A method for quality control of strength grading machines using non-destructive measurements

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ABSTRACT

To ensure that wood has strength properties as declared, quality control procedures have been developed to verify the output of grading machines For sawn timber, the correctness of the grading process in the production facility depends on the machine settings and machine data processing. To CE-mark machine graded timber according to EN 14081 a Factory Production Control that deals with these aspects has to be set up in a company. The standardised control of the result of the grading process is by destructive testing of randomly selected pieces. In this paper it is shown that the quality of the control process can be improved using non-destructive measurements. The method gives a better insight in the correctness of the grading process than the standardised method. The possible use of stress wave measurements in quality control will be presented.

INTRODUCTION

CE-marking of strength graded timber according to European standard EN 14081 will be obliged as of September 2009. This standard has officially been published in November 2005, so nowadays it is already possible to CE-mark strength graded timber. Settings for strength grading machines have to be derived according to EN 14081-2. With these settings the machine can grade the timber into one or more strength classes, using the strength predicting models in the machine. When the grading machine and the settings are accepted by the relevant Task Group of CEN/TC124, they can be listed in EN 14081-4.
An important condition for in the process of CE-marking strength graded timber in a company is the presence of a certified Factory Production Control (FPC). In this FPC the provisions for the control of the grading process are given. An additional requirement is given in EN 14081-3 for strength grades with a characteristic bending strength value above 30 N/mm^2. : "During each working shift, two pieces of timber from each grade produced shall be randomly selected and the bending strength shall be destructively tested according to EN 408. The fifth percentile value, determined by ranking of the 100 bending strength values from 50 consecutive shifts shall meet the required bending strength for the grade." The standard continues with the following remark: "However, another strength property may be used for quality control as an alternative, provided the relation between the two properties is verified from test data."
The method with destructive bending tests is not very effective for quality control purposes. First of all, the test results will only become available long after the timber has been graded and secondly it will be hard to judge if the timber is wrongly graded. Therefore, an alternative method is presented based on the method of non-destructive stress wave measurements.

Figure 1: Left: an in-line grading machine set-up, right: the Timber Grader MTG, a hand grading device based on stress waves

AN ALTERNATIVE METHOD FOR CONTROL BASED ON STRESS WAVE MEASUREMENTS

Background

The basis for the alternative method is the use of non-destructive measurements for strength prediction. These non-destructive measurements may be performed with a handheld strength grading machine, such as the Timber Grader MTG, any other machine type may be used as well. The machine should also be accepted for CE-marking strength grading timber and listed in EN 14081-4. The basis of the alternative method is that more information is used from the measurements than only the predicted strength class. To explain this we look at the diagram where the bending strength values according to EN 408 (f_{stat}) are plotted against the predicted bending strength based on the non-destructive measurements, see Fig. 2. Model 1 ($f_{mod,1}$) is the model in the control machine and model 2 ($f_{mod,2}$) is the model of the machine of which the output has to be controlled. Model 1 has an r^2- value of 0,70 and model 2 of 0,51.

We consider a case where the output of strength class C35 has to be controlled. The regression line for f_{stat} calculated from $f_{mod;1}$ is known. We determine the standard deviation around the regression line by determining the standard deviation from $f_{mod,1} - f_{stat}$. This results in a distribution that is close to a normal distribution around a mean 0. Then, for every point of $f_{mod;1}$ the distribution around the regression line is known, as illustrated in Fig. 2. For every value of $f_{mod;1}$ the probability that the result of f_{stat} is lower than 35 N/mm^2 can now be calculated, using the standard normal distribution. A diagram of these values is given in Fig. 3. In Fig. 3 the probability that the actual value of f_{stat} is lower than 35 N/mm^2 out of a destructive test is plotted against the values of $f_{mod;1}$. In the rest of this paper the probability that the actual value of f_{stat} is lower than 35 N/mm^2 out of a destructive test will be called the p-value of a model ($f_{mod;1}$ or $f_{mod;2}$) value. (The same dataset is used for model 1 and model 2)

