing and eigen frequency testing. These methods have been proposed for measuring of the strength of the board after pressing, for process control purposes. The ultra sound velocity and eigen frequency methods have been proved to be good instruments for doing this. The results show that Young's modulus and bending strength can be predicted with high accuracy with these methods. Internal bond can only be predicted with poor to fair accuracy with normal regression models. The use of multivariate models most often give better and more reliable models for Young's modulus and bending strength and gives much better predictions of the internal bond. Multivariate models are best suited for complex predictions and if the prediction variables are weak.

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1. Introduction

This master's thesis is the final moment in the Mechanical Engineering program, specialising in wood technology, at Luleå University of Technology. The objective for this thesis is the non-destructive testing of the elastic properties of particleboard using ultrasound- and eigen frequency methods.

1.1 Background

Particleboard has to meet certain performance demands. These demands regard properties such as bending strength and internal bond as well as other properties. In normal production, random samples are taken to determine these properties. The most commonly used reference test methods are destructive and very time-consuming, and only a very small part of the total production is tested. This means that production with false process settings could proceed for a long time before the error is noticed. This might lead to large amounts of reject boards or boards with inferior quality, which brings on large costs for the board manufacturer.

To evade this problem, equipment for fast testing has been developed, which conducts the tests automatically. In this case, the test process proceeds much faster but is still measured in hours. For this reason, a non-destructive test method for prediction of the properties of particleboard, which can be used directly after the pressing, is a desired goal. The possibility to determine the properties of the board with non-destructive methods on-line after the press and therefore be able to control the process quality better could bring great advantages in terms of a reduced amount of reject boards and quality losses.

1.2 Aim and purpose of the study

The purpose of the study is to determine the efficiency of two non-destructive test methods, ultra sound velocity- and eigen frequency analysis, and to examine the influence of conditioning on the non-destructive test results. The aim is to develop efficient models for prediction of in-plane bending strength, in-plane modulus of elasticity and the internal bond for the actual particleboard type.

1.3 Extent and delimitation

The study is limited to one specific industrially manufactured particleboard type. The work includes test design, data gathering and analysis and the development of models for prediction of internal bond, bending strength and Young's modulus. These models are based on sound velocity and the fundamental bending eigen frequency in and perpendicular to the plane as well as the physical properties of the actual particleboard type. For the testing of large board samples, the longitudinal eigen frequency is also used. The thesis also includes an evaluation of the influence of conditioning.

1.4 Theory and previous works

1.4.1 Non-destructive testing

A non-destructive evaluation of particleboard properties can be conducted in a number of ways. Some of the methods are:

- Measurement of the density profile.
- Eigen frequency testing for prediction of the different elastic properties of the board.
- Measurement of the ultra sound propagation time parallel and perpendicular to the board plane for prediction of the bending strength (MOR), Young's modulus (MOE) and internal bond (IB).
- Ultra sound amplitude analysis for delamination fault detection.
- Ultra sound frequency and amplitude analysis for IB prediction.

The only method that is industrially used on a larger scale in an on-line application is the non-contact delamination fault detection with ultra sound (by GreCon for example).

1.4.2 Eigen frequency analysis

Elastic bodies can be brought to vibrate in two ways

- Through periodic outer forces, which cause forced vibrations from which information is gathered by the different reactions at different frequencies. An example is when the periodic force frequency is the same as the natural frequency of the board, which causes resonance.
- Through a single impulse that causes free vibrations in the body. These vibrations have the eigen frequencies of the body. These vibrations consist of both a fundamental vibration mode as well as higher modes (overtones). The higher vibration modes decline faster than the fundamental mode because of inner friction in the material, which makes it possible to isolate the fundamental mode effectively.

Various methods of finding different elastic properties of a body, using its eigen frequency, are possible. These methods differ on three points (ASTM standard C-1259 [2]):

- Support/restraint location
- Excitation point location
- Signal pick-up point

Support/restraint location: The supports are placed in the nodal points for the desired vibration mode. When vibration in restricted boards is studied, the restraint location differs.
Excitation point location: The excitation point is placed in an anti-node for the desired vibration mode.
Signal pick-up point: The signal receiver is placed where the vibration mode sought for is easiest to measure. When a contact method is used, this should be close to a vibration node so that the test specimen does not become mass loaded by the signal pick-up needle, which could affect the frequency.

These different methods enables the measuring of the dynamic Young's modulus, dynamic shear modulus and Poisson's ratio in different planes of the test specimens.

The two main methods for eigen frequency testing of elastic properties are:

- Measurement of the natural frequency in a restricted board (clamped with one free end).
- Measurement of the eigen frequency of a free sample on supports, where the supports are placed in the vibration nodes.

This work concerns the fundamental eigen frequency of free samples for in-plane and out-of-plane flexure. This method has been derived by Görlacher [5], for the examination of the dynamic Young's modulus in wood. He found the method to be sufficiently exact for specimens with a length/height ratio higher than 15, when the shear influence becomes neglectible for moderate bending deflections.

Niemz, Kucera and Bernatowicz [18] have used this method for a non-destructive evaluation of the elastic properties of MDF. They reported a fair correlation between dynamic Young's modulus from eigen frequency, and static Young's modulus from DIN-tests with R^2=0,48. Eigen frequency measurements were reported to give 15-20% higher values of Young's modulus than DIN-tests. This difference was assumed to depend on the density profile in particleboard, since the theory applies to homogenous materials.

1.4.3 Ultra sound parallel to board plane

Ultra sound that propagates through a medium has a velocity that corresponds to the density in the medium. Since the density has a very large influence on the bending strength and Young's modulus, this velocity can be used to predict these properties. The dynamic modulus of elasticity is computed with the following well-known formula used for isotropic materials (Krautkrämer [13]).

$$MOE_{dyn} = \rho \times v^2 \left(\frac{(1+\mu)(1-2\mu)}{(1-\mu)} \right) \qquad \textit{(Equation 1)}$$

MOE_{dyn} - Dynamic Young’s modulus [MPa].
ρ - Density [g/cm^3].
v - Ultra sound velocity [m/s].
μ - Poisson’s ratio.

Since Poisson’s ratio is hard to determine, the following simplified equation is used:

$$MOE_{dyn} = \rho \times v^2 \qquad \textit{(Equation 2)}$$

Research has mostly been done on ultra sound velocity perpendicular to the board surface for the prediction of IB. For sound velocity parallel to the board plane, Niemz and Poblete [17] have shown that there is a fair correlation (R^2=0,55) between bending strength and the sound velocity, as well as a correlation between sound velocity and Young’s modulus (R^2=0,24). This method has not been utilised in the industry so far.

Since the sound velocity increases with increased density, the position of the transducers is important in particleboard with a distinct density profile. Because of the high damping in particleboard and the longer distances that are to be penetrated, transmission measurement (transmitter and receiver placed on opposite sides of the test object) is mostly used (Greubel, Plinke [12]). Due to the high damping of the sound in particleboard, a lower frequency, normally 20-100 kHz has to be used compared to normal applications for isotropic, homogenous materials (0,5-10 MHz) (Greubel, Plinke [12] and Krautkrämer [13]).

1.4.4 Ultra sound perpendicular to board plane

When using the ultra sound velocity perpendicular to the board surface for internal bond strength determination, one must take heed of the density profile. Since the sound propagation time is measured, the velocity is the integral of the sound propagation time over the different layers in the board. As the density decreases the sound velocity decreases and the sound pulse will need more time to pass the layer. This means that the low-density middle layer stands for the largest part of the running time for the sound wave (see figure 1). That is, the middle layer has the greatest effect on the sound propagation time. From this stems the possibility of determining the internal bond with ultra sound. A typical density profile is shown in figure 1.

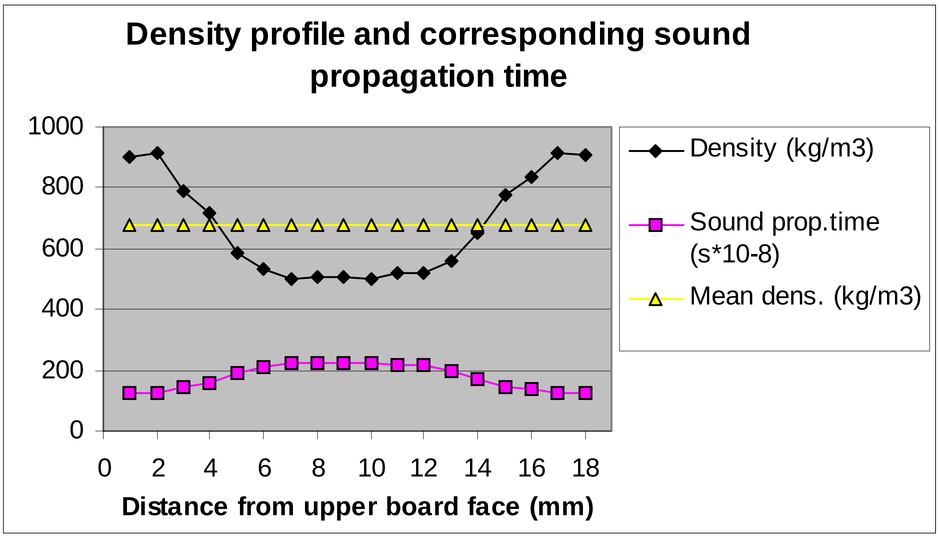

Figure 1: Typical density profile perpendicular to board plane and corresponding sound propagation time for each layer (δy), in the board.

Greubel and Plinke [12] have presented a paper where ultra sound velocity was used for the prediction of the internal bond in sanded boards. They came to the conclusion that the method could be used on still-standing boards under industrial conditions.

Kruse, Bröker and Frühwald [14] have presented a paper where they have used multiple regression for the prediction of the internal bond strength. The variables used were the minimum density from density profile measurements in a 4% interval in the middle layer together with the ultra sound velocity perpendicular to the board plane. This method gave a very good prediction of IB, with an explained variance ranging from R^2=0,53 to R^2=0,98.

In another paper, Kruse, Bröker and Frühwald [15] have evaluated a contact-free ultra sound method as an alternative to contact ultra sound velocity measurement. They found that this method of using frequency and amplitude analysis of defined ultra sound waves, passing through the panel, gave a good prediction of the internal bond in particleboards with a thickness of up to 34 millimetres. The prediction gave an explained variance, for models using mean values from each sample, of R^2=0,90 (sanded boards) and R^2=0,74 (unsanded boards).

2. Material and method

2.1 Material

In this study, 18 and 19 millimetres, three-layer industrial particleboards were tested. The boards were all provided by the same manufacturer and measured in the production plant. The tested boards were mainly intended for usage in the furniture industry. The tested boards had the following parameters:

Wood chip: Hammer milled, 100% softwood

- Face layer (35%): 100% planing chips/saw chips/sanding dust
- Middle layer (65%): 40-50% slabs
  20% wood chip
  20% planing chips/saw chips
  10% solid wood

Adhesive:	Ureaformaldehyde, produced at the plant.	
Adhesive content:	Middle layer:	8-8.5%.
	Face layer:	12-12.5%.
Density (target value):	682 kg/m^3.	
Pressing time/temperature:	280 seconds / 185°C.	

2.2 Test design

Since only one board quality from regular production at the plant was studied, special importance had to be placed upon reaching the maximal possible variation of the board properties within the normal production settings. To achieve this, some facts about the production line had to be considered. These facts provided from the technical staff at the actual plant were:

- The boards become thinner in the lower storeys in the press than in the upper storeys due to uneven pressure between the storeys.
- An uneven pressing made the boards a little denser at one side of the press.

To span the total board density variance in the production in the model, the samples were alternately taken from the top and bottom storeys of the press. Since the density also varied over the board width, the bending samples were taken from different locations in different boards according to the test design described in appendix 1.

2.3 Test method

The test boards were cut out of the raw boards directly after the cooling wheel where the quality control samples are normally cut out. The test procedure followed the main steps below:

First the board edges were trimmed and four strips, 50 mm wide, were cut from the board perpendicular to the direction of production. These strips were tested in a testrob (a fast testing device), two strips before and two strips after conditioning. The tested properties were density, out-of-plane bending strength and internal bond strength.

The remaining part of the test board (137x50 cm) was tested using ultra sound in both directions parallel to the board plane, and longitudinal eigen frequency perpendicular to the direction of production, parallel to the board plane, as described in appendix 6. The temperature, density and measurements of the board were also measured.

The board was cut into test samples both in and perpendicular to the direction of production of the board, since the elastic properties for each direction differs. These samples were tested both before and after conditioning, using the non-destructive methods.

Finally each sample was tested after DIN-EN standards to give a reference value for the measured properties and the moisture content in each sample was determined. The complete test schedule can be found in Appendix 7.

The specimens for the various tests were sawn out of the original test board according to the saw pattern shown in figure 2.

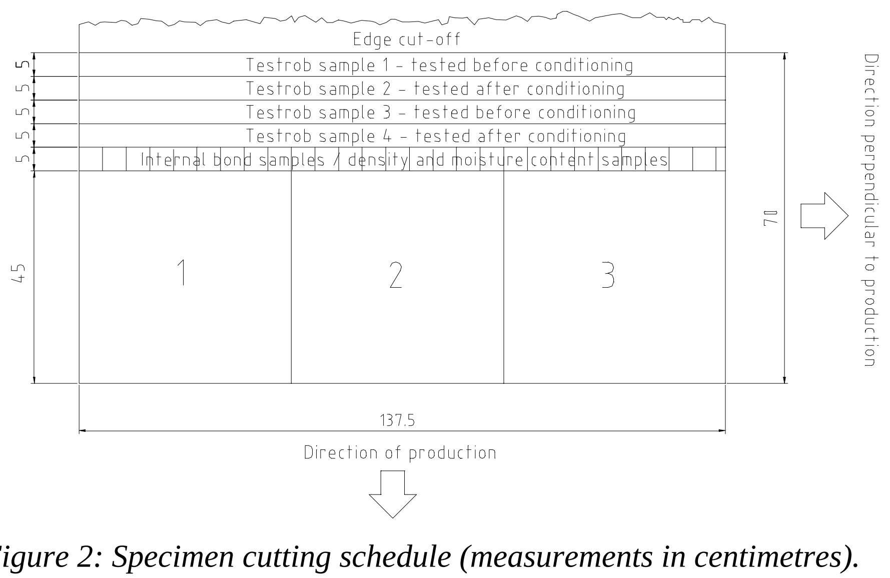

Figure 2: Specimen cutting schedule (measurements in centimetres).

