Comparison of different machine strength grading principles

M. Bacher

MiCROTEC GmbH, Julius Durst Straße 98, 39042 Brixen (BZ), Italy
martin.bacher@microtec.eu

ABSTRACT

In compliance with European Regulation and with particular reference to EN 14081, grade assignment of timber is based upon observation of three properties: strength, stiffness and density. Timber is hereby segregated into different grades. However, characteristic values are statistical properties: strength and density are described by 5% percentile values and stiffness by the mean value. In other words, even though every piece is assigned to a single grade, the properties can only be determined for the overall population of observations and not for every single piece of timber.
ViSCAN, with it's built in laser interferometer, measures the frequency of vibration. X-ray scanning is used to compute density on cross (DENSCAN) and longitudinal (GoldenEye) transport. These measurement units can be used stand-alone or in combination. In this paper different combinations are compared with respect to their performance in grade prediction.
Since moisture content influences wood properties an in-line moisture meter (M3SCAN) optionally can be installed so to adjust the measured properties to reference conditions.
By using camera based systems, visual override and aesthetical requirements can be considered during grading. Most common are limitations on warp (twist, bow, spring, cup), wane, fissures, knot size and colour changes.

INTRODUCTION

End user's needs for structural timber are a mix of engineering properties, utility and aesthetic requirements. Even if grading is targeted to performance rather than appearance, customers are more and more looking for timber with good mechanical properties yet nice looking. As the mechanical properties are often quite difficult to understand by end users, quality marks have been built so to instil confidence, yet timber with large knots doesn't sell as easy even if the performance requirements should be fulfilled.

STRENGTH GRADING

If timber is used in a permanently in construction works it must meet the requirements of the Construction Products Directive (CPD), which are specified in the European standard EN 14081 as for structural timber. By 1st of September 2009 all structural timber (with rectangular cross section) needs to be produced in compliance with EN 14081 standards since by then and in most European countries the CE mark is going to be obligatory.
EN 14081 mentions three methods for the strength grading of the timber:

i. Visual grading
ii. Machine grading (machine controlled)
iii. Machine grading (output controlled)

At last, the end user expects a product with well described characteristics and should not be aware about the grading process as there should be no difference in the reliability and performance of the product.
Regarding point i): visual grading rules were established in many countries based on many destructive tests. Visual grading rules are valid for a defined species from a specified growth area. The grading rules are observed by the visual grader, but it is assumed that he will not change the rules according to the timber quality.
Next and to point ii): the grading machine uses settings which are published in part 4 of the standard. As in visual grading many destructive tests were performed so to identify the correct settings for a defined species again for a specified growth area. The producer only uses the grading machine and is not allowed to change any settings. For this kind of operation it is crucial that all grading machines of the same type operate equally within well defined limits.
Finally and to point iii): in output controlled machine grading the output of the grading process is checked continuously. Different grading machines of the same type can give different results, as they are verified independently and every installation has its own settings.
Recently a new concept of adaptive settings for machine grading was proposed to react to occurring quality shifts (Sandomeer et.al 2007, Sandomeer et.al. 2008). Such quality shifts can be detected on several measured parameters simultaneously and can be quite dramatic (Fig. 1).