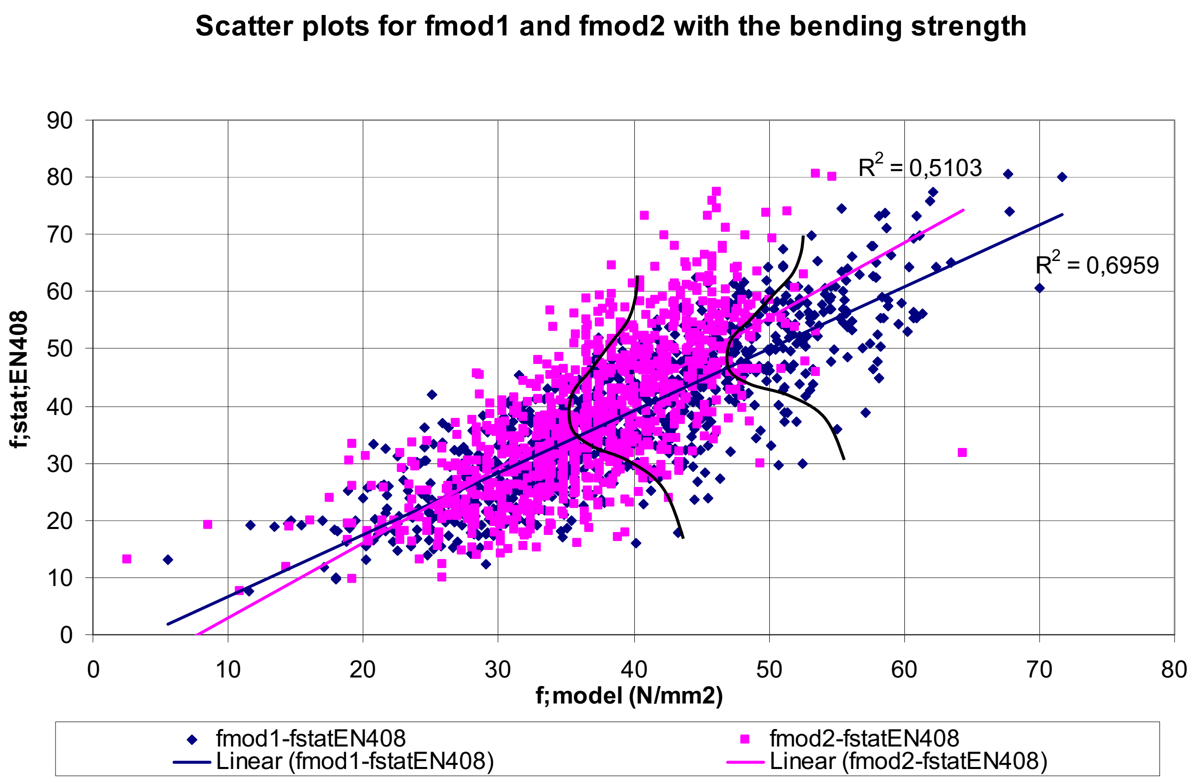

Figure 2: f_{stat} plotted against $f_{mod;1}$ and $f_{mod;2}$

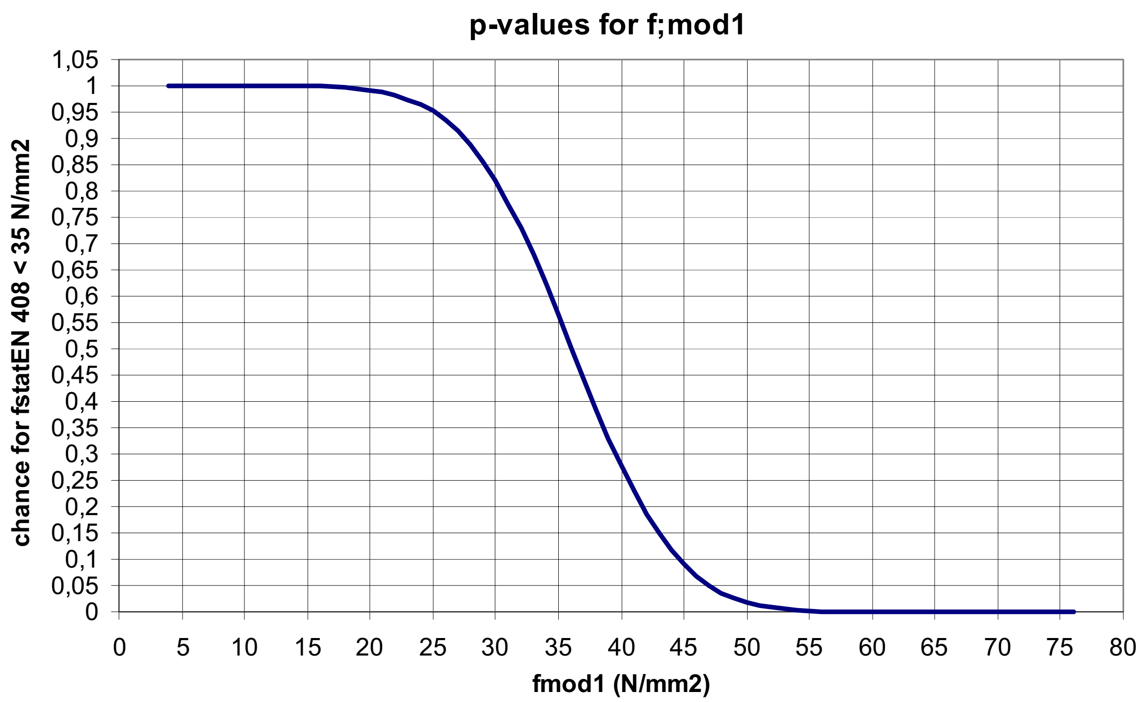

Figure 3: The probability of the actual value of f_{stat} being lower than 35N/mm^2 plotted against the values of f_{mod1}

Application on a test sample of pine.

The method is illustrated on a dataset of 920 pine beams. With model 1 30% of the test sample is assigned to C35 while with model 2 15% is assigned to C35. For every value of f_{mod1} graded into C35 the p-value is calculated for both model 1 and model 2. The histograms of the frequency of p-values are given in Fig. 4.

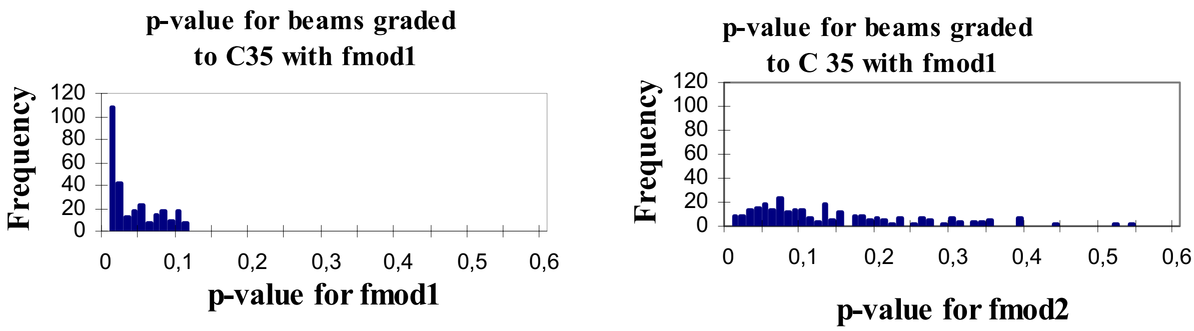

Figure 4a en b: Histograms of p-values for timber graded with fmod1