The areas marked 1, 2 and 3 were used for the bending rods. Eight bending test samples were sawn out of two of the three areas, one area for each direction, in- and perpendicular to the direction of production. The positions for the test boards were varied according the test plan (appendix 1).

2.4 PLS modelling and data analysis

PLS analysis is a relatively new tool for multivariate modelling and calibration. The following summary of the method originates from a book on the subject by Martens and Naes [22], the SIMCA user's manual [23], and a master's thesis (Andersson [27]). For papers concerning the theory and applications of PLS analysis, readers might find the works [24], [25] and [26] interesting.

2.4.1 The PLS method

For the multivariate models, the PLS (partial least square) method has been used. PLS is a bilinear regression method. PLS analysis can be utilised for analysis of many variables simultaneously. An advantage of PLS is that it can separate "noise" (irrelevant information) from the information sought for. PLS can also handle correlation between the variables in the model.

Before PLS analysis, a PCA (Principal Component Analysis) is often done. In PCA, uncorrelated principal components (dominating factors) are derived as linear combinations of the original data. The principal components are found by setting the original variables on orthogonal axes in a multidimensional vector space. In the cluster of points that is obtained, the first principal component is fitted to the dominating direction of the cluster. The next principal component corresponds to the second dominant direction, orthogonal to the first. This procedure is repeated for the following principal components. Through a projection of the principal components on a two-dimensional plane, in a "score scatter plot", one gets a good graphical overview of the data set with outliers, groups and other vital information which can easily be detected.

In PLS analysis, the factors (x) are separated from the responses (y). Principal components are calculated for both, and then matched to find the best model. The models can contain one or several responses (y). The models are in the form $y = c_0+a.x_1+b.x_2+\dots$, with one response, as in this study.

The validity of a PLS model is shown through the explained variance (R^2), which shows how much of the variation in the data set that the model explains. $R^2=0$ means that no variance is explained by the model and $R^2=1$ that the entire variation is explained by the model. The variation can consist of useful information as well as "noise". Noise is irrelevant information, which means that a model with $R^2=1$ might not be the best one, since it could also be modelling noise. To determine what is noise and what is useful information, the prediction power (Q^2) of the model is used. This is a measure of the ability of the model to predict the value of y for new observations, not included when making the model. Q^2 is calculated by using cross validation (SIMCA manual [23]).

3. Test methods – theory and utilisation

The DIN-EN test methods used in this study as references for the tests are direct tests to determine the wanted properties. This means that the actual bending strength of the board is measured by loading it until a failure occurs and so on for all properties. The non-destructive methods on the other hand, are indirect methods. This means that one or several properties, which correlate with the property sought for, is measured and used to predict the desired property of the board.

3.1 DIN/EN test method

The most commonly used methods for the determination of particleboard properties are the destructive methods. These are described in the European standards (EN) and are used as reference values for the board properties. The following standards were used in this study:

- DIN-EN 310 - Determination of bending strength and the static modulus of elasticity.
- DIN-EN 319 - Internal bond strength.
- DIN-EN 322 - Moisture content.
- DIN-EN 323 - Density.

3.1.1 DIN-EN 310 Determination of modulus of elasticity in bending and of bending strength

The bending strength and static Young's modulus are determined with a three-point static-bending test. The achieved value of Young's modulus is the apparent and not the real modulus since the test also includes shear stresses.
The test specimens had the following measurements:

Length (l): 450 mm
Width (b):50 mm
Thickness (t): 20 mm (unsanded 19-mm board)

The width between the supports was 400 mm ($20 \times t$).
The deflection was measured with an accuracy of 0,01 mm in the test. The modulus of elasticity was measured twice, and the specimen was turned around for the second test so that it was measured with both faces up. This was made to get a mean value of both directions and reduce possible strength differences caused by uneven build-up between the both face layers. For half of the specimens, the bending strength was tested with the "forming mat side" faced up in the testing machine. The other half were tested with the blank side faced up in the testing machine because of the same reasons as above.

3.1.2 DIN-EN 319 Determination of tensile strength perpendicular to the plane of the board

The internal bond tests were conducted on eleven samples (50x50 mm) per board, evenly distributed over the board width. The test specimens were glued to steel holders using a hot-melt adhesive. The samples were sanded before the test because of the bad surface soundness of raw boards. The sanding was done by hand with a small belt sander.

3.1.3 DIN-EN 322 Determination of moisture content / DIN-EN 323 Determination of density

The density and moisture content were determined on eleven samples (50x50 mm) per board, evenly distributed over the board width. This was done to get a density profile over the board. The samples had measurements according to the standard. These tests, governed by the standards above, were also conducted for every sample that was tested from each board with the exception of the moisture content in the internal bond test samples.

3.2. Ultra sound velocity

If the measurements and the density of a homogenous body are known, the dynamic modulus of elasticity can be calculated from the sound propagation time for a sound wave going through the body. This is made using the following well-known simplified formula, (Krautkrämer [13]):

$$MOE_{US,dyn} = \rho \times v^2 \qquad \textit{(Equation 2)}$$

$MOE_{US,dyn}$ - Dynamic modulus of elasticity [MPa].
ρ - Density [kg/m^3].
v - Ultra sound velocity [m/s].

Since particleboard and especially multi-layer particleboard is not a homogenous material due to its distinctive density profile perpendicular to the board surface, this formula can only be regarded as an approximate estimation.

The sound velocity was determined using a sound propagation timer (BP5 from Steinkamp), from the sound propagation time and the length of the specimen.
The sound velocity parallel to the board plane was measured. The used frequency was 50 kHz through an exponential sound emitter. No coupling agent was used during the measurements.
In the internal bond testing, sound velocity perpendicular to the board plane was measured (see figure 3). This was made in five locations for each sample, as described in appendix 6, and the mean value of the five measurements was

used in the evaluation. The sound velocity was also measured after sanding (in the midpoint only), for the boards 8 to 25.

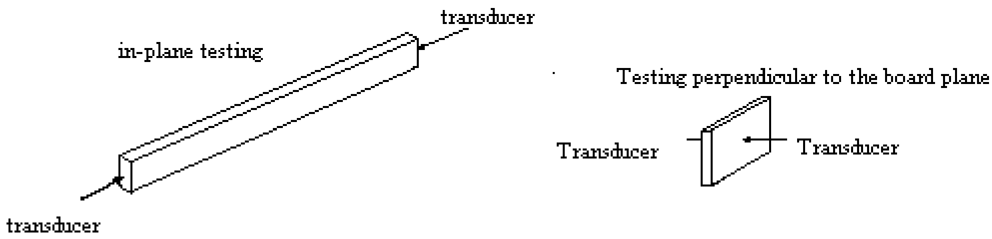

Figure 3: Ultra sound test directions.

3.3 Eigen frequency

The test method measures the fundamental eigen frequency of a test specimen of a suitable geometry excited by a singular elastic strike with an impulse tool (a small hammer). A piezoelectric needle (or a microphone) pressed against the specimen senses the mechanical vibrations of the specimen and transforms them into electric signals. Specimen supports and/or locking points, impulse location and signal pick-up points are selected to induce and measure specific modes of the transient vibrations. The signals are analysed, and the fundamental eigen frequency is isolated and measured by the signal analyser and the result is displayed numerically on a display. The appropriate eigen frequency, specimen dimensions and mass are used to calculate dynamic Young’s modulus, dynamic shear modulus and Poisson’s ratio. In this study, the dynamic Young’s modulus was calculated for flexural vibrations using the following formula (Görlacher [5]) without account to shear influence. (The formula is valid for support distance/specimen thickness ratio higher than 15 - comparable with EN 310).

$$MOE_{EF,dyn} = \frac{4 \times \pi^2 \times l^4 \times f^2 \times \rho}{m_n{}^4 \times i^2} \left(1 + \frac{i^2}{l^2} \times K_1 \right) \times 10^{-9} \qquad \textit{(Equation 3)}$$

$MOE_{EF,dyn}$ - Dynamic Young’s modulus [MPa].
l - Specimen length [mm].
ρ - Density [g/cm^3].
f - Frequency [s^{-1}].
i - Radius of inertia ; $i^2 = h^2/12$ (h = specimen height in mm), [mm^2].

For bending vibrations of the first order the following constants are used (Görlacher [5]):

$K_1 = 49{,}8$
$m_n^4 = 500{,}6$

The specimens were placed on the supports as shown in figure 4. The eigen frequency was measured close to a node of the specimen with a piezoelectric needle. The instrument used for the eigen frequency measurement was ”Grindosonic Mk5 industrial” from J.W. Lemmens GmbH. The eigen frequency was measured both in- and perpendicular to the board plane (figure 4), both in- and perpendicular to the direction of production.

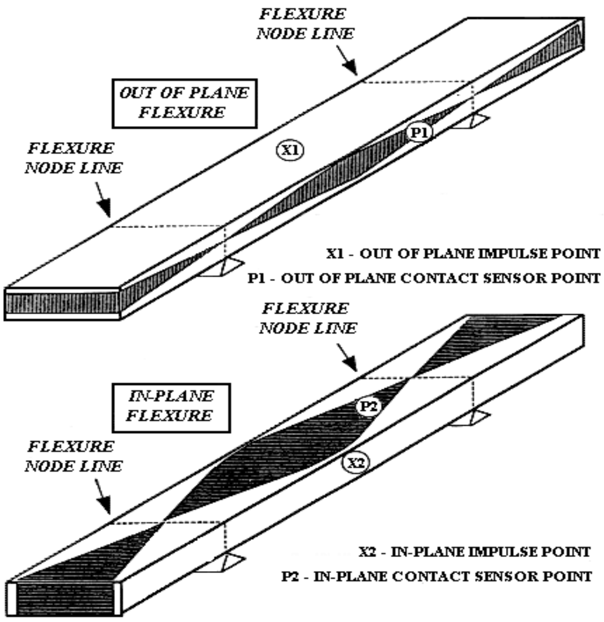

Figure 4: Tested eigen modes of flexure (ASTM C1259-94 [2]).

The support width was $0{,}552 \times l$ according to the results from Görlacher [5].

For the test on large boards, the eigen frequency for longitudinal vibrations was studied. This was made since the flexural eigen frequency of the first order is too low for easy and exact frequency measurement with this equipment when the test specimen is large. For in-plane longitudinal vibration, the dynamic Young’s modulus is calculated from the following simplified formula (Leban, Haines, Herbé [6], Spinner, Thefft [9]):

$$MOE_{dyn} = 4 \times \rho \times l^2 \times f^2 \qquad (Equation\ 4)$$

MOE_{dyn} - Dynamic Young’s modulus [MPa].
l - Specimen length [mm].
ρ - Density [g/cm^3].
f - Frequency [s^{-1}].

In this case the specimen was placed on a support placed under the middle of the board and then struck lightly in the middle of one side of the board. The frequency was measured on the opposite side using a piezoelectric needle. The test setting is shown in Appendix 6.

3.4 Testrob – fast testing machine

Testrob, from Schenk, is a device for a fast testing of the mechanical properties of wood based boards. It conducts automatic destructive tests on a board stripe, 50 millimetres wide. This model could determine the density, bending strength and shear strength and internal bond (calculated value from the shear strength) for a board. Testing with the Testrob normally takes place half an hour after the test sample is produced, so that it will have time to cool off. This is made to allow for after-curing to take place and to reduce temperature influences on the measurements. The total test time, with 6 samples per board and property, is about 40 minutes. The measurements are presented continuously on a personal computer as the test run proceeds. At the end the results are presented together with statistics for each measured property.

The first testing with the Testrob took place about one hour after the board was taken from the production line. Two 50 mm wide board stripes were tested, one for bending strength and one for density and shear strength and internal bond. The stripes were about 1700 mm long which means that five to six bending samples and about eight to nine density/IB samples were evaluated. The second test run was made after conditioning, simultaneously with the other tests on the samples from the same board.

4. Results and discussion

All predictions of MOR and MOE concern the mean values of the both directions, parallel and perpendicular to the direction of production, when nothing else is stated. The “ordinary linear regressions” used for the prediction of MOR and MOE, are not true single-variable methods, since the dynamic MOE for the test methods is calculated from more than one variable. The included data are physical measures and the density, which can easily be determined for every test piece in a normal production.

4.1 Prediction of Internal bond

The internal bond has been measured and modelled using the sound velocity perpendicular to the board plane. The multivariate models also incorporate density and covariation variables to explain the variations in IB.

4.1.1 Prediction with linear models

The prediction of internal bond using sound velocity with simple linear regression ($y=A_0+A_1 \cdot x$) gives very poor results. If every measured piece is used in the regression, the best result is found using the sound velocity measured on sanded specimens, which give an explained variation of R^2=0,30. If the mean values from all measurements on a single board are used for the regression, the predictions get better. The best result is found with sanded boards which give an explained variation R^2=0,64. This model is based on 17 boards.

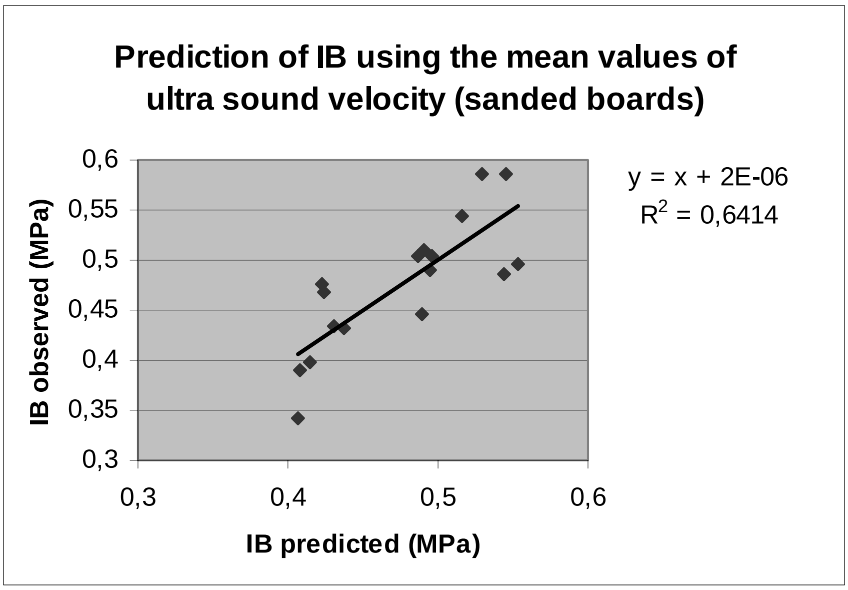

Figure 5: The best single-variate model for prediction of internal bond for sanded boards.

