DEVELOPMENT OF GRADING RULES FOR SCAFFOLD BOARDS

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ABSTRACT

A programme of work has been completed for the UK Health and Safety Executive (HSE) concerned with the development of visual and machine grading rules for 38 x 225 mm scaffold boards spanning either 1.2m or 1.5m between supports. Both the machine and visual grading rules, reported in full elsewhere, were derived from grading measurements and bending tests on the same set of 300 boards, thereby giving the opportunity for a direct comparison of the effectiveness of the strength-indicating parameters underpinning the two methods of grading. Flatwise modulus of elasticity (FMOE), as measured by flatwise bending machines, was found to be far more accurate in predicting bending strength than any of the visual defect measures (or combinations thereof), with knot measures proving to be a poor indicator of bending strength.

Keywords: Scaffold boards, Visual Grading, Machine Stress Grading

INTRODUCTION

The current British Standard BS2482 [1] giving the specification for scaffold boards has not been widely used by the UK scaffolding industry. This situation has arisen because it contains a board specification which is not commercially viable for a support span for which there is little demand from industry. Instead, the industry has opted to supply scaffold boards using a plethora of Trade Standards. This itself is an unsatisfactory situation as they often have no proven scientific basis.

In view of this situation, the HSE commissioned a project to develop revised machine and visual grading rules for scaffold boards for incorporation into BS2482. This project ranged from consideration of the loads acting on scaffold platforms, through to grading and testing 300 boards, and finally to analysing this data in order to derive grading rules[2]. This paper, however, concentrates on comparing the effectiveness of the grade-indicating parameters underpinning machine and visual grading. Initially a summary of the test programme undertaken is presented before considering the relative effectiveness of machine and visual grading in predicting the flatwise strength of scaffold boards. The overall conclusions from this work have been drawn in the final section.

TEST PROGRAMME

Three hundred and twenty 3.9m long scaffold boards of nominal cross-section 38 x 225mm were delivered to the University of Brighton between October 1999 and March 2000 for the purpose of deriving new machine and visual grading rules for scaffold boards. All the boards were European Whitewood and to ensure that they were representative of those in use in the UK, each of the four main board suppliers, who are estimated to supply 60-70% of the UK market, provided 80 boards. The boards were supplied unsorted and had not been subjected to any grading prior to dispatch to the University of Brighton. On their arrival, each board was subjected to the following series of measurements:

1. Each board was assigned a reference number and then marked on one of its edges at 100mm intervals, being the spacing at which grading machines normally take their readings. The boards were passed through a Cook-Bolinder grading machine which had been installed for this specific purpose. The Cook-Bolinder grading machine operates by applying a fixed deflection across a 900mm span and measuring the loads at 100mm increments as the timber passes flatwise through the machine. In the case of 38mm sawn timber the magnitude of the fixed deflection is 7.1mm and the speed at which the boards were passed through the machine was 60m/minute. For each board a full record of the loads measured was taken and stored on computer.

2. The full 3.9m board length was inspected with a view to identifying its worst three cross-sections in respect of visual defects. Usually these cross-sections were selected based on the knots present in the board, though occasionally one of the cross-sections was chosen because of high slope of grain on edge. For each cross-section a knot plot was drawn taking note of the pith position. The three knot plots from each specimen were all drawn on the same sheet of paper to facilitate comparisons between them.

3. The locations of the three worst cross-sections identified in point 2 were then cross-referenced against the board's full-length machine grading record and the cross-section to be subjected to structural test was chosen. For broadly half of the boards the cross-section with the worst visual defects coincided with the location of the lowest grading machine reading. A 1.5m test length was cut out such that the predicted 'failure' cross-section was located at approximately the centre of this test length.

4. The following measurements were taken on the 1.5m test length:

a) Thickness, width, length, weight and moisture content (Protimeter digital moisture meter)
b) The number of growth rings counted across as large a dimension as was practical on one end of the test length
c) The underlying slope of grain on edge not directly associated with a specific visual defect. This measurement was assigned one of the following four categories:

Category A -	Less than	1:20.
Category B -	Between	1:20 and 1:10.
Category C -	Between	1:10 and 1:6.
Category D -	Greater than	1:6.

5. From the hand-drawn knot plot relating to the predicted 'failure' cross-section, produced as described in point 2, a graphics tablet and digitising puck were used to record the co-ordinates of the board corners, pith position and knots for the cross-section on computer as a text-output file. Software was written to tabulate these data in Excel-format and to enable a computer-generated knot plot to be produced.

6. After ensuring that the board reference had been re-marked on the shortened board, each 1.5m test length was immersed in a tank of water for a duration of usually one week. After removal from the tank a check was made, using a Protimeter moisture meter, that the moisture content of the test length was above the fibre saturation point. The test length was then loaded to failure in 4-point bending. The ultimate bending moment and mode and location of failure were recorded.

For the purpose of giving some indication of the quality of the timber used in the UK for scaffold boards, Table 1 gives a synopsis of the results of the grading and bending strength measurements taken. In respect of slope of grain no values are presented as it was found that very few boards had a slope of grain on edge exceeding 1 in 10.