In Fig. 5 the same is done for the same sample graded with $f_{mod,2}$ in C35. So this is 15% of the test sample. The p-values according to model 1 and 2 are calculated. The histograms of the frequency of p-values are given in Fig. 5.

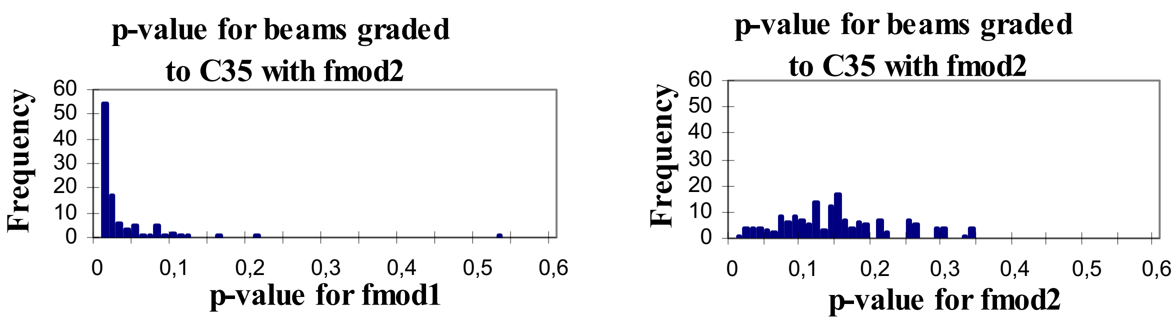

Figure 5a and b: Histograms of p-values for timber graded with fmod2

Fig. 4a shows that when you look at the individual test results, a probability of 0,11 for timber graded and controlled with $f_{mod,1}$ can still be correctly graded into C35. Fig. 4b shows that it will be difficult to use the measurements of $f_{mod,2}$ to predict the correctness of the output graded with $f_{mod,1}$. Fig. 5 shows that the method will be effective if the r^2-value of the control model is higher than or equal to that of the model that is to be controlled.