Unsanded boards give a model with R^2=0,47. In this case the model is built from 24 boards.

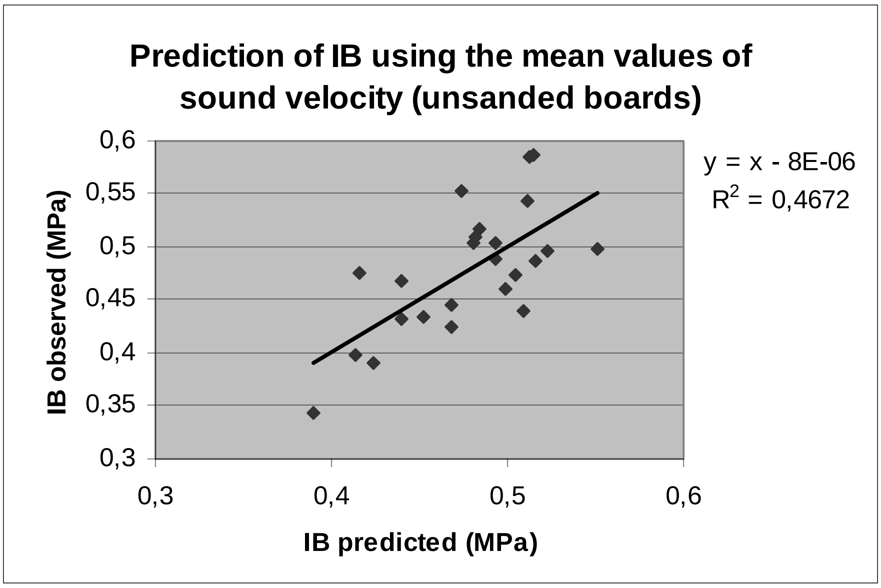

Figure 6: The best single-variate model for prediction of internal bond for unsanded boards.

The results are shown in table 1 below.

Table 1: Best ordinary regressions for prediction of internal bond strength.

Predicted property	**Prediction Variable**	**R^2**	**n**
IB	V	0,28	281
IB	V_{sanded}	0,30	199
IB_{mean}	V_{mean}	0,47	24
IB_{mean}	$V_{mean,sanded}$	0,64	17

Density has also been used to model IB, but with less success (results in Appendix 2).

4.1.2 Prediction of internal bond with multivariate models

With a multivariate model for unsanded samples, the boards with IB < 0.42 MPa can be sorted out. The model has been built using the measured properties from every test sample in each board as a variable. That is, the velocities and densities (v_1, v_{sand1}, ρ_1, v_2, v_{sand2}, ρ_2,…) for all test samples *i* in a board have been used as variables. The variables v_{sandi}, were not used in this model. The prediction results of the model are presented in figure 7.

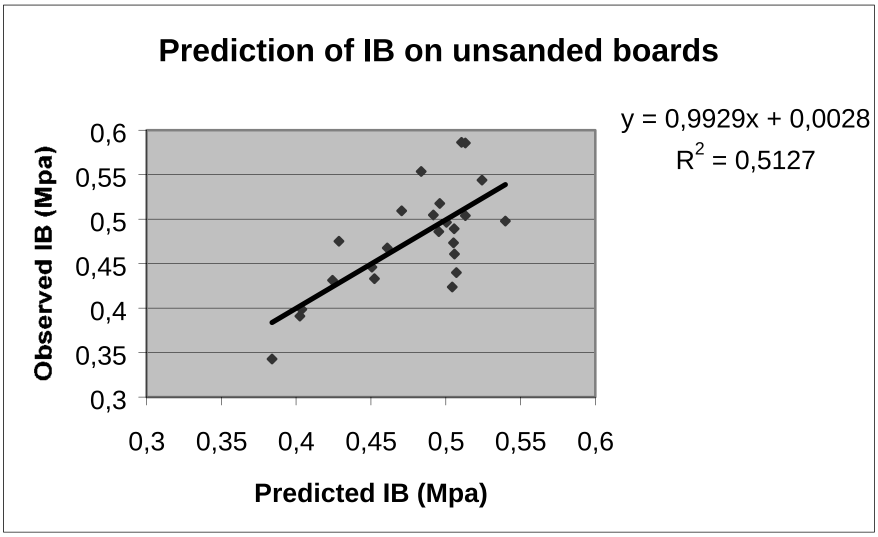

Figure 7: Prediction of IB on unsanded boards using sound velocity and density as variables.

The model can sort out samples that have IB < 0.42 MPa. To verify the validity of this model, the measurements for a number of boards were removed to form a test set. Then a model was built from the remaining observations. This model was used to predict the results in the test set. The result from this test (observed IB vs. predicted IB) is shown in figure 8.

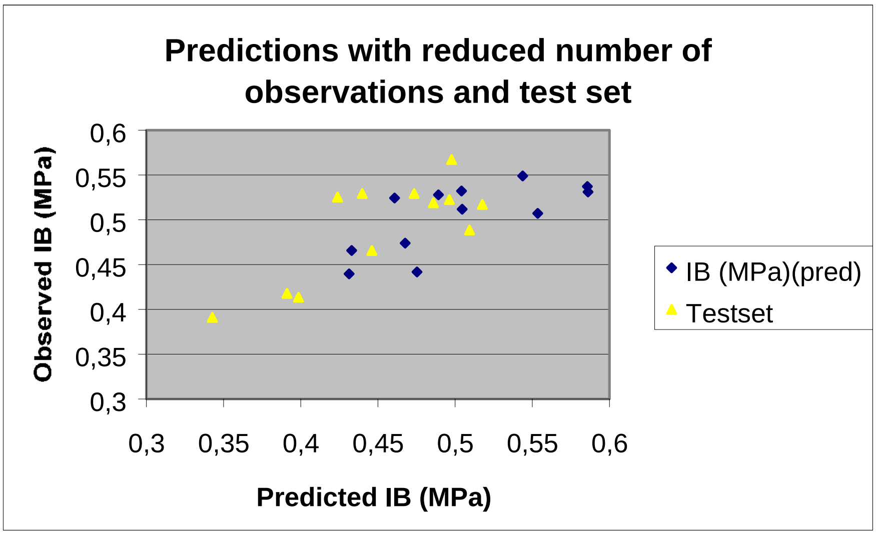

Figure 8: Prediction of a test set using a model built from a few observations (triangles - test set, rhombus - observation used to build the model).

The verification model, using only half of the observations, still manages to sort out the specimens with IB < 0,42 MPa. This implies that the model is robust and that there is an underlying structure, and not a chance coincident, which leads to this result. This assumption is based on the fact that the model cannot be fitted to these deviating boards if they are not included in the model.

A model for sanded boards was also developed, which gives very good results. With a model built from the mean values of the observations for 17 boards, the explained variation is R^2=0,88. The result is shown in figure 9.

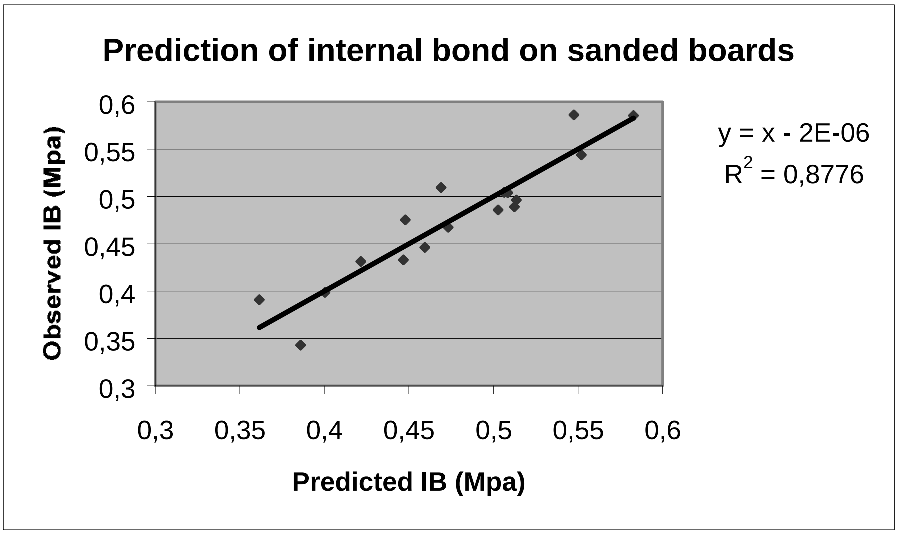

Figure 9: Prediction of IB on sanded boards using density and ultra sound velocity as base variables.

Discussion:
Prediction of IB on unsanded boards is possible for boards with a low IB. Higher values seem to be influenced by a variable not included in the model. This might be surface roughness and surface hardness, since sanded samples give much better prediction results. The reason for this could be that the porous board face influences the sound propagation time through bad coupling. Different pressing forces on the transmitters might compress this layer in various degrees and lead to a relatively large variation in the measured sound velocity. This "noise" becomes larger as the IB of the board increases. This is due to the fact that a good middle layer stands for a lower part of the total propagation time than a bad one. This would explain the conical form of the observations in the observed/predicted-plot for unsanded boards.
On sanded boards with a harder and more even surface, this is not a problem and the prediction becomes better according to this.

4.2 Prediction of bending strength and Young's modulus for large boards

Tests were also conducted on the test boards (50x137cm) before cutting the test specimens. From these data, models were made for the prediction of in-plane bending strength and Young's modulus. The eigen frequency used here is the longitudinal eigen frequency, perpendicular to the direction of production.

4.2.1 Prediction of MOR

The best result for the prediction of MOR using ordinary regression models was achieved with the dynamic MOE, calculated from the eigen frequency, perpendicular to the direction of production as variable. This model gives an explained variance of R^2=0,76. The best multivariate model gave a prediction with an explained variance of R^2=0,84. This model used the density, eigen frequency, ultra sound velocity parallel to the direction of production and covariation factors to predict the bending strength (see appendix 3 for model coefficients).The prediction result for both models is shown in figure 10.

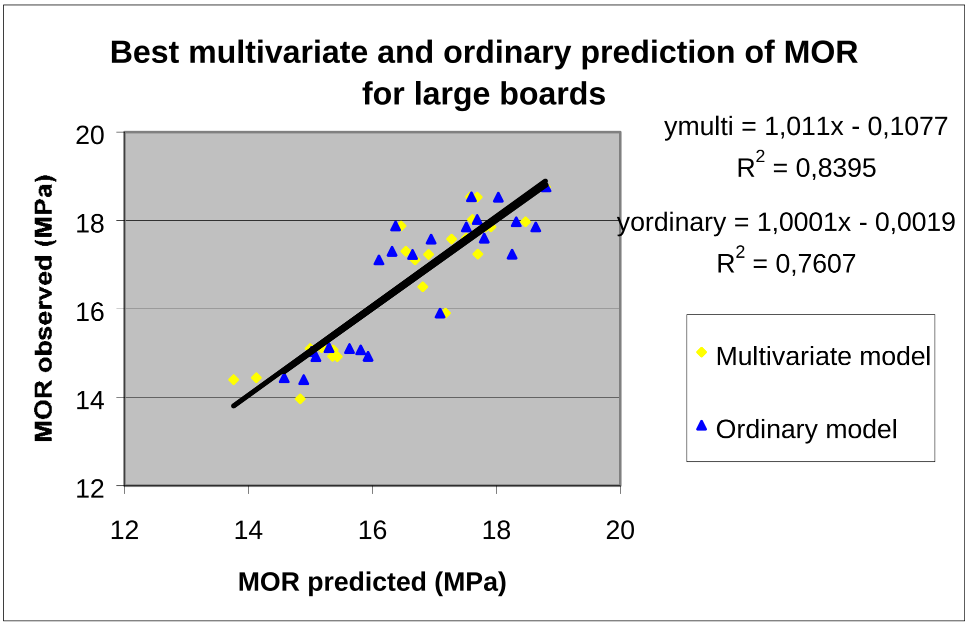

Figure 10: Best multivariate and ordinary models for prediction of MOR for large boards.

4.2.2 Prediction of MOE

Ordinary regression models resulted in a maximal explained variance of R^2=0,61 for a prediction of Young's modulus using ultra sound parallel to the direction of production. Multivariate models gave better results. The best multivariate model is built using the variables density, MOE computed from the longitudinal eigen frequency, and the ultra sound velocity parallel to the direction of production. This gives an explained variance of R^2=0,72. The prediction result for both models is presented in figure 11.

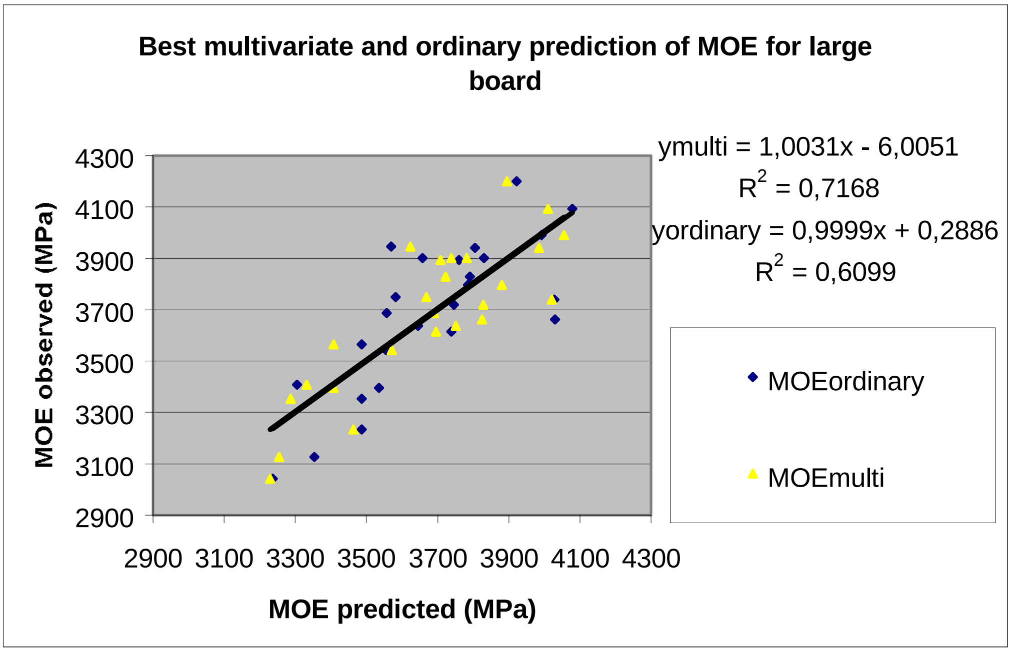

Figure 11: The best multivariate and ordinary prediction of MOE in large boards.