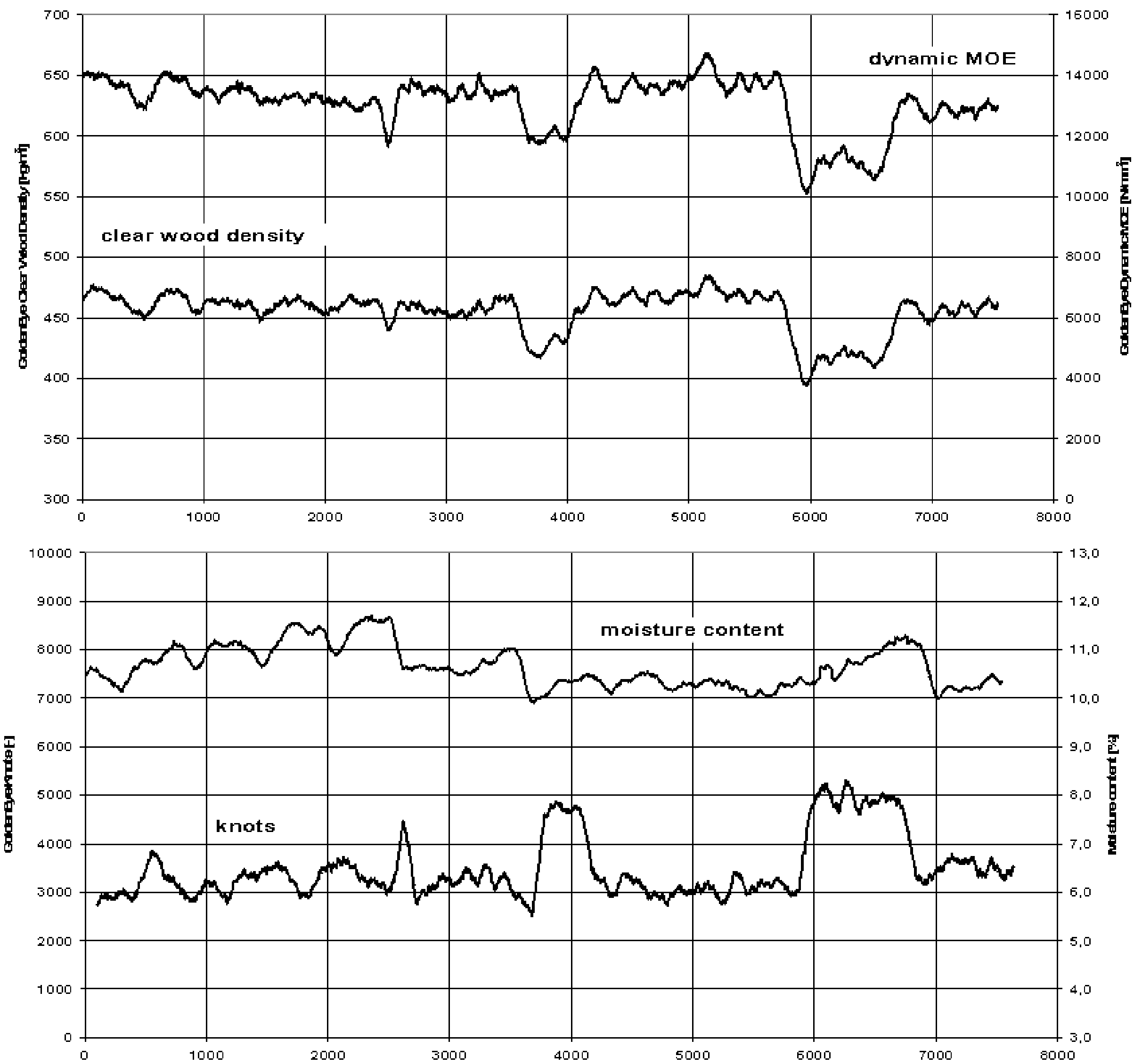

Figure 1: Quality shifts observed by GoldenEye-706 within 4 hours of production of spruce 44x88 (mean values calculated with a sliding window of 100 pieces for clear wood density, dynamic MOE, knots and moisture content)

For standard or high quality raw material these settings may be too conservative and for the low quality material still too optimistic. Adaptive thresholds have the potential to improve the overall yield for the producer and simultaneously also to increase the reliability in the product for the end user.

The European strength grade system is described in EN 338 as follows:

- i) Strength is considered to be the most important property, as strength is related to the structural safety of our buildings. Therefore also the lower 5th percentile value of the graded population was chosen as characteristic value.
- ii) Stiffness is important for design engineers, as commonly the requirements on deflection limit the design. Stiffness determines the performance of the building. The characteristic value is given by the mean value of the population.
- iii) Density is the third grade determining property and sometimes considered less important, since density as a single parameter is not a good predictor for strength.

According to the strength class system described in EN 338 the compression and tensile strength perpendicular to grain are derived from the characteristic density. Some recent studies (Ranta-Maunus A. 2007 and Steiger et.al. 2006) found a good correlation between density and compression strength parallel to grain. Density is also important for the design of connection (embedment strength for dowel type fasteners) and the strength of glued finger joints. Density as a grade determining property is needed as long these secondary properties are not derived in a better way from other parameters. As density is used as a predictor for strength properties also the lower 5th percentile value is relevant.