In the next section three different scenarios for the timber grading process are presented and the consequences on the standard method and the control method are shown.

THREE DIFFERENT SCENARIOS FOR THE TIMBER GRADING PROCESS

Description of three scenarios.

In the next section three different scenarios for the timber grading process will be presented.

- Scenario 1: The timber is correctly graded and marked with the predicted strength class for each beam.
- Scenario 2: There is an error in the marking process and each timber beam is marked with the strength class result of the preceding beam
- Scenario 3: The error mentioned in the bullet point before has occurred only for 10 beams (5 shifts)

These scenarios are simulated where real destructive and non-destructive data is available. This data has been used for deriving strength grading models 1 and 2, i.e. $f_{mod,1}$ and $f_{mod,2}$ is known for every beam.

Scenario 1. The timber is correctly marked with the predicted strength class for each beam based on model 1.

In Fig. 6 the fifth percentile values out of destructive bending tests, determined by ranking of the most recent 100 bending strength values are given for a dataset of n=276. This is done for beams that are graded into C35 with model 1. So for test result 100, the fifth percentile value of result 1 to 100 is given, for test result 101, the value of result 2 to 101, etcetera.

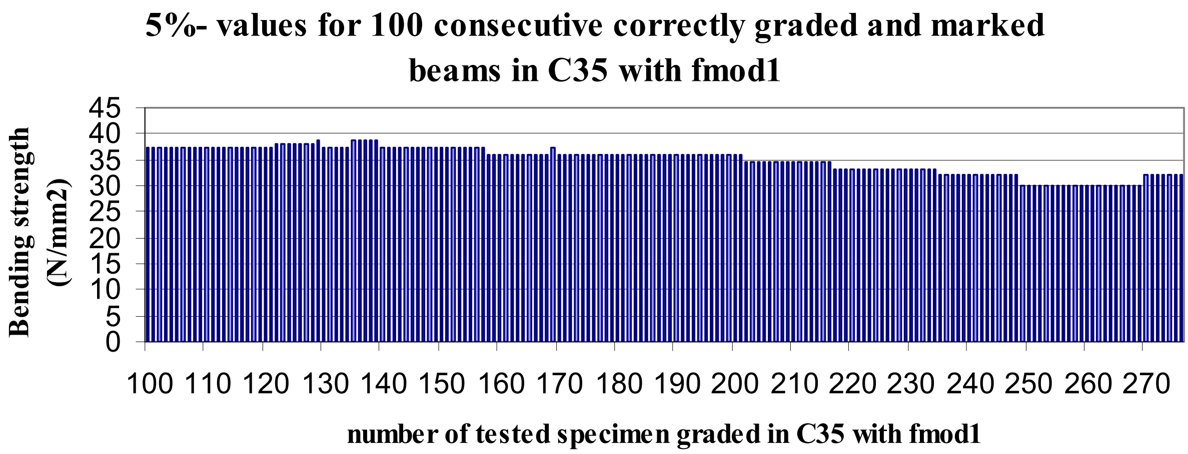

Figure 6: Fifth percentile values for 100 consecutive test results for beams correctly graded and marked in C35

Fig. 6 shows that, although all beams were correctly graded, the fifth percentile value of 100 consecutive bending test results can vary between 30 and 37 N/mm^2.

To get an impression of the results with the presented alternative control method using model 1 a sensitivity analysis was made in two ways. The first manner was by randomly selecting 10 datasets of 100 pieces out of 276 beams. The second was by selecting 10 datasets of 10 pieces of the sample of 276 beams. For every dataset the mean and standard deviation of the p-values of $f_{mod,1}$ are calculated. In Table 1 the average values of the mean values and standard deviation values for each dataset are given.

Table 1: P- values for beams graded and controlled with model 1 for scenario 1

Number of specimen in each of the 10 generated datasets	Average mean p-values (n=10)	Average p-values standard deviations (n=10)	Average of fifth percentiles of destructive test results (N/mm^2)
N=100	0,033	0,032	34,0
N=10	0,034	0,036	[-]

Next we see what happens when we calculate the predicting values for beams graded with a machine using model 2. Since this model has a lower r-squared value a smaller percentage will be graded in C35. For this example we use n= 155 beams graded in C35 from 78 shifts. We now use the alternative control method using model 1. The predicting results are given in table 2.