Discussion:
The relatively small difference between the multivariate and ordinary models probably lies in the fact that there are few and relatively similar variables in the multivariate models. Since most variables measure the same thing, the dynamic modulus of elasticity, or something correlated with it, they have almost the same effect on the model. If the variables all describe the same variance in the data set, the difference between an ordinary regression method and a multivariate method will be small if the measurements are good. If the measured variables contain noise, due to bad conditions et cetera, the multivariate model will have better chances of a successful prediction than an ordinary linear regression model. The reason for this is that PLS can handle noisy data, which is not the case for an ordinary linear regression.

4.3 Prediction of bending strength from specimen data

The prediction of the bending strength is done by correlating the dynamic MOE calculated for each non-destructive test method with the bending strength. This means that the prediction uses the known correlation between MOE and MOR and uses the predicted MOE for a sample to predict the MOR.
For the bending test, eight samples in each direction (parallel and perpendicular to the direction of production) were cut from each board. All these samples have been used as observations to make the models. This approach represents the ability of the models to predict the bending strength from a single measurement. Models have also been built from the mean values of the measurements from each board. This is a likely case in a production line with a

continuously non-destructive testing of the manufactured particleboards. Then the board would be measured in a number of points, and the strength properties predicted from the mean value of these measurements.

4.3.1 Linear models

In this case, all the samples (both perpendicular and parallel to the direction of production) are used to build models for prediction of MOR. The best ordinary model for prediction of MOR is given by the in-plane eigen frequency, which gives R^2=0,68. These models use measurements in both directions of the board (parallel/perpendicular to the direction of production). This might be hard to achieve in a production line, especially when measuring the eigen frequency. If models are based on only one direction for a prediction of the mean value of the board, the results indicate that the eigen frequency perpendicular to the direction of production gives the best results. This method also gives the lowest values for the modulus of elasticity.

Table 2: Best regression results for prediction of MOR from all observations.

Predicted property	**Prediction Variable**	**R^2**	**N**
MOR	$MOE_{EF\perp,n.c}$	0,68	400
MOR⊥	$MOE\perp_{EF\perp,n.c}$	0,76	200
MOR•	$MOE\bullet_{EF\perp,n.c}$	0,59	200

4.3.2 Multivariate models

A prediction of the bending strength with models based on single measurements, gives a best prediction for the overall MOR of R^2=0,69. This is insignificantly better than the ordinary regression model. The prediction result is shown in figure 12.

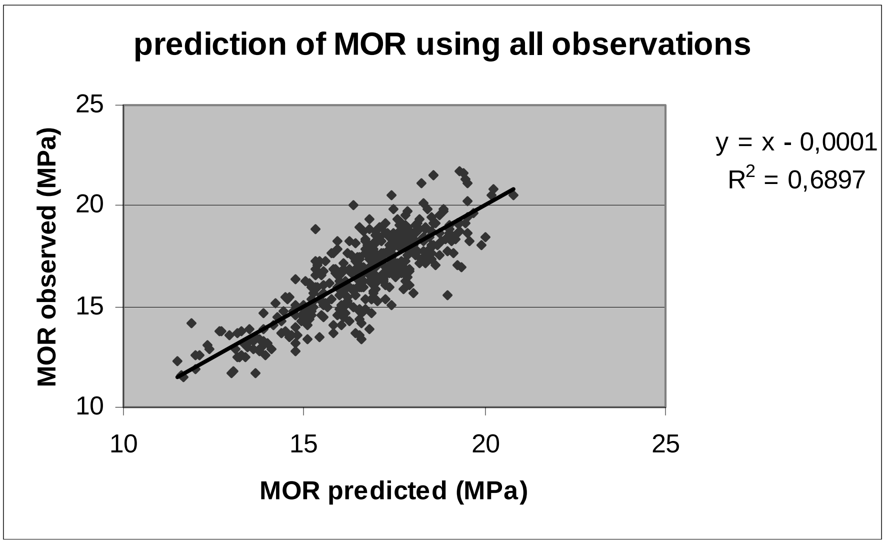

Figure 12: Best multivariate model for prediction of overall MOR from single measurements.

If only variables from measurements in one direction are used, the best prediction is found when using the variables perpendicular to the direction of production. The results for the multivariate models, using only one direction, are shown in table 3 below.

Table 3: Multivariate models for prediction of MOR parallel and perpendicular to direction of production.

Modelled property	**R^2**	**Q^2**	**N**
MOR⊥	0,73	0,73	200
MOR•	0,56	0,56	200

4.3.3 Models for MOR prediction built from mean values

If the mean values of the measurements for each board direction are used for the prediction of the bending strength, the results get better. This is the normal situation when one has continuos measuring over the board length in normal production. The use of linear models gives the best result for MOR prediction with R^2=0,87. The best multivariate model gives a prediction result with R^2=0,82. The result is shown in figure 13.

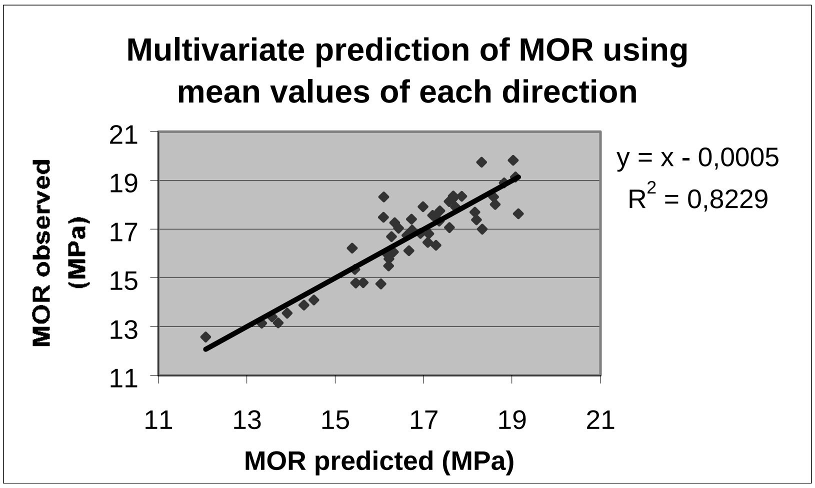

Figure 13: Best multivariate model for prediction of MOR from the mean values of the board.

4.4 Prediction of Young’s modulus from specimen data

A prediction of the MOE perpendicular to the direction of production can be predicted better than the mean MOE from both directions. This could depend on the different properties for the both directions. A mean value of two components is harder to simulate using only one component. The most interesting values are the overall MOE or the lowest value (perpendicular to the direction of production in this case).

4.4.1 All samples

Multivariate modelling gives good predictions also for the overall (mean value of both directions) MOE in a test sample. The multivariate model gives R^2=0,82 instead of R^2=0,68 for the best ordinary regression model, see figure 14.

Table 4: Ordinary regression models for prediction of MOE using all observations (unconditioned samples).

Predicted property	**Prediction Variable**	**R^2**	**N**
MOE	$MOE_{EF\bullet ,n.c}$	0,68	400
MOE⊥	$MOE\perp_{EF\perp,n.c}$	0,83	200
MOE•	$MOE\bullet_{EF\perp,n.c}$	0,73	200

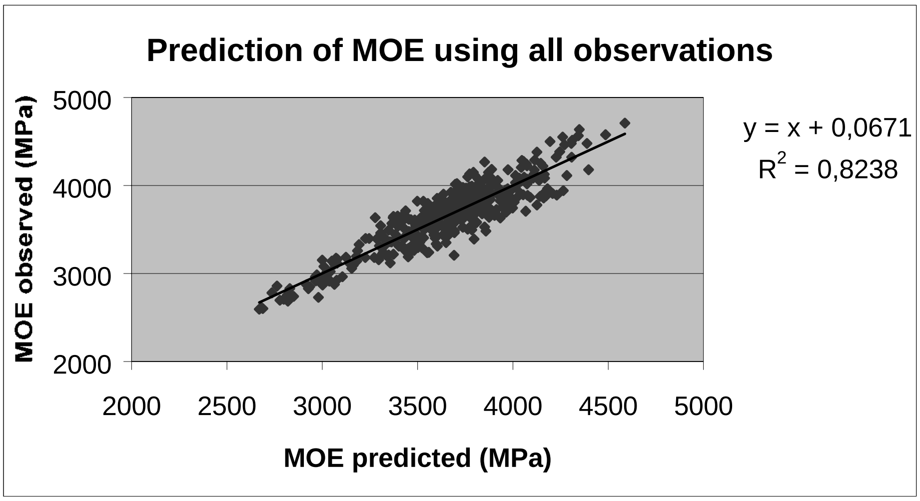

Figure 14: Best multivariate prediction of MOE using all observations.

4.4.2 Mean values

The use of the mean value of several measurements for each board when determining the strength gives better predictions. Ordinary regression gives a best prediction with R^2= 0,88 for the out-of-plane eigen frequency for prediction of the mean MOE in a board. The best multivariate model gives a prediction with R^2= 0,87 of the mean MOE in a board (see figure 15).

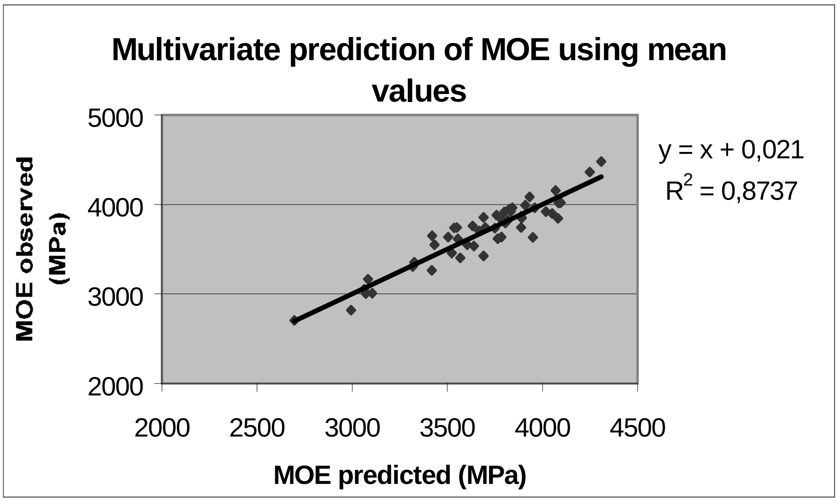

Figure 15: Best multivariate model for prediction of MOE from the mean values of the board.

4.4.3 Differences between static method and dynamic methods

Young's modulus (MOE) can be calculated directly from the eigen frequency and sound velocity according to equation (1) and (2). The values differ from the values from the static testing of MOE. The correlation between the dynamic and static methods is linear. The difference between the values given through the different dynamic methods and the static MOE from DIN-EN test is shown in table 5 below.

Table 5: Difference between the dynamic methods and DIN-EN values in %.

	$MOE_{US,nc}$	$MOE_{US,c}$	$MOE_{EF\perp,nc}$	$MOE_{EF\perp,c}$	$MOE_{EF\bullet,nc}$	$MOE_{EF\bullet,c}$
Mean	-13,87	-12,18	-46,39	-42,70	-11,44	-9,13
Max	1,02	2,53	-24,67	-26,63	9,18	1,22
Min	-29,93	-30,15	-61,17	-59,74	-23,98	-22,76

nc not conditioned
c conditioned

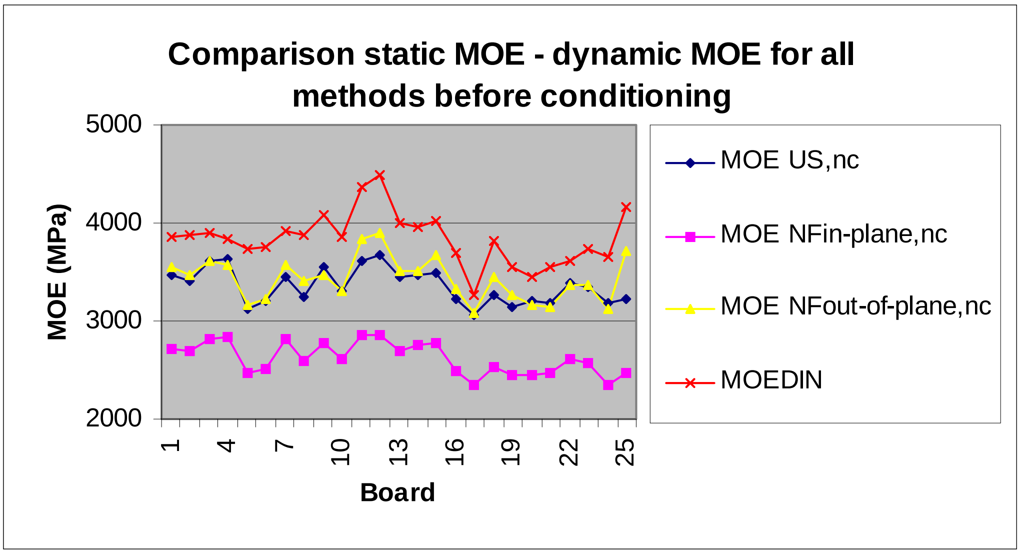

Figure 16: Static and dynamic Young's modulus for all boards (mean values).

Notable is the fact that dynamic methods all give lower values for MOE than DIN-EN testing. This stands in contrast with previous results from Niemz, Kucera and Bernatowicz who reported higher values of MOE on MDF boards with these methods compared to DIN-values [18].