The output control procedure currently requires only a verification of the bending strength (by proof loading the graded pieces) and the bending stiffness. The density is not required to be verified. Also for this production process, end users should expect to get a product with met density requirements.

Strength:

The real strength of timber can only be measured by a destructive test and, unfortunately, can not be used anymore for construction afterwards. Therefore strength can only estimated from non-destructive measurements of wood characteristics (knots, density, rate of growth, modulus of elasticity, slope of grain). Several studies showed the benefit of combining different grading parameters (Diebold et.al. 2000, Denzler et.al. 2005, Hanhijärvi et.al. 2008).

Stiffness:

The stiffness can be measured almost directly by several methods:

- bending machines (by bending each piece as a plank over a short span)
- ultrasonic method (measuring the velocity of sound)
- vibration method (measuring the natural frequency of vibration after a short impact)

The ultrasonic and vibration method both need also the length and density of the piece to calculate the dynamic modulus of elasticity:

$$MOE_{dyn} = \rho \cdot v^2 = \rho \cdot (2 \cdot l \cdot f)^2 \qquad (1)$$

It is important to keep always in mind that the bending stiffness which is relevant for C-grade assignment of a piece of timber is measured in laboratory by bending the piece as a joist ("edgewise"). The relationship between the methods used for grading and this reference methods used in the laboratory are quite good, yet not flawless.

Density:

In laboratory the density according to the European standard EN 384 can be determined by two methods:

- Small sample (preferred method described in ISO 3131:1975)
- Whole specimen (by measurement of the mass and volume; this method is allowed only "where not all the specimens are test to failure"; this values have to be divided by the factor 1.05 to convert them to clear wood density)

The density can be measured by several methods also in a production environment:

- Industrial scale: Load cells measure the mass. They are very sensitive components and it is difficult to achieve high accuracy at high feeding speed. The volume is needed to calculate the density.

- Newton's 2nd law of motion ($F = m \cdot a$): By measuring the acceleration of the piece the mass can be calculated. The volume is needed so to calculate the density.
- Attenuation of radiation: Measures directly the product of density and thickness. Only thickness is needed as dimension, as the measurement does not depend on width and length of the board.

According to EN 14081-2 (machine controlled) it is not necessary to perform specific measurements, but to demonstrate that the grading machine is able to correctly assign any piece of timber to its grade on condition that the required characteristic values of the three grade determining properties are fulfilled. The assignment of too many pieces to a wrong grade is avoided by calculating the cost-matrix (Rouger 1997). There is a limitation on the amount of wrongly upgraded pieces. Wrongly downgraded pieces are allowed, as they are no risk for the customer, but lower the yield of the producer. It is explicitly mentioned that it is not necessary to actually measure the density by the grading machine, but to show the density requirement is fulfilled.

NON CONTACT GRADING MACHINES

MiCROTEC's strength grading approach is based completely on non contact measurements (Giudiceandrea 2005):

> *GoldenEye uses X-ray to determine knots and density of a board. The radiation is partially absorbed, depending on the thickness, moisture content and density of the board. This results in a grey scale image which can be processed by means of image processing. Since the density of knots is approximately twice as high as the density of the surrounding clear wood, knots can be detected accurately regarding size and position.*

DENSCAN measures the density on several positions over the length of the board with low power X-ray sources and high performance X-ray sensors. The X-ray sources work without water cooling and need no lead shielding.

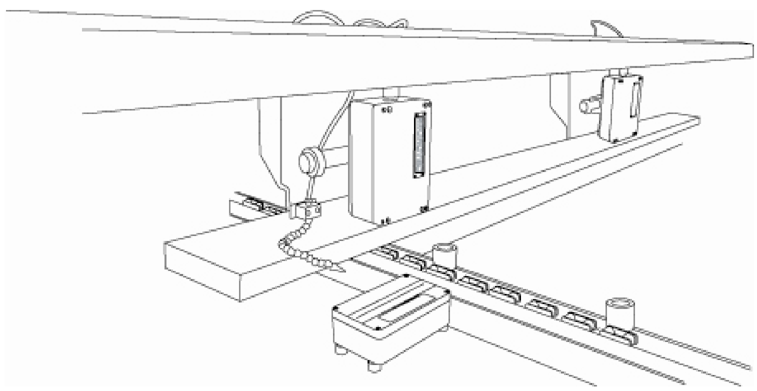

Figure 2: DENSCAN (measuring density based on X-ray technology on transverse transport)

ViSCAN measures the oscillation contact free with a laser interferometer, thus operating totally independently of interfering ambient conditions such as noise which can cause relevant problems for microphones. Together with the measured length, ViSCAN is used as a stand-alone grading machine without measuring the density. ViSCAN can be combined with DENSCAN, which then includes also density information. Thereby mainly the prediction of the grade determining properties density and stiffness is improved.