Table 2: P-values for beams graded with model 2 and controlled with model 1 for scenario 1

Number of specimen in each of the 10 generated datasets	Average mean p-values	Average p-values standard deviations	Average of fifth percentiles of destructive test results (N/mm^2)
N=100	0,040	0,080	35,2
N=10	0,036	0,065	[-]

The reason that the standard deviation in Table 2 is bigger than in table 1 remains in the fact that although model 1 has a higher r-squared value than model 2 there can be a small number of beams that are graded in a lower class with model 1 than with model 2, which shows in a higher p-value.

Scenario 2. There is an error in the marking process and each timber beam is marked with the strength class result of the preceding beam.

Fig. 7 shows the result of beams marked with C35 with a process using model 1. However, an error has occurred in the marking process and each beam is marked with the grade of its preceding beam. It shows that this has a disastrous effect on the fifth percentile values of the bending test results of the control beams, all being far under 35, so it shows that something is wrong.

In Table 3 the results for the p-values are given based on measurements with the control machine using model 1, similar to the grading machine

In Table 4 the results for the p-values are given based on measurements with the control machine using model 1 and the original machine using model 2.

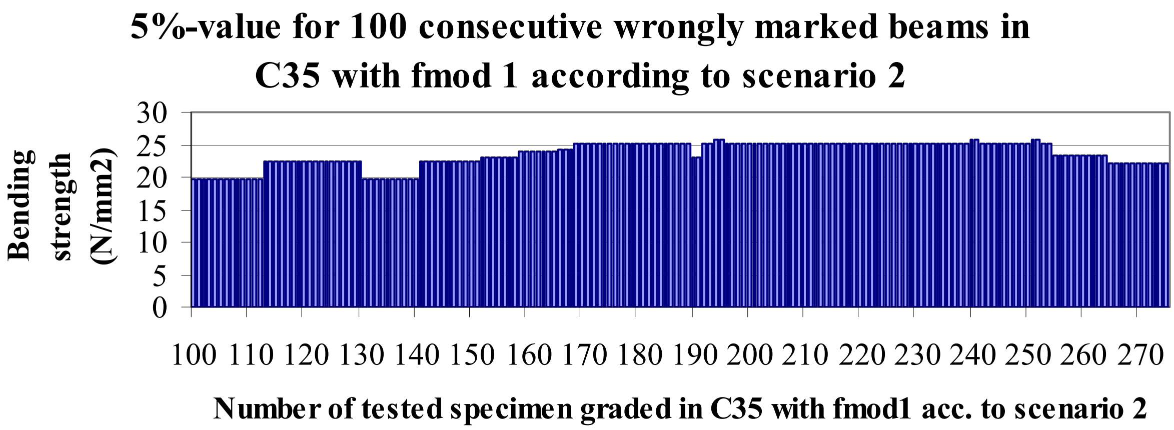

Figure 7: Fifth percentile values for 100 consecutive bending test results where each timber beam is marked with the strength class result of the preceding beam

Table 3: P- values for beams graded and controlled with model 1 for scenario 2

Number of specimen in the 10 generated datasets	Average mean p-values	Average p-values standard deviations	Average of fifth percentiles of destructive test results (N/mm^2)
N=100	0,34	0,34	20,0
N=10	0,33	0,32	[-]

Table 4: P-values for beams graded with model 2 and controlled with model 1 for scenario 1 for scenario 2

Number of specimen in the 10 generated datasets	Average mean p-values	Average p-values standard deviations	Average of fifth percentiles of destructive test results (N/mm^2)
N=100	0,32	0,34	20,0
N=10	0,33	0,32	[-]

It shows that for the control of both methods it is clear that there is something wrong with the grading process. Remarkably is that this already shows with only 10 beams evaluated with the proposed control method.

Scenario 3: There is an error in the marking process so that 10 timber beams are marked with the strength class result of the preceding beam.

All beams are graded correctly, but for 5 shifts (giving 10 control beams) the same problem occurred as in scenario 2. In Fig. 8 the effect on the fifth percentile value of the last 100 subsequence bending tests are shown. The beams that have got the grade of the preceding beam are the numbers between 130 and 140. These beams were graded as C35, but 5 beams should have been marked C35 and 5 beams C24. The influence area on the fifth percentile bending strength of the wrongly marked beams is from beam 130 until beam 240.