4.5 Influence of conditioning

The samples were conditioned in a storing room at 25°C, 55% R.H. for six days. Thereafter they were once again tested with the non-destructive methods and finally tested with the reference methods. The results before and after conditioning have relatively small differences, see table 6:

Table 6: Mean values of different parameters before and after conditioning.

Parameter	**Before cond.**	**s**	**After cond.**	**s**	**D**	**D (%)**	**Significant (95%) Yes/No?**	**C.I.**
Density (g/cm3)	0,683	0,021	0,685	0,021	0,002	0,29	No	0,0021
velocity (m/s)	2166	69	2187	69	20,650	0,95	Yes	6,7595
MC (%)	6,15	0,54	7,16	0,40	1,010	16,42	Yes	0,0530
MOE_{USnew}	3211	266	3258	281	46,869	1,46	Yes	26,1127
$MOE_{EF\perp new}$	2498	251	2562	267	63,747	2,55	Yes	24,6415
$MOE_{EF\bullet\ new}$	3291	313	3351	326	60,380	1,83	Yes	30,7126
Eigen frequency⊥	475,2	19,9	482,1	20,3	6,87	1,42	Yes	1,953
Eigen frequency•	225,6	10,9	229,4	11,1	3,86	1,68	Yes	1,066

Before / After cond. :	Mean value of the property before and after conditioning.
s:	Standard deviation.
D:	Difference between unconditioned and conditioned samples.
C.I:	Confidence Interval (interval that with 95% certainty contains a single measurement).
MOE_{USnew}	Dynamic MOE from in-plane ultra sound velocity before conditioning.
$MOE_{EF\perp new}$	Dynamic MOE from the in-plane eigen frequency before conditioning.
$MOE_{EF\bullet\ new}$	Dynamic MOE from the out-of-plane eigen frequency before conditioning.
Eigen frequency⊥	The in-plane eigen frequency before conditioning.
Eigen frequency•	The out-of-plane eigen frequency before conditioning.

The fact that almost all changes are significant depends on the large number of observations (n=400). The changes are relatively small, except the change in moisture content, which is expected. A surprising result is that the standard deviation for the non-destructive measurements of the dynamic modulus of elasticity increases with conditioning.

4.6 Testrob measurements

The Testrob device gives good results for measuring of the internal bond (see figure 17).

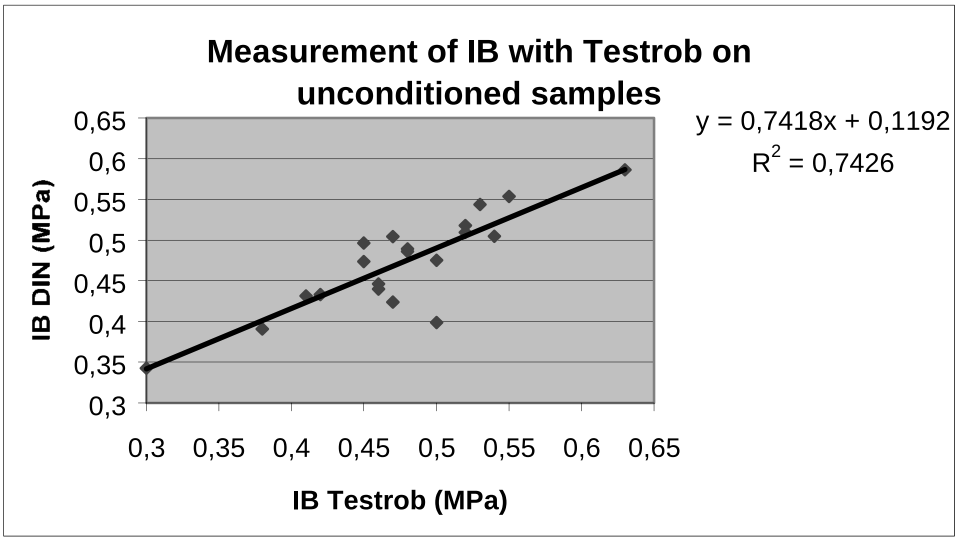

Figure 17: IB measurement with Testrob on unconditioned samples.

The correlation gets better after the test samples have been conditioned. Measurement of the bending strength with the testrob shows a surprisingly bad correlation to the DIN tests for the boards (figure 18).

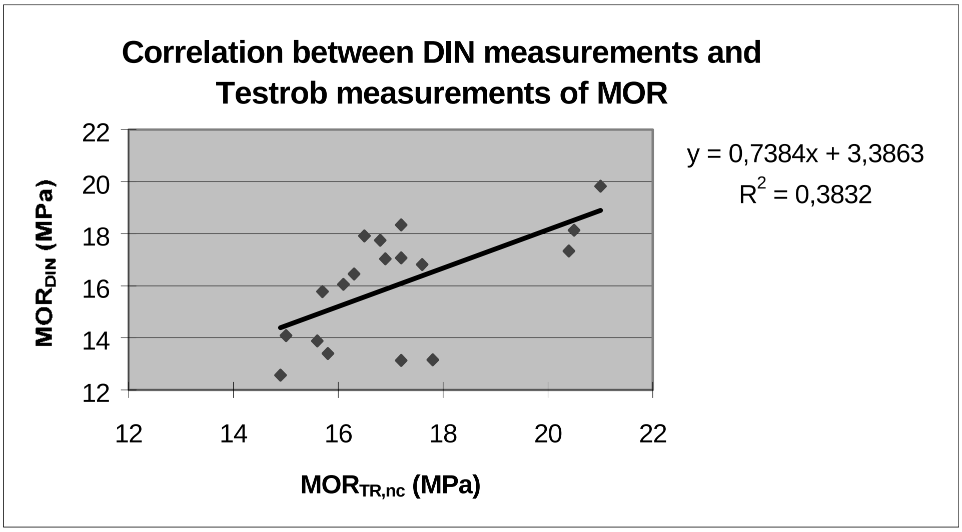

Figure 18: Correlation between bending strength measuring with Testrob and DIN-test on unconditioned samples.

Better results were expected since the only thing that separates the both tests is the support width in the bending test. All bending samples for the testrob are taken perpendicular to the direction of production and are correlated to the DIN bending strength for this direction in figure 18 above.

Table 7: Correlation between Testrob and DIN measurements (mean values for each board).

Predicted property	Prediction Variable	R^2	n
MOR	$MOR_{TRn.c}$	0,38	18
MOR	$MOR_{TR.c}$	0,53	21
IB	$IB_{TRn.c}$	0,74	21
IB	$IB_{TR.c}$	0,84	20

5. Conclusions

The models are built for the evaluation of the methods, to see if it is possible to use and implement such techniques in the manufacturing process.

When making an indirect test of the strength properties of the board, there are a number of factors that might influence the result. This means that a perfect prediction cannot be achieved. If as many relevant factors as possible are included or kept constant, a better approximation of the strength can be reached.

The optimal situation in a process industry such as particleboard manufacturing, is a stable model that predicts the properties of the board from process setting and raw material data. This means that the board quality can be set directly in the process control room. This is done today but this is mostly based on experience and a trial-and-error process. Such a model could be implemented, provided that the control and measuring systems are exact enough. PLS regression provides an excellent tool for development of such multivariable models. Since use for process controlling means that the board will be tested directly or shortly after pressing, all models have been built from the measurements from samples in an unconditioned state.

5.1 The efficiency of the models for process controlling

5.1.1 Ultra sound velocity for internal bond prediction

Validity of the measurements (prediction quality) and influencing factors

From the results, one can see that with raw unsanded boards there are some problems with the coupling between the transducers and the board. Sanding removes the porous layer on top of the board, which comes from the forming mat and dust, which lies on the surface. Sanding gives a harder and more even surface, which makes it easier to get an even pressure of the transducers against the board. This is important since the sound velocity is dependent on the coupling pressure between the transducers and the board [15]. In this study, the transducers were handheld, which might lead to a variance in coupling pressure and therefore in the sound velocity in the tests. If the contact method for sound velocity measurement is to be used for on-line control of board quality, this problem must be solved if an exact prediction is to be achieved.

Ordinary regression models

These models cannot be used for effective process controlling purposes since they give a weak prediction of the internal bond. The boards that are tested were hammer-milled which means that the particles have a relatively low surface to volume ratio. This means that they are not very homogenous over the thickness and are therefore harder to predict. Other studies have shown better results for IB prediction with ultra sound velocity only [14]. This indicates that linear models using only ultra sound velocity for IB prediction, can be used for boards from an even forming process and a stable process as well as an even particle form and size.

Multivariate approach

A prediction of IB on unsanded boards is possible for boards with a low IB. Higher values seem to be influenced by a variable not included in the model. This might be surface roughness and surface hardness, since sanded samples give much better prediction results. The reason for this could be that the porous board face influences the sound propagation time through bad coupling. Different pressing forces on the transmitters might compress this layer in various degrees and lead to a relatively large variation in the measured sound velocity. This "noise" becomes larger as the IB of the board increases. This is due to the fact that a good middle layer stands for a lower part of the total propagation time than a bad one. This would explain the conical form of the observations in the observed/predicted-plot for unsanded boards.
On sanded boards with a harder and more even surface, this is not a problem and the prediction becomes better according to this.

The results from [15], achieved with ordinary regression methods, indicate that the use of multivariate models can give a better prediction of IB than in this study. Also, the use of more variables could give a more effective prediction. A designed test with a larger variation in board quality and more variables, that could explain the variation in better boards, would probably give a better model. In this study, all boards fulfilled the demands on internal bond in DIN 68 763 (IB > 0,35 MPa). A good training set should also contain data from boards that do not fulfil these demands.

The variable importance for the variables used to predict IB for unsanded boards shows an interesting effect. The influence of the density variables varies over the board and is clearly higher on the side where the press gives lower density (press table is not plane which leads to uneven thickness where one side of the board is slightly thicker). This indicates that the sensitivity of the model might be too low for samples with a high IB, since the IB correlates with the density.

The model for sanded boards provides a good prediction of IB, which can be used for precise process monitoring. Since the measurements have been made after conditioning, temperature and curing effects have not been considered.
This makes this model suited for quality control of boards before shipping, but not for production control. Measurements for production control have to be made on unsanded boards where the possibilities for the model are limited to the detection of boards with insufficient strength properties (fault detection).

Possibilities and limitations for industrial use

The use of ultra sound together with density (and possibly other variables) in multivariable models for prediction of internal bond shows very good promise. On sanded boards the method already shows very good results. Unsanded boards however, are more difficult to measure with this method. This is probably due to bad contact between the transducer and the specimen because of the porous face layer. If an even and relatively high contact pressure can be enabled, it would most probably lead to better results.

For use on sanded boards, a multivariate method including sound velocity and density gives very good results for the prediction of IB with an explained variance of R^2=0.88. This method could easily be implemented in most particleboard factories since it does not require much space. A number of evenly distributed measuring devices over the board width could give a good prediction result. Problems lie mainly in the following fields:

- Contact between transducer and specimen
- Continuos density measurement at transducer location.
- Temperature and curing influence are not modelled.

Continuous measurement of the board density could be realised with gamma ray or x-ray density measurement. With a good transducer design, the internal bond could be predicted for every board in an on-line measuring system. For this to be possible for unsanded boards, a good insusceptible coupling between transducer and specimen has to be developed for on-line use. The models also have to incorporate variables governing temperature and curing effects.

Another interesting alternative for internal bond prediction lies in using non-contact methods such as on-line density profile measurement (gamma ray), together with non-contact ultra sound evaluation as described in [14] and [15]. This could reduce the problems caused by the insufficient contact at unsanded boards.

5.1.2 Ultra sound velocity for MOR and MOE prediction

Validity of the measurements (prediction quality) and influencing factors

The use of ultra sound velocity for the prediction of MOR and MOE places high demands on a good edge surface for coupling of the transducers for good results. The placement of the transducers on the board edge is also important because of the density profile. The influence of the coupling location on ultra sound velocity was investigated in a small test, which gave indications that measurements in the surface layer give higher velocities than measurements in the middle layer. The both layers do influence each other so that if the surface layer is cut out, the measured ultra sound velocity becomes higher than measurements in the complete board. If the ultra sound velocity in a free middle layer is measured, it will be lower than the velocity in a complete board. These results are only orientating and they need to be controlled in order to enable someone to draw conclusions about the optimal transducer location. There is also an uncertainty of how large specimens that can be tested with this frequency, with good prediction results.

Ordinary regression models

Ultra sound velocity gives good prediction results with ordinary regression models. The explained variance, R^2, varies between 0,58 and 0,83 for the prediction of MOR, and between 0,67 and 0,77 for the prediction of MOE. These models are all based on measurements perpendicular to the direction of production.

Possibilities and limitations for industrial use

Ultra sound velocity shows good results for prediction of MOR and MOE. The measurements that are done on large test boards shows that the method can also be used on larger samples.
A prerequisite for the use of this method is that the edges of the boards are evenly cut, and have a good surface quality. This is important since the quality of the method depends on the contact between the transducers and the specimen. Such surfaces might be hard to achieve on boards directly after pressing. The method is relatively simple to introduce in normal production if the problems with contact between transducer and specimen can be solved.
For continuos measuring, transducers formed as rollers with a soft plastic as sound transmission material might be used. Measuring on still-standing specimens is easier to carry out but has a lower capacity. For the prediction of bending strength, ultra sound is the easiest way but a slightly less effective tool than eigen frequency analysis.

5.1.3 Eigen frequency measurement for MOR and MOE prediction

Validity of the measurements (prediction quality) and influencing factors

The measurement of the eigen frequency gives reliable and stable data when used on small samples. The measurements are influenced by the board density profile so that the calculated MOE is lower for in-plane flexure measuring than for out-of-plane measuring.

Ordinary regression models

Regression with the eigen frequency for each sample gives relatively good predictions of MOE with R^2=0,83, and MOR with R^2=0,68. The use of the mean value of each direction in the boards gives better prediction results. The best correlation results for MOE are found for samples tested in out-of-plane flexure (R^2=0,88). The best correlation for MOR is found for in-plane flexure testing (R^2=0,87). These models give very accurate predictions of both bending strength and modulus of elasticity.