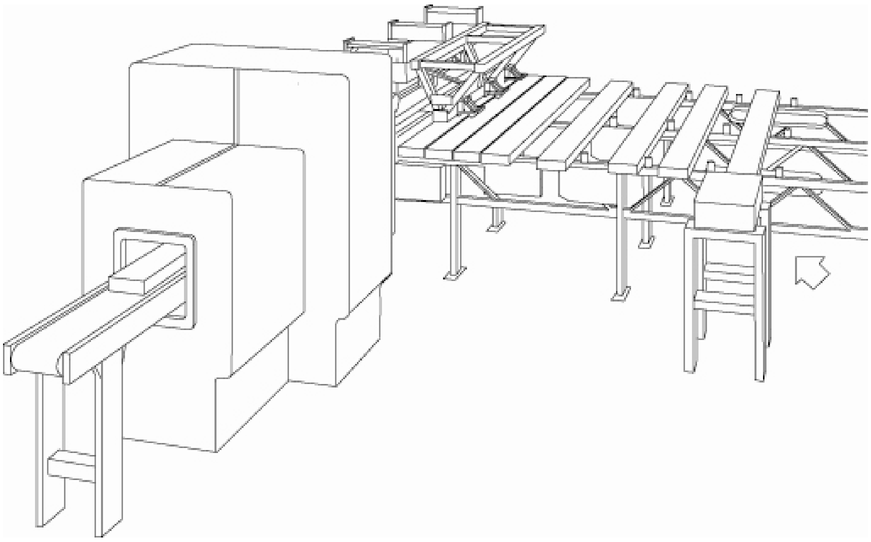

Figure 3: GoldenEye-706: combination of GoldenEye 702 with ViSCAN (arrow)

The concept is modular, as the measurements units can be used stand-alone or in combination, depending on the producers needs, which very often change over time:

- GoldenEye-706 (X-ray scanner and ViSCAN vibration)
- GoldenEye-702 (X-ray scanner)
- ViSCAN (stand-alone)
- ViSCAN PLUS (combination of ViSCAN and DENSCAN)

Machine settings for different species, growth areas and grade combinations are available in EN 14081-4.

Timber which is used in applications where the tensile strength controls the design (glulam, flange material for I-joists, cross laminated timber) is graded most efficiently by considering tensile parameters already during the grading. Therefore timber is tested in the laboratory in tension and tensile strength and tensile stiffness is measured.
Currently, EN 14081-4 features machine settings for three different types of tensile grades, namely:

- L-grades (derived from C-grades)
- LS-grades (for density only indicative values are given and density is not guaranteed)
- LD-grades (for high grades lower density values than L-grades)

MiCROTEC machine settings, listed currently in EN 14081-4 for spruce (*picea abies*) and fir (*abies alba*) grown in Central Europe for L-grades, were derived from 3,333 tensile tests. In Fig. 4 the scatter plots with the coefficient of determination (R^2 value) for the grading machines GoldenEye-706, GoldenEye-702 and ViSCAN are represented:

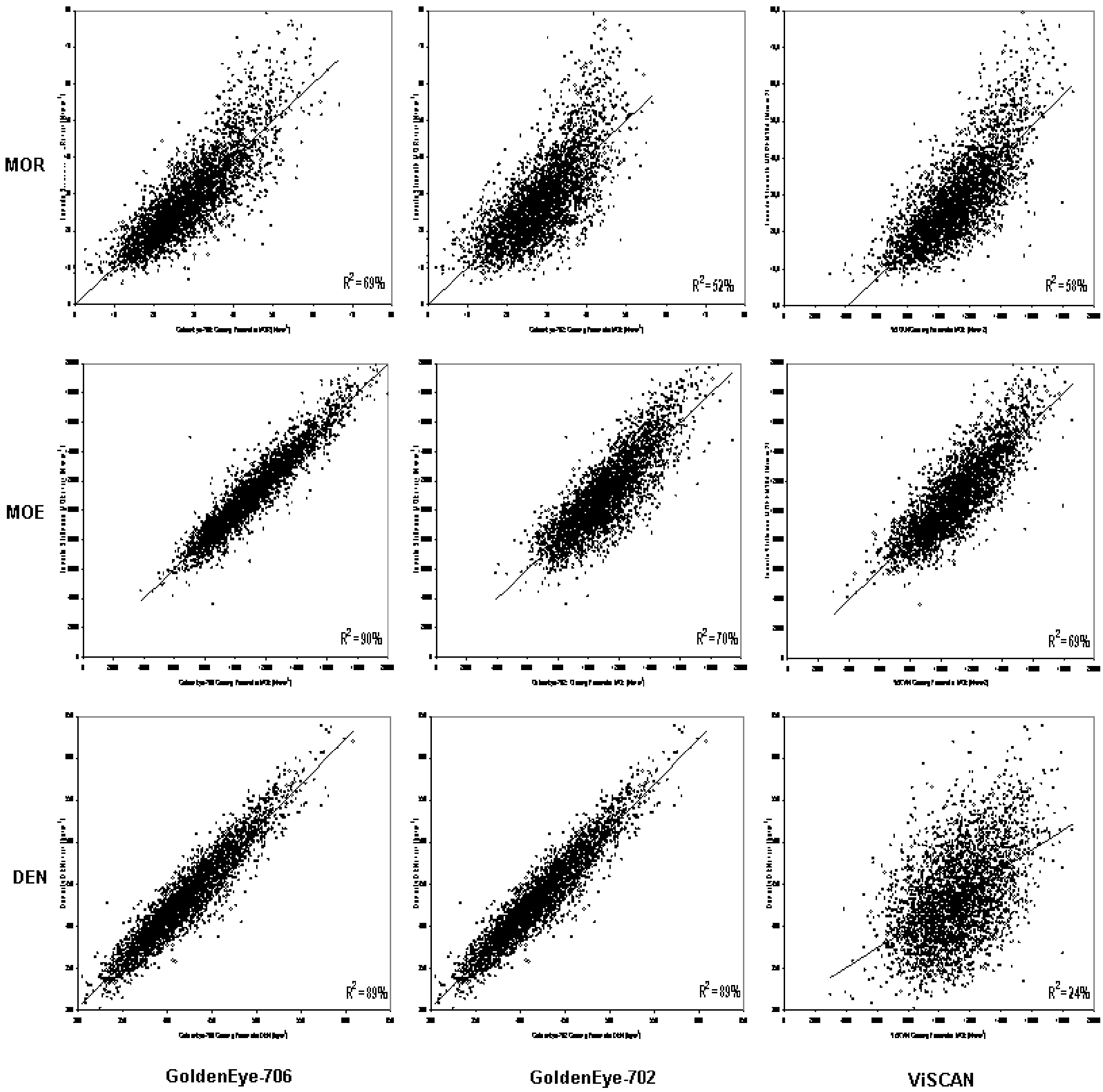

Figure 4: Scatter plots (grading parameters versus grade determining properties)

MOR: modulus of rupture (strength)
MOE: modulus of elasticity (stiffness)
DEN: density

GoldenEye-706:	MOR=69%	MOE=90%	DEN=89%
GoldenEye-702:	MOR=52%	MOE=70%	DEN=89%
ViSCAN:	MOR=58%	MOE=69%	DEN=24%

Conclusions:

- GoldenEye-706 is predicting all three grade determining properties independently and achieves today the highest grading performance for industrial strength grader.
- GoldenEye-702 and ViSCAN sport a very similar performance in predicting stiffness (69%-70%). Currently, some common growth areas are valid only for “settings based on modulus of elasticity”. The vibration and ultrasound measurements are considered often as stiffness based grading. As long density is not included the term “velocity based grading” should be used.
- GoldenEye-706 and GoldenEye-702 measure clearly wood density with high accuracy (R^2=89%). The correlation between the velocity based grading parameter of ViSCAN and density is poor (R^2=24%).
- Similar results were obtained for spruce grown in Nordic Europe tested in tension (Hanhijärvi et.al. 2008):