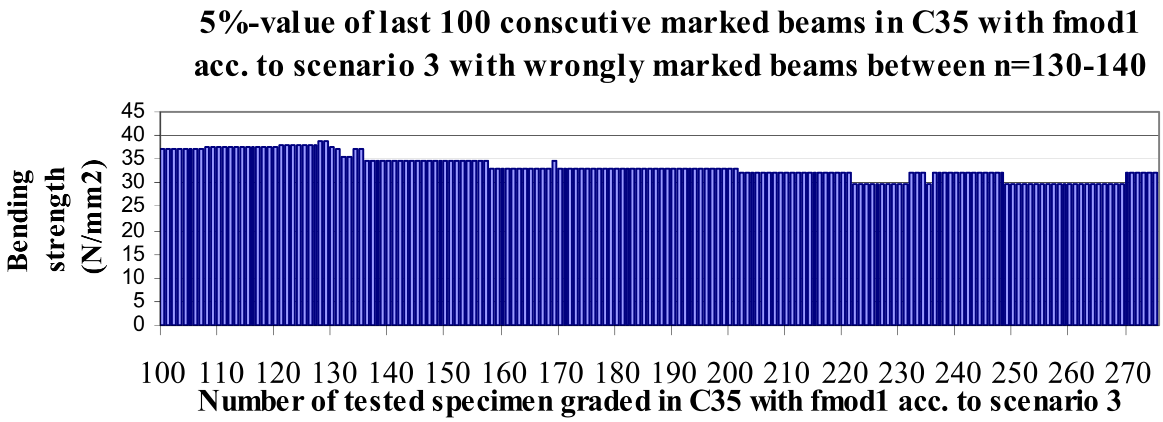

Figure 8: Fifth percentile values for 100 consecutive bending test results according to scenario 3 for beams graded and controlled with model 1

In Fig. 9 the p-values of model 1 of the beams graded in C35 with model 1 with the mistake in the marking between beams 130-140 are shown.

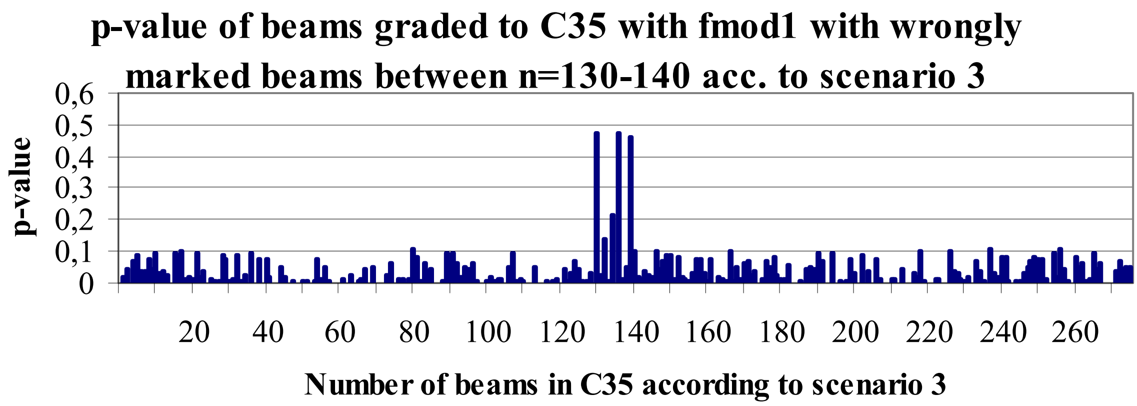

Figure 9: The p-values of the beams graded to C35 with wrongly marked beams between n= 130-140 according to scenario 3

In Fig. 10 the mean p-value of the last consecutive 10 p-values are shown. This also shows that there is a problem between n=130 until n=140.