Possibilities and limitations for industrial use

Eigen frequency measuring for the prediction of MOR and MOE in large boards, is hard to implement. The fundamental flexural eigen frequency for boards with a length of 6 metres is only a few Hertz. Longitudinal eigen frequency has an acceptable fundamental frequency for boards in this size, but has the nodepoint in the middle of the board. This means that it will have large bending deflections in the ends by testing. This also caused some problems in this study, as the eigen frequency was hard to determine due to unstable measurements. This was probably due to vertical movements at the recieving end of the board. These vertical movements came up if the blow was to hard or if the impulse point deviated from the centre of the board edge.
There is also a problem in the number of possible repetitions for each board with maintained capacity, since the measurements probably have to be conducted on a still-lying board. The repetitions also measure the same thing, the eigen frequency, which has a very low variation. That means that more repetitions do not give a better result. Repetitions are only used to make sure that the measured frequency is stable, and not an overtone or a mixed vibration mode. (Not a pure bending vibration but a mixture of bending and torsional vibrations for instance.)
The most suited system for industrial use is probably clamped boards with one free end (such a system is proposed by Greubel, [3]) or the use of longitudinal waves during crossover transport or on still boards.

5.1.4 Multisensor models for MOR and MOE prediction

Multisensor prediction using multivariate models can give very good results using eigen frequency and ultra sound velocity.

Validity of the measurements (prediction quality) and influencing factors

The multivariate models generally give better predictions than the ordinary regression models. In some cases the differences are small, as for the models for the prediction of MOR using all samples. The reason for this is that some multivariate models use variables that have almost the same influence on the model and therefore model the same variation. These models might be more stable than ordinary models for the prediction of new observations than ordinary regression models but could also be “overfitted”. Overfit means that the model uses too many variables and is too adapted to the test set and therefore models random variations (noise). The overfit of a model can be controlled by using a cross validation (SIMCA Manual [23]) which gives the prediction ability (Q^2). A low Q^2 indicates an overfitted model.

Influence of measuring direction

The best results are found for measurements perpendicular to the direction of production. The reason for this probably lies in the forming of the particleboard. There is a small orientation of the particles in the direction parallel to the direction of production because of the movement of the forming mat. The forming also leads to small ridges of particles in the direction of production, which might lead to variations of the sound velocity between or inside a test specimen. This might give predictions inferior to those perpendicular to the direction of production where these variations are connected in series which gives a lower impact on the model result.

Possibilities and limitations for industrial use

The best models in general use both methods and measurements in both directions. This might not be possible for application in a production line. If only one direction is to be used for prediction, the best results are given for measurements perpendicular to the direction of production. If only one method should be used, the easiest method is ultra sound velocity measurement. The main reasons for this are the moderate space requirements for this test equipment and the easy installation. The use of eigen frequency methods give better and less susceptible results, but might be hard to implement because of high space requirements and low capacity.

5.1.5 Use of the methods on large boards

Ordinary models

Ultra sound gives fair results for the prediction of MOE (R^2=0,61) and MOR (R^2=0,68). The best predictions have been achieved parallel to the direction of production. The prediction results when using the ultra sound velocity perpendicular to the direction of production were bad with a top R^2=0,25. This is probably due to the difficulty of measuring the ultra sound velocity on large samples manually. Since one person conducted these measurements alone, a good and even coupling was hard to achieve due to the specimen size. The large distance between the ends made it hard to find a precise location of the transducers and reach an even pressure. Since the results from the measurements on the bending samples have shown that the results are normally better perpendicular to the direction of production, measurements in this direction should give better results. The results might also indicate that the size of the specimen is too large for measurements with this frequency.

Multivariate models

Multivariate models gave better results for both MOR (R^2=0,84) and MOE (R^2=0,72) than ordinary linear regression models. The models include the variables density, longitudinal eigen frequency perpendicular to the direction of production and ultra sound velocity parallel to the direction of production. The ultra sound velocity perpendicular to the direction of production is not included or has little importance in the model because of the bad prediction power. Better measuring conditions should increase the importance of this variable and perhaps lead to better predictions.

Summary

Since the specimen was sufficiently large to have a noticeable bending deflection, vertical movements at the receiving end caused some problems in the eigen frequency testing. These vertical movements came up if the blow was to hard or if the impulse point deviated from the centre of the board edge. This made it hard to get a stable reading of the longitudianal eigen frequency.

The models built from the measurements on the larger boards have shown that the methods also give good results for larger specimens. However, new investigations should be made on full size particleboard for a control of the validity of the methods in industrial use.

5.1.6 Measuring with the Testrob

The Testrob provides a good instrument for the measurement of the internal bond in the produced boards. For bending strength the results do not have a high correlation with the results from the DIN-EN test. This is unexpected since the both tests are almost identical, with the only difference being the support width.
Possible causes for the bad bending strength measuring could be a bad calibration of force or displacement measuring in the testrob or in the laboratory devices. The displacement measurement device in the laboratory was brand new and calibrated so the most likely difference there, lies in a bad calibration of the testrob. As for the force measuring, both devices might have calibration problems. Other possible reasons are shear influence, because of the low support width (10x specimen thickness) in the testrob, or unevenly cut test stripes. Since the computer programme uses the specimen width 50-mm as default in all calculations, bad cutting might influence the results if the width differs much. The most probable reason is that one or both devices have a false calibration. With a correct calibration, the testrob should provide good results also for bending.

The major drawback of this method is that a test is normally started half an hour after the pressing and the final results are given after another half-hour. This means that a result is received more than an hour after the actual production time, which leads to the fact that about 140 boards have been produced during this time. That is, the “sampling rate” in the control is low. There is an additional problem in the fact that a large piece of the board is cut out when the test stripes are gathered which means that the board cannot always be used for the desired product size in the following cutting.

5.2 Influence of conditioning

Conditioning increases the dynamic MOE for both methods. The increase differs from 1,4% to 2,6 %. The fact that the difference is so small probably relates to the fact that the time between pressing and testing was sufficiently large for “post-curing” (additional curing after the board has left the press) and cooling to take place. If the boards were to be tested on-line, the difference would be higher.
Conditioning also gave better predictions (a higher R^2) in general (see appendix 2).

5.3 Temperature calibration

The influence of the temperature on the sound velocity in particleboard has been shown to be strictly linear in the temperature interval from 20ºC to 115ºC (see appendix 4). This means that temperature calibration can easily be done in an on-line system for non-destructive testing with ultra sound. The effect of temperature on the eigen frequency has not been investigated. Systems using only ultra sound can be calibrated to correct for temperature differences, which would lead to a better accuracy of the system.

6. Further work

Further work and improvements could be conducted in the following fields.

- An investigation of in-plane length vibration on whole boards.
- The prestanda of the methods should be checked directly after the cooling wheel in an integrated on-line test on full-sized boards.
- The relations governing the sound propagation in the plane of the board for multi-layer boards should be investigated since the theory today is only valid for homogenous materials. The influence of the density profile on sound velocity should be investigated.
- A method to ensure a good and unsusceptible contact between transducers and the raw particleboard in industrial environment has to be developed.
- The results need to be controlled on a larger variety of particleboard types and dimensions.

Further work could also evaluate the possibilities to integrate on-line density profile measuring with ultra sound velocity analysis. If every measured density layer in the board is utilised as a variable together with ultra sound propagation velocity, very good predictions could be reached for the internal bond when using PLS analysis. The reason for this is the largely increased information one gets over the density in the middle of the particleboard, where the fracture normally occurs. This could also lead to better methods for the use of ultra sound parallel to the board plane. The mean density used in this study is a very crude tool for this.
As an alternative to this, a totally contact free system with ultra sound or microwave scanning together with density profile measuring could be investigated. In such a system, density data together with the ultra sound frequency and amplitude analysis could provide good predictions of the internal bond.

7. Literature and references

The literature in this field is rather limited and dates back to the early sixties. The largest part of the literature consists of articles from a number of mainly German wood research journals as "Holz als Roh- und Werkstoff" and "Holzforschung und Holzverwertung". The literature has been found using the LIBRIS database, Internet and the local library network at ETH, Zurich.
Some key-words to search by: Prüfung von Spanplatten, Schallprüfung, Schallgeschwindigkeit, Resonansfrequenz, Zerstörungsfreie Prüfung, Non-destructive testing, Particleboard, Resonance flexure method, Ultrasonic testing.

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Appendix 1: Test design for board selection

Board number	Test board 1	Test board 2	Test board 3	Press storey: High/Low
1	-	P	A	?
2	A	-	P	H
3	P	A	-	L
4	-	P	A	H
5	A	-	P	L
6	P	A	-	H
7	-	P	A	L
8	A	-	P	H
9	P	A	-	L
10	-	P	A	H
11	A	-	P	L
12	P	A	-	H
13	-	P	A	H
14	A	-	P	L
15	P	A	-	L
16	-	P	A	H
17	A	-	P	L
18	P	A	-	H
19	-	P	A	L
20	A	-	P	H
21	P	A	-	L
22	-	P	A	H
23	A	-	P	L
24	P	A	-	H
25	-	P	A	L

A – Specimens for tests parallel to the direction of production
P – Specimens for tests perpendicular to the direction of production
H – Board taken from the top of the press
L – Board taken from the bottom of the press

Appendix 2. Results of linear regressions

Results - Mean values for the tested board in each direction

		simple linear regression		$y=A_0+A_1*x$	
Modelled property	**Modelling variable**	**A_0**	**A_1**	**R^2**	**n**
MOR_{DIN} (Mean)	MOE_{DIN} (Mean)	1,0123	0,0043	0,77	50
MOE_{DIN} (Mean)	$MOE\bullet_{US,n.c}$	107,07	1,1125	0,54	25
MOE_{DIN} (Mean)	$MOE\bullet_{US,c}$	301,29	1,0432	0,53	25
MOE_{DIN} (Mean)	$MOE\bullet_{EF,\bullet,n.c}$	130,21	1,0811	0,80	25
MOE_{DIN} (Mean)	$MOE\bullet_{EF,\bullet,c}$	517,53	0,9482	0,74	25
MOE_{DIN} (Mean)	$MOE\bullet_{EF,\perp,n.c}$	647,31	1,2192	0,55	25
MOE_{DIN} (Mean)	$MOE\bullet_{EF,\perp,c}$	577,2	1,2175	0,59	25
MOE_{DIN} (Mean)	$MOE\perp_{US,n.c}$	-935,77	1,452	0,77	25
MOE_{DIN} (Mean)	$MOE\perp_{US,c}$	-682,9	1,3483	0,75	25
MOE_{DIN} (Mean)	$MOE\perp_{EF,\bullet,n.c}$	-261,32	1,1998	0,88	25
MOE_{DIN} (Mean)	$MOE\perp_{EF,\bullet,c}$	-141,83	1,1389	0,86	25
MOE_{DIN} (Mean)	$MOE\perp_{EF,\perp,n.c}$	282,45	1,3603	0,78	25
MOE_{DIN} (Mean)	$MOE\perp_{EF,\perp,c}$	142,96	1,3885	0,82	25

Modelled property	**Modelling variable**	**A_0**	**A_1**	**R^2**	**n**
MOR_{DIN} (Mean)	$MOE\perp_{US,n.c}$	-9,2161	0,0083	0,83	25
MOR_{DIN} (Mean)	$MOE\perp_{US,c}$	-6,3937	0,0073	0,72	25
MOR_{DIN} (Mean)	$MOE\bullet_{US,n.c}$	0,2173	0,005	0,52	25
MOR_{DIN} (Mean)	$MOE\bullet_{US,c}$	2,3659	0,0044	0,43	25
MOR_{DIN} (Mean)	$MOE\perp_{EF,\bullet,n.c}$	-3,4966	0,0063	0,79	25
MOR_{DIN} (Mean)	$MOE\perp_{EF,\bullet,c}$	-2,0371	0,0057	0,71	25
MOR_{DIN} (Mean)	$MOE\bullet_{EF,\bullet,n.c}$	2,2973	0,0043	0,60	25
MOR_{DIN} (Mean)	$MOE\bullet_{EF,\bullet,c}$	4,9811	0,0035	0,46	25
MOR_{DIN} (Mean)	$MOE\perp_{EF,\perp,n.c}$	-2,5313	0,0079	0,87	25
MOR_{DIN} (Mean)	$MOE\perp_{EF,\perp,c}$	-2,6095	0,0077	0,84	25
MOR_{DIN} (Mean)	$MOE\bullet_{EF,\perp,n.c}$	1,7609	0,0059	0,60	25
MOR_{DIN} (Mean)	$MOE\bullet_{EF,\perp,c}$	2,826	0,0053	0,53	25
MOR_{DIN} (Mean)	$MOE_{US,n.c}$	-1,8165	0,0058	0,67	50
MOR_{DIN} (Mean)	$MOE_{US,c}$	-0,6987	0,0053	0,60	50
MOR_{DIN} (Mean)	$MOE_{EF,\perp,n.c}$	0,1143	0,005	0,71	50
MOR_{DIN} (Mean)	$MOE_{EF,\perp,c}$	1,664	0,0045	0,63	50
MOR_{DIN} (Mean)	$MOE_{EF,\perp,n.c}$	0,7115	0,0064	0,76	50
MOR_{DIN} (Mean)	$MOE_{EF,\perp,c}$	1,0653	0,0061	0,72	50

Results - Whole unconditioned boards

simple linear regression $y=A_0+A_1*x$

Modelled property	Modelling variable	A_0	A_1	R^2	n
MOR_{DIN} (Mean)	MOE_{DIN} (Mean)				
MOE_{DIN} (Mean)	$MOE\bullet_{US,n.c}$	142,42	1,0817	0,61	25
MOE_{DIN} (Mean)	$MOE\perp_{US,n.c}$	2712,4	0,3664	0,15	25
MOE_{DIN} (Mean)	$MOE\perp_{EF,\bullet,n.c}$	1221,4	0,9839	0,54	23

Modelled property	Modelling variable	A_0	A_1	R^2	n
MOR_{DIN} (Mean)	$MOE\bullet_{US,n.c}$	-2,752	0,0059	0,68	25
MOR_{DIN} (Mean)	$MOE\perp_{US,n.c}$	10,063	0,0025	0,25	25
MOR_{DIN} (Mean)	$MOE\perp_{EF,\bullet,n.c}$	0,624	0,0064	0,76	23
$MOR\bullet_{DIN}$ (Mean)	$MOE\bullet_{US,n.c}$	3,0407	0,0043	0,51	25
$MOR\perp_{DIN}$ (Mean)	$MOE\perp_{US,n.c}$	7,5562	0,0032	0,23	25
$MOR\perp_{DIN}$ (Mean)	$MOE\perp_{EF,\bullet,n.c}$	-4,3501	0,0082	0,63	23