GoldenEye-706:	MOR=64%	MOE=91%	DEN=92%
GoldenEye-702:	MOR=49%	MOE=69%	DEN=92%
ViSCAN:	MOR=53%	MOE=64%	DEN=14%

ViSCAN and ViSCAN PLUS return only grading parameters for the whole piece (average stiffness and average density) and are not able to determine a low point position. Instead GoldenEye-702 and GoldenEye-706 are able to calculate strength, stiffness and density profiles over the entire length of the board. By applying also the limits on every position a grade profile is generated. Depending of the final application, the minimum grade defines the final grade, or the board can be upgraded into a higher grade thanks to cutting optimization (as it was always done in visual grading). This optimizing process can improve yields dramatically and is therefore the first choice for finger-joint lines (finger-jointed structural timber, glulam, I-beams).

Strength grading currently is done mainly after kiln drying (“dry graded”). For many applications a well controlled drying process is crucial. Also for the grading process the moisture content is relevant, as many wood parameters vary with moisture content of the wood. If the relationship between measured parameters and moisture content is known, the parameters can be adjusted to reference conditions (typically 12%). The contact free in-line moisture meter M3SCAN incorporates a new approach in density compensation and measures the moisture content of every piece on both, cross and longitudinal transport.

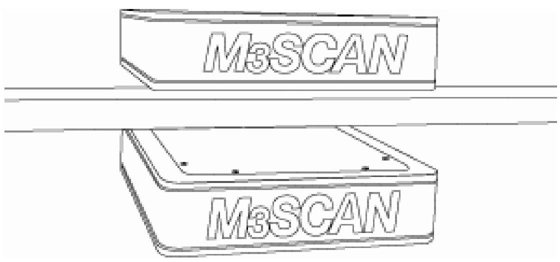

Figure 5: M3SCAN (contact free in-line moisture meter)

VISUAL OVERRIDE, VISUAL STRENGTH GRADING and APPEARANCE GRADING

EN 14081-1 requires for machine grading also some visual characteristics to be checked for each piece:

- Dimensions (thickness, width measured according EN 336)
- Wane
- Fissures
- Soft rot and dote
- Warp
- Abnormal defects

MiCROTEC's grading machines measure the complete length of each piece (including the ends). Therefore no special visual override for the ends has to be applied.

Visual grading rules are based in Europe on common strength reducing characteristics defined in Annex A of EN 14081-1:

- Knots
- Slope of grain
- Rate of growth (or density)
- Fissures
- Wane
- Warp
- Other characteristics (reaction wood, mechanical damage, in bark, covered damage to the stem and top rupture)

In addition, end customers have aesthetic requirements which not necessarily affect the strength (blue stain, oil from the machinery).

In past, these characteristics were checked by visual graders. Today this task is increasingly supported or replaced by visual scanning systems, which incorporate a combination of different technologies:

- X-ray scanning (used already for machine strength grading)
- Laser scanning (combination of lasers and black-and-white cameras)
- Colour scanning (for optimized detection of colour errors)