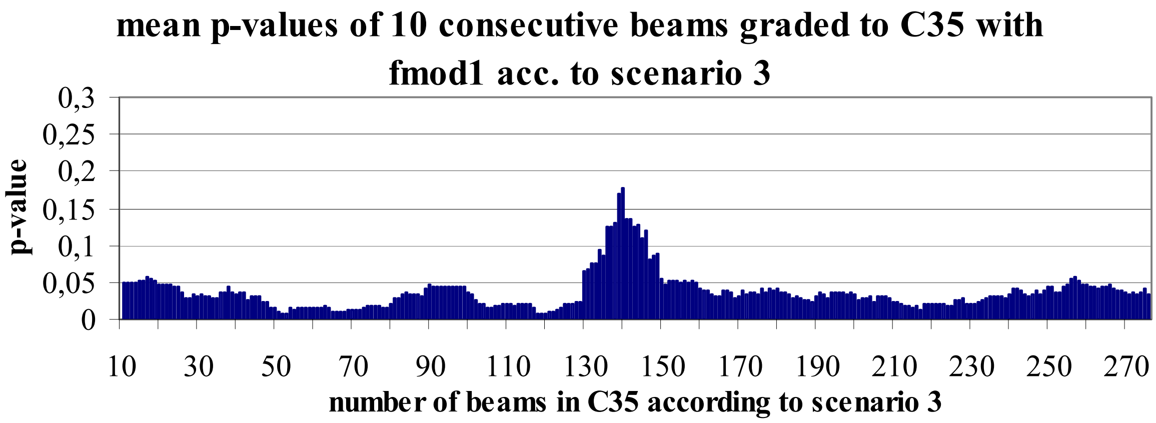

Figure 10: Mean p-values of 10 consecutive beams graded to C35 with wrongly marked beams between n= 130-140 according to scenario 3

Fig. 8 shows that it is not possible to recognize the problem based on the fifth percentile values of the last 100 consecutive bending tests, because the influence of these 10 test results on the characteristic value by ranking is only minor. When we look at Fig. 9 and 10 with the results of the p-values of the beams that were graded C35 it becomes instantly clear that there is a problem with the beams between n= 130 to n=140. The average mean p-value between n=130 to n=140 is 0,18 and the standard deviation is 0,21, which is a clear indication that something is wrong.

In Fig. 11, 12 and 13 the same pictures are shown as 8, 9 and 10 for the shift of 1 week for beams graded with model 2 and controlled with model 1. The shift here occurs between beams n= 120 to n=130.

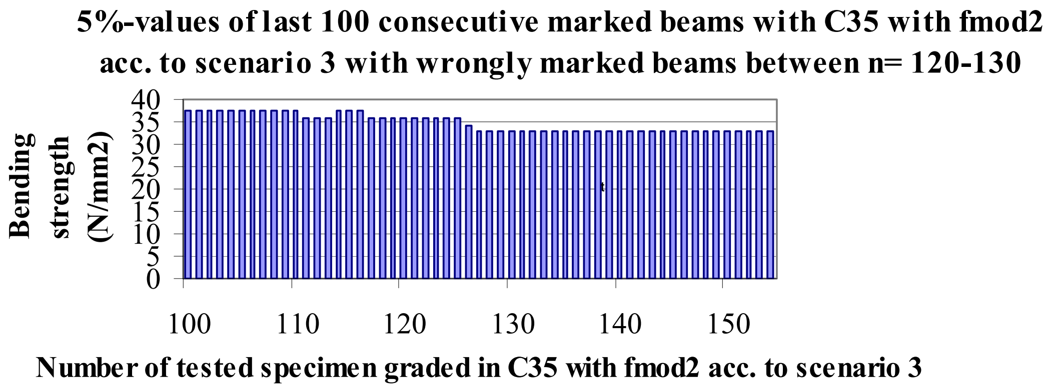

Figure 11: Fifth percentile values for 100 consecutive bending test results according to scenario 3 for beams graded with model 2 and controlled with model 1

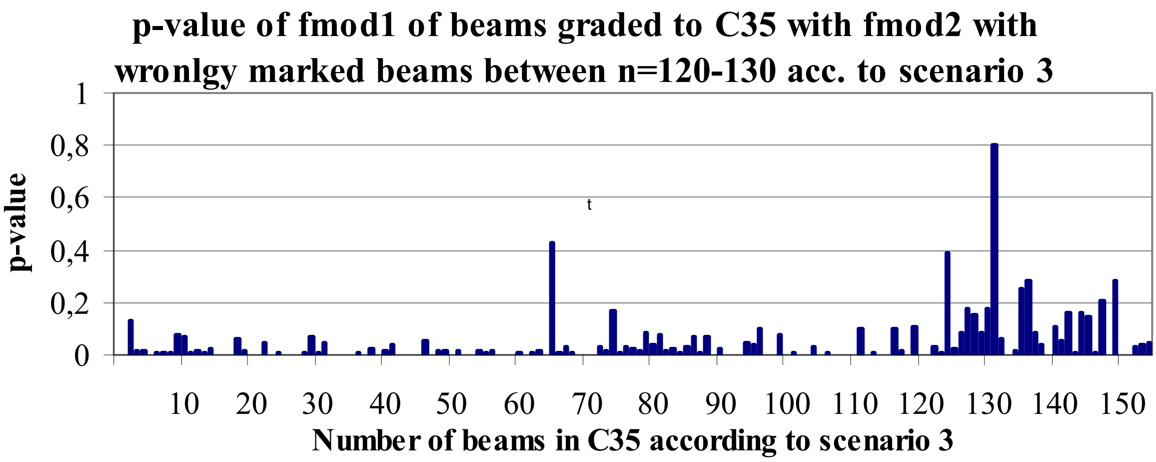

Figure 12: The p-values of the beams graded to C35 with model 2 and controlled with model 1 with wrongly marked beams between n= 120-130 according to scenario 3