Results - Measurements across the direction of production

simple linear regression $y=A_0+A_1*x$

Modelled property	Modelling variable	A_0	A_1	R^2	n
MOR_{DIN}	$MOE\perp_{DIN}$	-2,1547	0,0052	0,79	200
MOE_{DIN}	$MOE\perp_{US,n.c}$	-913,69	1,4377	0,76	200
MOE_{DIN}	$MOE\perp_{US,c}$	-518,42	1,3072	0,76	200
MOE_{DIN}	$MOE\perp_{EF,\bullet,n.c}$	-109,45	1,1447	0,78	200
MOE_{DIN}	$MOE\perp_{EF,\bullet,.c}$	-226,93	1,1615	0,88	200
MOE_{DIN}	$MOE\perp_{EF,\perp,n.c}$	91,95	1,4313	0,83	200
MOE_{DIN}	$MOE\perp_{EF,\perp,c}$	141,73	1,3765	0,85	200

Modelled property	Modelling variable	A_0	A_1	R^2	n
MOR_{DIN}	$MOE\perp_{US,n.c}$	-0,3514	0,008	0,68	200
MOR_{DIN}	$MOE\perp_{US,c}$	-5,8055	0,007	0,64	200
MOR_{DIN}	$MOE\perp_{EF,\bullet,n.c}$	-3,0659	0,0061	0,65	200
MOR_{DIN}	$MOE\perp_{EF,\bullet,.c}$	-3,1397	0,006	0,68	200
MOR_{DIN}	$MOE\perp_{EF,\perp,n.c}$	-3,0547	0,0081	0,76	200
MOR_{DIN}	$MOE\perp_{EF,\perp,c}$	-2,1819	0,0075	0,74	200

Results - Measurements along the direction of production

		simple linear regression		$y=A_0+A_1*x$	
Modelled property	**Modelling variable**	**A_0**	**A_1**	**R^2**	**n**
MOR_{DIN}	MOE_{DIN}	0,8145	0,0043	0,59	200
MOE_{DIN}	MOE• $_{US,n.c}$	-161,37	1,1854	0,67	200
MOE_{DIN}	MOE• $_{US,c}$	171,74	1,0728	0,63	200
MOE_{DIN}	MOE• $_{EF,•\ ,\ n.c}$	450,05	0,9811	0,68	200
MOE_{DIN}	MOE• $_{EF,•\ ,c}$	185,76	1,0383	0,82	200
MOE_{DIN}	MOE• $_{EF,\perp,\ n.c}$	201,11	1,3806	0,73	200
MOE_{DIN}	MOE• $_{EF,\perp,c}$	390,73	1,2745	0,74	200

Modelled property	**Modelling variable**	**A_0**	**A_1**	**R^2**	**n**
MOR_{DIN}	MOE• $_{US,n.c}$	-2,0884	0,0057	0,50	200
MOR_{DIN}	MOE• $_{US,c}$	0,7815	0,0048	0,41	200
MOR_{DIN}	MOE• $_{EF,•\ ,\ n.c}$	1,4252	0,0046	0,48	200
MOR_{DIN}	MOE• $_{EF,•\ ,c}$	1,5931	0,0044	0,48	200
MOR_{DIN}	MOE• $_{EF,\perp,\ n.c}$	-0,8916	0,0069	0,59	200
MOR_{DIN}	MOE• $_{EF,\perp,c}$	1,5351	0,0058	0,50	200

Property

MOR - Modulus of rupture (out-of-plane bending strength)

MOE - Modulus of elasticity (Young's modulus)

Direction index

MOR/MOE⊥ - MOR/MOE perpendicular to direction of production

MOR/MOE• - MOR/MOE parallel to direction of production

Method index (low index)

$_{EF,•\ ,c}$ - Eigen frequency in-plane, c=conditioned

$_{EF,\perp,\ n.c}$ - Eigen frequency out-of-plane, n.c = not conditioned

Results - all

samples

simple linear regression $y=A_0+A_1*x$

Modelled property	Modelling variable	A_0	A_1	R^2	n
MOR_{DIN}	MOE_{DIN} (Mean)	0,0477	0,0045	0,71	400
MOE_{DIN}	$MOE_{US,n.c}$	-405,87	1,2649	0,76	400
MOE_{DIN}	$MOE_{US,c}$	-237,56	1,195	0,76	400
MOE_{DIN}	$MOE_{EF,\bullet,n.c}$	68,264	1,0903	0,79	400
MOE_{DIN}	$MOE_{EF,\bullet,c}$	-60,767	1,1092	0,88	400
MOE_{DIN}	$MOE_{EF,\perp,n.c}$	171,38	1,3947	0,83	400
MOE_{DIN}	$MOE_{EF,\perp,c}$	261,83	1,3247	0,84	400

Modelled property	Modelling variable	A_0	A_1	R^2	n
MOR_{DIN}	$MOE_{US,n.c}$	-2,2972	0,0059	0,58	400
MOR_{DIN}	$MOE_{US,c}$	-1,0374	0,0054	0,54	400
MOR_{DIN}	$MOE_{EF,\bullet,n.c}$	0,0617	0,005	0,58	400
MOR_{DIN}	$MOE_{EF,\bullet,c}$	0,0839	0,0049	0,60	400
MOR_{DIN}	$MOE_{EF,\perp,n.c}$	-0,3008	0,0068	0,68	400
MOR_{DIN}	$MOE_{EF,\perp,c}$	0,8169	0,0062	0,63	400

Property

MOR - Modulus of rupture (out-of-plane bending strength)

MOE - Modulus of elasticity (Young's modulus)

Direction index

MOR/MOE⊥ - MOR/MOE perpendicular to direction of production

MOR/MOE• - MOR/MOE parallel to direction of production

Method index (low index)

$_{EF,\bullet,c}$ - Eigen frequency in-plane, c=conditioned

$_{EF,\perp,n.c}$ - Eigen frequency out-of-plane, n.c = not conditioned

Results - Internal bond

simple linear regression y=A0+A1*x

Modelled property	Modelling variable	A_0	A_1	R^2	n	Boards
IB_{DIN}	V(m/s)	-0,1403	0,0009	0,28	281	2-25
IB_{DIN}	V,sanded(m/s)	-0,0144	0,0008	0,30	199	9-25
IB_{DIN}	$\rho(g/cm^3)$	-0,5255	1,4747	0,25	281	2-25
IB_{DIN}(Mean)	V_{mean}(m/s)	-0,1907	0,001	0,47	24	2-25
IB_{DIN}(Mean)	$V_{mean,sanded}$(m/s)	-0,2602	0,0012	0,64	17	9-25
IB_{DIN}(Mean)	ρ_{mean}(g/cm3)	-0,6141	1,6075	0,29	24	2-25
IB_{DIN}(Mean)	$IB_{tr,nc}$	0,0032	1,0011	0,74	20	2-31
IB_{DIN}(Mean)	$IB_{tr,c}$	0,0564	0,907	0,84	20	2-32

IB_{DIN} - Internal bond from DIN-EN 319 test

IB_{DIN}(Mean) - Internal bond (Mean value of all samples from each board)

$IB_{tr,nc}$ - Internal bond from testrob, before conditioning

$IB_{tr,c}$ - Internal bond from testrob, after conditioning

Appendix 3. Multivariate models and results

The multivariate models for internal bond predictions are listed in table 1. The prediction results are listed in table 2.

The multivariate regressions are in the form:

$$Y = C_0 + a_1 \times x_1 + a_2 \times x_2 + ... + a_n \times x_n$$

Where a is a variable, and x is the corresponding constant.

Multivariate models for prediction of IB

Predicted variable

IB	Predicted internal bond for the sample
IB_s	Predicted internal bond for sanded samples
IB_{mean}	Predicted mean value of internal bond for a board
$IB_{mean,s}$	Predicted mean value of internal bond for a sanded board

Variables used in the models

ρ	The density of the sample or board.
v	Ultra sound velocity, perpendicular to the board plane for unsanded boards (m/s)
v_s	Ultra sound velocity, perpendicular to the board plane for sanded boards (m/s)

Model		R^2	Q^2	n
IB	$-67{,}594+\rho\cdot97{,}594+ v\cdot0{,}20095+ v^2\cdot-0{,}00015+ v\cdot\rho\cdot-0{,}28849+ v^2\cdot\rho\cdot0{,}000214$	0,3752	0,372	281
IB_s	$-60{,}937+\rho\cdot90{,}627+ v_s\cdot0{,}19605+ v_s^2\cdot-0{,}00016+ v_s\cdot\rho\cdot+ v_s^2\cdot\rho\cdot$	0,5256	0,517	199
IB_{mean}	$-77{,}795+\rho\cdot127{,}27+ v\cdot0{,}19962+ v^2\cdot-0{,}00015+ v\cdot\rho\cdot-0{,}28849+ v^2\cdot\rho\cdot0{,}000214$	0,572	0,56	24
$IB_{mean,s}$	$-143{,}98+\rho\cdot216{,}34+ v_s\cdot0{,}47195+ v_s^2\cdot-0{,}00039+\rho^2\cdot-21{,}674+v_s\cdot\rho\cdot-0{,}28598+ v_s^2\cdot\rho\cdot0{,}00021$	0,8776	0,789	17

Multivariate models for prediction of MOR and MOE on large boards

<u>Predicted variable</u>

MOR_{mean}	Predicted mean modulus of rupture, (mean bending strength) for the board.
MOE_{mean}	Predicted mean modulus of elasticity, (mean Young's modulus) for the board.

<u>Variables used in the models</u>

ρ	Density of the sample or board.
T	The temperature of the board (ºC).
v_{per}	Ultra sound velocity, perpendicular to the direction of production (m/s).
v_{par}	Ultra sound velocity, parallel to the direction of production (m/s).
$NF\perp$	Longitudinal eigen frequency perpendicular to the direction of production (Hz).
$MOE\perp_{EF}$	Dynamic modulus of elasticity, calculated from the longitudinal eigen frequency perpendicular to the direction of production.
$MOE\bullet_{US}$	Dynamic modulus of elasticity, calculated from the ultra sound velocity parallel to the direction of production.
$MOE\perp_{US}$	Dynamic modulus of elasticity, calculated from the ultra sound velocity perpendicular to the direction of production.

Model		**R^2**	**Q^2**	**n**
MOR_{mean}	$11588+ NF\perp\cdot 0{,}027447+ v_{par}\cdot -10{,}829+ \rho\cdot -16850+ v_{par}^2\cdot 0{,}00252+\rho\cdot v_{par}\cdot 15{,}743+\rho\cdot v_{par}^2\cdot -0{,}00366$	0,8327	0,746	25
MOE_{mean}	$-3658{,}8+ MOE\perp_{US}\cdot -0{,}0815+ MOE\bullet_{US}\cdot 0{,}49773+ MOE\perp_{EF}\cdot 0{,}44805+\rho\cdot 6141{,}8+T\cdot 12{,}017$	0,7168	0,635	25

Multivariate models for prediction of MOR on bending samples.

The models are built from the measurements from all samples before conditioning.

<u>Predicted variable</u>

MOR_{mean}	Predicted mean modulus of rupture, (mean bending strength) for the board.
MOR	Predicted modulus of rupture, (bending strength) for the board.

<u>Variables used in the models</u>

ρ	The density of the sample or board.
v	In-plane ultra sound velocity in middle layer (m/s).
$NF\perp$	Flexural eigen frequency perpendicular to the direction of production (Hz).
$MOE_{NF\perp}$	The dynamic modulus of elasticity, calculated from the longitudinal eigen frequency perpendicular to the direction of production.
$MOE_{NF\bullet}$	Dynamic modulus of elasticity, calculated from the ultra sound velocity parallel to the direction of production.
MOE_{US}	Dynamic modulus of elasticity, calculated from the ultra sound velocity perpendicular to the direction of production.

Model		R^2	Q^2	**N**
MOR_{mean}	$-18{,}559+\rho\cdot 37{,}692+ v\cdot -0{,}00085+MOE_{US}\cdot 0{,}00083+ MOE_{NF\perp}\cdot 0{,}001687+MOE_{NF\bullet}\cdot 0{,}001349$	0,8176	0,795	50
MOR	$-14{,}854+\rho\cdot 27{,}612+ MOE_{NF\perp}\cdot 0{,}002548+ MOE_{NF\bullet}\cdot 0{,}001893$	0,6897	0,686	400

Multivariate models for prediction of MOE on bending samples.

The models are built from the measurements from all samples before conditioning.

<u>Predicted variable</u>

MOE_{mean}	The predicted mean modulus of elasticity, (mean Young’s modulus) for the board.
MOE	The predicted modulus of elasticity, (Young’s modulus) for the board.

<u>Variables used in the models</u>

ρ	The density of the sample or board.
v	In-plane ultra sound velocity in middle layer (m/s).
$MOE_{NF\perp}$	The dynamic modulus of elasticity, calculated from the longitudinal eigen frequency perpendicular to the direction of production.
$MOE_{NF\bullet}$	Dynamic modulus of elasticity, calculated from the ultra sound velocity parallel to the direction of production.
MOE_{US}	The dynamic modulus of elasticity, calculated from the ultra sound velocity perpendicular to the direction of production.

Model		R^2	Q^2	**N**
MOE_{mean}	$-1412{,}7+\rho\cdot 3221+v\cdot -0{,}21584+ MOE_{US}\cdot 0{,}011403+ MOE_{NF\perp}\cdot 0{,}13929+ MOE_{NF\bullet}\cdot 0{,}90409$	0,8737	0,851	50
MOE	$-3267{,}1+\rho\cdot 27{,}612+v\cdot 1{,}0366+ MOE_{US}\cdot 0{,}29342+ MOE_{NF\perp}\cdot 0{,}32354+ MOE_{NF\bullet}\cdot 0{,}25293$	0,8238	0,823	400

Appendix 4. Temperature influence on sound velocity

Since the temperatures of the specimens have varied during the tests, an experiment was conducted to examine the influence of temperature on the sound propagation time in particleboard specimens. That is, the influence of temperature on the ultrasound velocity.

The experiment was conducted on 8 samples with 0% moisture content at 6 different temperature levels in a temperature interval ranging from 20°C to 115°C.