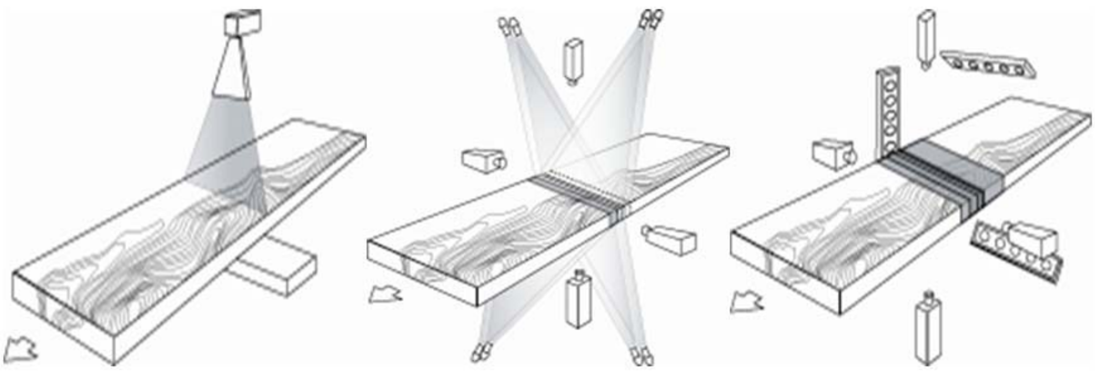

Figure 6: X-ray, laser and colour scanning

Warp is a significant defect since timber is very difficult to use should the shape not be within defined limitations. Warp is closely related to drying practise. Strong warp is as well a strength reducing characteristic as it is caused by reaction wood or spiral grain. Bow, spring and twist can be measured accurately with CURVESCAN during longitudinal or transversal transport.

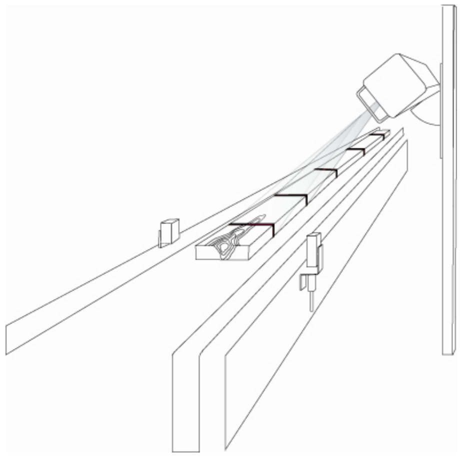

Figure 7: CURVESCAN (warp measurement unit in longitudinal transport)

CONCLUSIONS

The ongoing introduction of the CE marking has accelerated the introduction of quality control systems by many producers of structural timber. The end customer's expected quality is represented today by a mix of structural and aesthetic characteristics, which can only be efficiently guaranteed in high speed production environment by the most recent and top-notch innovations in measurement technology.

REFERENCES

Denzler J., Diebold R., Glos P. (2005) Machine strength grading – commercially used grading machines – current developments. *Proceedings of the 14th International Symposium on Nondestructive Testing of Wood*, May 2nd-4th 2005, Hannover, pp. 9-16

Diebold R., Schleifer A., Glos P. (2000) Machine grading of structural sawn timber from various softwood and hardwood species. *Proceedings of the 12th International Symposium on Nondestructive Testing of Wood*, September 13th-15th 2000, Sopron, Hungary, pp. 139-146

Giudiceandrea F. (2005) Stress grading lumber by a combination of vibration stress waves and X-ray scanning. *Proceedings of the 11th International Conference on Scanning Technology and Process Optimization in the Wood Industry (ScanTech 2005)*, July 24th-26th 2005, Las Vegas, Nevada U.S.A., pp. 99-108

Hanhijärvi A., Ranta-Maunus A. (2008) Development of strength grading of timber using combined measurement techniques – Report of the Combigrade-project – phase 2. VTT Publications 686, Espoo, Finland, 2008

Ranta-Maunus A. (2007) Strength of Finnish grown timber. VTT Publications 668, Espoo, Fnland, 2007

Rouger F. (1997) A new statistical method for establishment of machine settings. *Proceedings of the 30th Meeting, International Council for Research and Innovation in Building and Construction, Working Commission W18 – Timber Structures*, CIB-W18, Paper No. 30-17-1, Vancouver, Canada, 1997

Sandomeer (ne Deublein) M.K., Köhler J., Linsenmann P. (2007) The efficient control of grading machine settings. *Proceedings of the 40th Meeting, International Council for Research and Innovation in Building and Construction, Working Commission W18 – Timber Structures*, CIB-W18, Paper No. 40-5-2, Bled, Slovenia, 2007

Sandomeer M.K., Köhler J., Faber M.H. (2008) Probabilistic output control for structural timber – Fundamental model approach. *Proceedings of the 41th Meeting, International Council for Research and Innovation in Building and Construction, Working Commission W18 – Timber Structures*, CIB-W18, Paper No. 41-1-1, St. Andrews, Canada, 2008

Steiger R., Arnold M. (2006) Revisiting EN 338 and EN 384 basics and procedures. *Proceedings of the 39th Meeting, International Council for Research and Innovation in Building and Construction, Working Commission W18 – Timber Structures*, CIB-W18, Paper No. 39-6-2, Florence, Italy, 2006