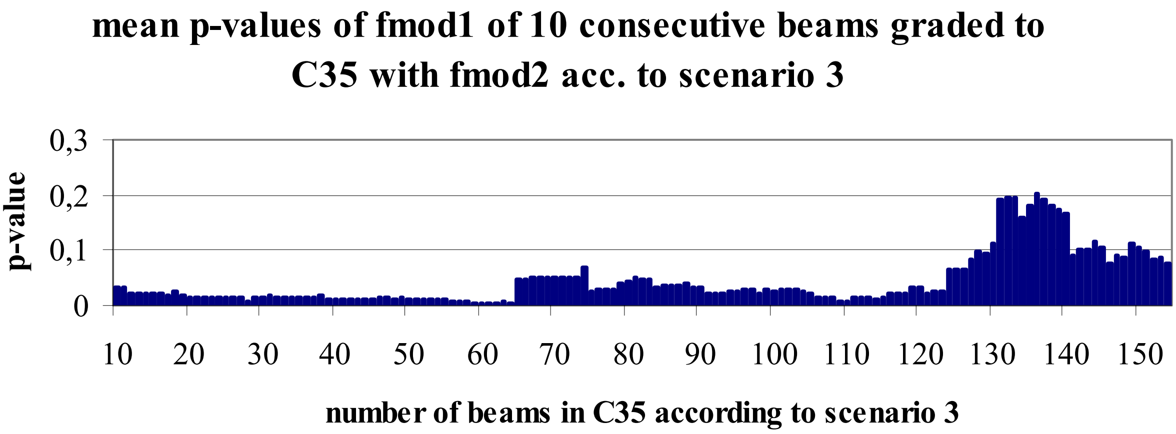

Figure 13: Mean p-values of 10 consecutive beams graded to C35with model 2 and controlled with model 1 with wrongly marked beams between n= 120-130 according to scenario 3

Out of table 1 it can be calculated that the value for the average 10 p-values for which with 95% probability can be stated that these are incorrectly graded into C35 is 0,033 + 1,65 * 0,0343 = 0,085 for beams graded with model 1 and checked with model 1.
Out of table 2 it can be calculated that the value for the average 10 p-values for which with 95% probability can be stated that these are incorrectly graded into C35 is 0,036 + 1,65 * 0,065 = 0,14 for beams graded with model 2 and checked with model 1.
When these values are compared with the results in Fig. 9 and 12, it shows that these limit values show that the problem of the shifted marking is detected for both situations.

SUMMARY AND CONCLUSIONS

A dataset of 920 pine beams was graded with two different models and the maximum strength class of C35. The beams assigned to the highest strength class were controlled with a non-destructive approach. Three different scenarios in the grading process have been analysed of which two contained a deliberate mistake, in order to verify whether the non-destructive approach would be able to detect grading errors. The following conclusions could be drawn:

- The method where the fifth-percentile values of 100 consecutive destructive bending tests have to be evaluated is not very effective to detect grading errors and a number of 10 wrongly graded beams within these 100 beams can not be detected.
- An alternative method based on non-destructive measurements is presented. The method calculates the probability that the beam has a lower strength than the assigned strength class. When setting an appropriate limit to this probability value possible grading errors can easily be detected without the need of expensive laboratory testing.
- Analysis shows that with the presented method 10 wrongly graded beams in a set of 100 can clearly be detected.
- The presented method can be used as an alternative method for the quality control of strength grades. The method may serve as an alternative for the current requirements in EN 14081-3 with regard to the Factory Production Control .

REFERENCES

EN 14081-1. Timber structures - Strength graded structural timber with rectangular cross section - Part 1: General requirements

EN 14081-2. Timber structures - Strength graded structural timber with rectangular cross section - Part 2: Machine grading - additional requirements for initial type testing

EN 14081-3. Timber structures - Strength graded structural timber with rectangular cross section - Part 3: Machine grading - additional requirements for factory production control

EN 14081-4. Timber structures - Strength graded structural timber with rectangular cross section - Part 4: Machine grading - Grading machine settings for machine controlled systems