Results

The sound propagation time was measured for each specimen at all six temperature levels. From this and the corresponding length, the ultrasound velocity was calculated.
The results are listed in the table below (all velocities in m/s):

Table 1: The ultra sound velocity in the test samples at different temperatures

	115°C	**100°C**	**85°C**	**60°C**	**40°C**	**20°C**
Sample 1	1933	1940	1956	2016	2069	2113
Sample 2	1927	1958	1976	2019	2066	2115
Sample 3	1921	1937	1960	2004	2062	2073
Sample 4	1886	1908	1925	1977	2019	2063
Sample 5	1880	1911	1928	1988	2032	2070
Sample 6	1919	1966	1996	2033	2076	2118
Sample 7	1902	1941	1961	2011	2053	2089
Sample 8	1892	1927	1946	1987	2034	2070
Mean value	***1908***	***1936***	***1956***	***2004***	***2051***	***2089***

These values show a very good linear correlation between temperature and sound velocity in particleboard, with a very high R^2=0,996. The result is shown in figure 1.

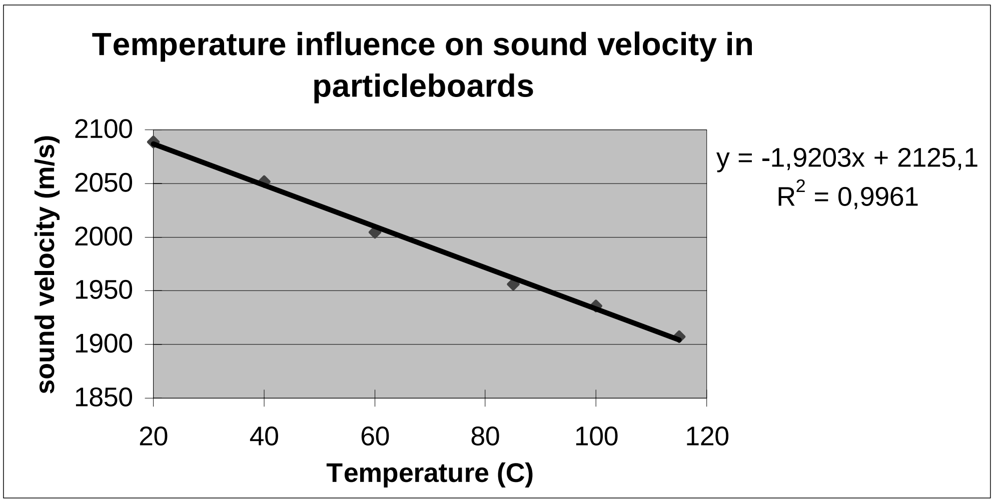

Figure 1: Temperature influence on sound velocity in particleboard

The results for all specimens are shown in figure 2 below.

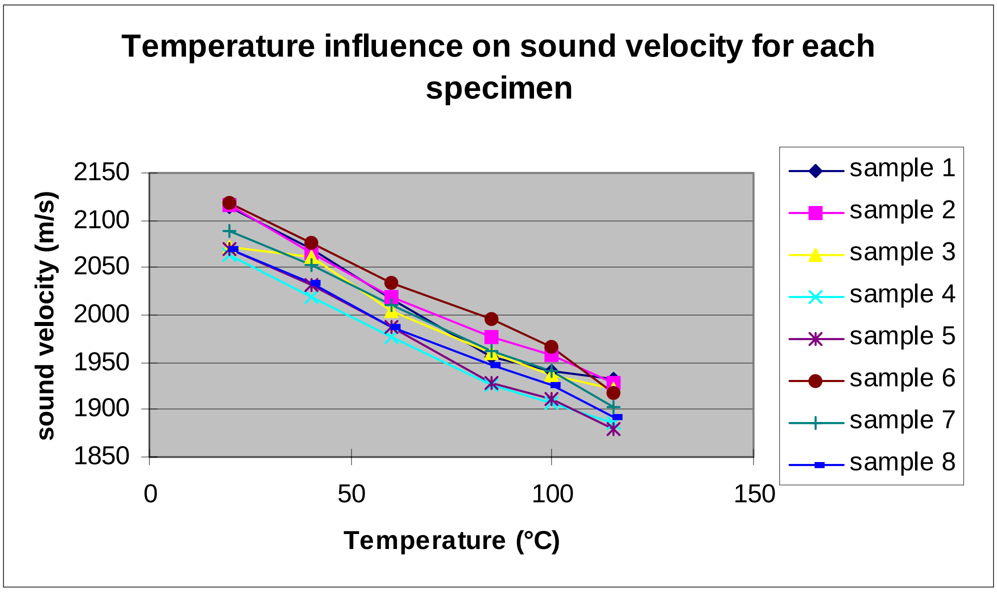

Figure 2: Temperature influence on sound velocity in each test specimen.

Conclusions

The velocity of ultra sound waves in particleboard shows a linear declination with increasing temperature in the board in the temperature range from 20°C to 115°C. This means that calibration for temperature can easily be done. There might be some problems with curing effects though, if the boards are tested shortly after pressing.

Appendix 5. Glossary of terms

In this appendix some of the words and terms that are used in this thesis are explained.

Glossary of words and terms:

Cross-validation	Cross-validation is done by building N models from the data, each time excluding an Nth part of the observations and thereby creating a test set. Each model is then tested on the observations that were excluded when builing the model (test set). When using the software SIMCA, the result of the cross-validation is expressed as Q^2.
Eigen frequency	The frequency of a free, unrestricted vibration in a sample without influence from outer forces and restrictions. (EF or NF are used as short notations in tables etc.).
Flexural vibration	Bending vibration.
IB	Internal bond, the tensile strength perpendicular to the board plane.
MOE	Modulus of Elasticity, Young’s modulus – the stiffness of a sample.
MOR	Modulus of Rupture, the bending strength.
Non-destructive testing	Testing that does not affect the properties of the specimen to be tested.
R^2	Represents the fraction of the variation in the data set that is explained by the model.
Q^2	Q^2 is a measure of the model’s ability to predict future observations, i.e. observations that were not included when building the model.
Transducer	A system to mediate the ultra sound waves into the specimen. In this case it also works as transmitter and receiver of the signal.
Ultra sound	Sound waves with a frequency higher than 20 kHz. (US is sometimes used as a short notation in tables etc.).

Appendix 6. Measuring locations in the different tests

Measuring locations for ultra sound measurements, perpendicular to the board plane.

The ultra sound running time perpendicular to the board plane was measured five times on each sample on the locations marked in figure 1. After sanding, the running time was measured once again on location five (in the middle of the sample). The mean value of the five points was used in the evaluation.

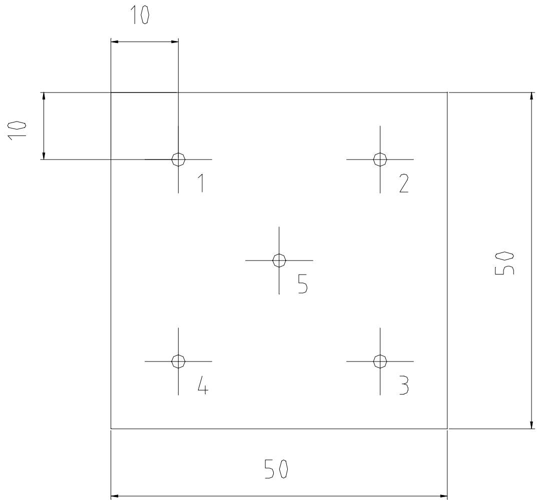

Figure 1: Ultra sound measuring locations on the internal bond samples (all measurements in mm).

Measuring locations on large boards

In regular production, test boards can be cut out of the main boards directly after passing the cooling wheel for process control purposes. The test boards for this test were taken here, and their measurements are set by the restriction that is placed on the location of the saw. Before the test board from the quality control was cut into test samples for the different tests, the whole board was tested. This was made to examine if the methods work on larger pieces of particleboard. The test locations for the testing on the large board are shown in figure 2.

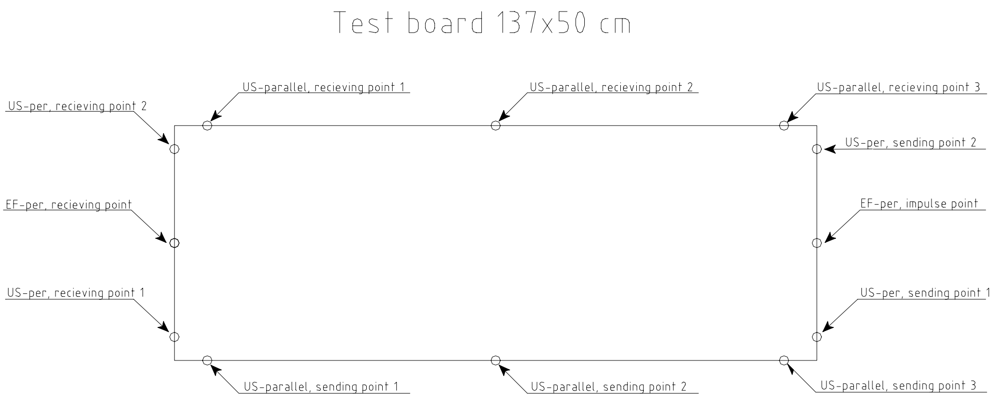

Figure 2: Measuring points on large test board before cutting.

Longitudinal eigen frequency testing was used for these samples. The support was a 4-cm wide and 2-cm thick foam stripe. The receiver (the piezo needle) was placed against the board edge in the location according to figure 2 and the longitudinal vibrations were induced with a light hammer blow against the edge in the impulse point.

Appendix 7. Test schedule

Each board was tested according to a test plan. The test procedure is described step-for-step below:

1. Cutting of the test board according to test plan in appendix 1.
2. Cutting of 4, 50 millimetre wide, stripes for testrob testing.
3. Cutting out moisture samples in laboratory – vacuum packing.
4. Testing of whole test board in laboratory (density, temperature, longitudinal eigen frequency, ultra sound velocity perpendicular and parallel to direction of production).
5. Cutting of test samples (density, bending samples perpendicular and parallel to direction of production, internal bond).
6. Testing of bending samples (density, temperature, flexural eigen frequency, in-plane ultra sound velocity) parallel and perpendicular to the direction of production.
7. Testrob testing on unconditioned samples.
8. Determination of moisture content on half of the moisture content samples – others to conditioning.
9. Determination of density on the density samples.
10. Determination of dry density on the density samples and moisture content.
11. Conditioning, seven days at 25• C, 55% RF.
12. Testing of bending samples (density, temperature, flexural eigen frequency, in-plane ultra sound velocity) parallel and perpendicular to the direction of production.
13. DIN-310 Testing of Young’s modulus and bending strength in test machine.
14. Moisture content determination of bending samples (dry weight method).
15. Testing of internal bond samples (ultra sound propagation time, density).
16. Sanding of internal bond samples.
17. Testing of sanded internal bond samples (ultra sound propagation time, density).
18. DIN 319 test – internal bond.
19. Testrob testing on conditioned samples.
20. Determination of moisture content on conditioned moisture content samples.

Time between pressing and testing

Since time plays an important role as the influence of conditioning was to be determined the time between pressing and testing is important. The normal time from pressing to testing for each operation is shown in figure 1. The time interval depends on the distance between the production hall and the test laboratorium as well as on the large number of test samples to be sawn from each board. Since all test were conducted by one person alone, the tests took some time.
The tests after conditioning were not so influenced of time differences, since the boards have already equalised their moisture content, cooled off and are totally cured.

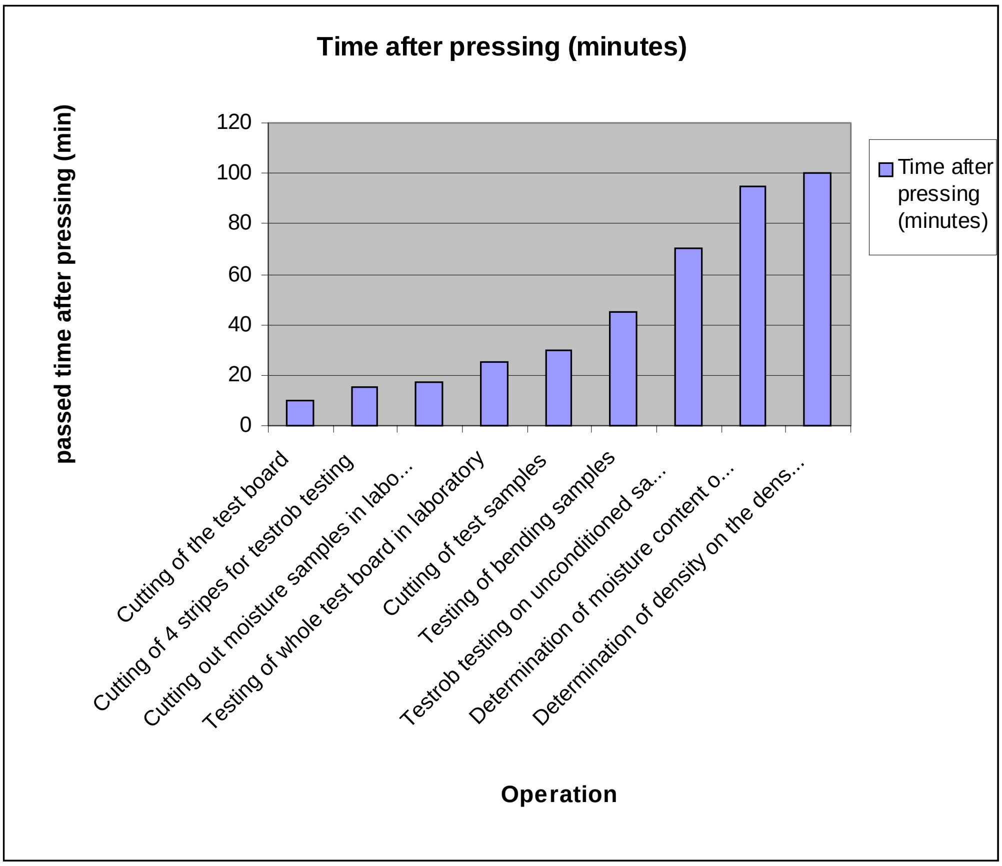

Figure 1: The accumulated time from pressing to the test operations on unconditioned boards.