Table 1. Summary of results of grading and bending strength measurements taken on European Whitewood 38 x 225mm scaffold boards

Parameter (units)	Magnitude of parameter	
	Mean	Range
Oven-dry specific gravity	0.39	0.30 – 0.60
Flatwise modulus of elasticity (N/mm^2)	7372	3638 - 11186
No. of growth rings per 25mm	8.0	3.8 – 17.1
Knot area ratio	0.22	0 – 0.51
Modulus of rupture (N/mm^2)	28.6	10.7 – 50.9

ACCURACY OF FLATWISE MODULUS OF ELASTICITY AS A GRADE-INDICATING PARAMETER FOR SCAFFOLD BOARDS

Regression analyses were undertaken between flatwise modulus of elasticity (FMOE) and modulus of rupture (MOR). It was found that a linear regression had a higher coefficient of determination (R^2) at 0.71 than a power regression at 0.69. It was also found that the linear regression passed very close to the origin such that forcing the linear regression through the origin resulted in virtually no decrease in coefficient of determination. Equation 1 is the mean regression line of this type:

$$MOR = 0.00388\,(FMOE) \qquad (1)$$

The coefficient of determination of 0.71 found for scaffold boards is substantially higher than that (R^2 = 0.50-0.55) generally found for European Whitewood [3] used in mainstream structural work. This difference can be attributed to the fact that scaffold boards, unlike mainstream structural timber members, are loaded in use about the same axis as they are during the machine strength grading operation.

ACCURACY OF VARIOUS VISUAL DEFECT MEASURES AS GRADE-INDICATING PARAMETERS FOR SCAFFOLD BOARDS

Three physical characteristics that have a direct effect on bending strength are rate of growth, knots and slope of grain. Regression relationships for these characteristics, firstly considered in isolation and then in combination, were established as in the following sections.

Regression relationship between modulus of rupture and rate of growth

The coefficient of determination of a linear regression between modulus of rupture and rate of growth, defined in terms of the number of growth rings per 25mm, is 0.33.

Regression relationships between modulus of rupture and various defect measures for knots

In a number of the existing Trade Standards for scaffold boards, separate rules are listed for each of the various types of knot. It was therefore decided, before commencing the regression analyses, to investigate whether there was any type of knot that had a particularly adverse effect on board strength. The boards were split into six categories in respect of the knots present as illustrated in Figure 1. The mean values of modulus of rupture, growth ring width and knot area ratio for these six categories of board are given in Table 2.

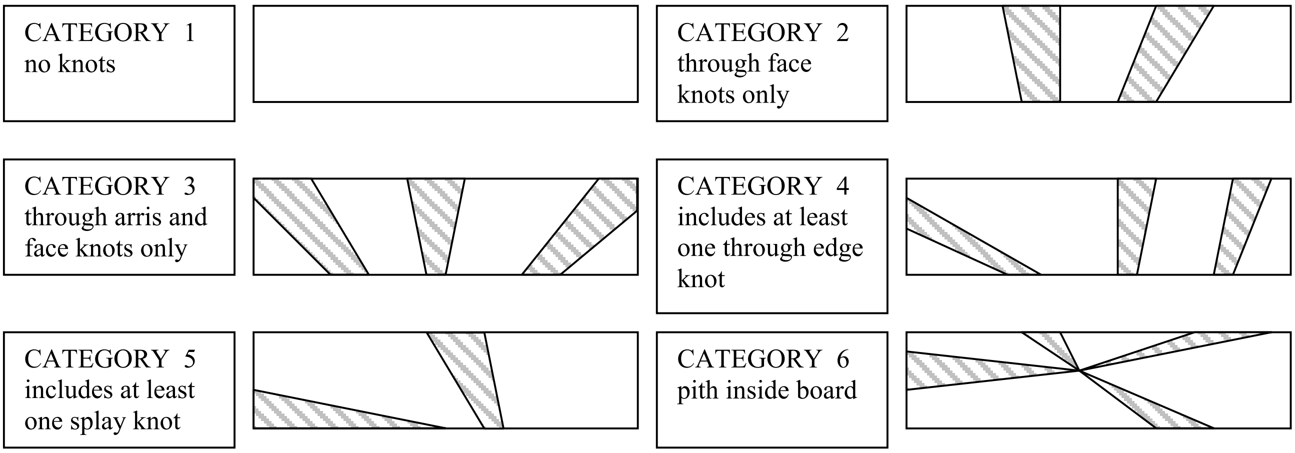


Figure 1 Categories related to the disposition of knots present

Table 2. Variation of MOR, rate of growth and knot area ratio with differing dispositions of knots in boards.

Knot type (refer also to Figure 1)	Number of specimens	Mean modulus of rupture (N/mm^2)	Mean growth ring width (mm)	Mean knot area ratio
No knots	5	36.4	2.8	0
Through face knots only	58	31.1	3.2	0.18
Through arris and face knots only	45	27.7	3.3	0.26
Contains at least one edge knot emerging on face	52	29.7	3.2	0.23
Contains at least one splay knot	56	26.9	3.5	0.23
Pith located inside board	55	25.9	3.8	0.22

The following observations are made with respect to the findings of Table 2:

a) The knot area ratios are relatively uniform across the various dispositions of knot considered. However, the higher than average modulus of rupture of boards with through face knots only, can broadly be attributed to their lower than average knot area ratio with the reverse being true for the category of boards with through arris and face knots only.

b) Similarly, the rate of growth characteristics are broadly uniform across the various dispositions of knot considered. However, as expected, on account of their higher proportion of juvenile wood, the boards with the pith located inside the board have the greatest mean growth ring width. This in turn explains why these boards have the lowest average modulus of rupture of all the categories considered.

c) Overall it is concluded that there is no knot type that has an especially adverse effect on board strength.

The regression analyses undertaken between modulus of rupture and knot dimensions fall into two categories. In the first category the regression analyses only involve single knot measures whereas in the second category multi-variate regressions have been carried out. Table 3 summarises the findings of the first category of regressions in terms of the efficiency of the various knot measures in predicting modulus of rupture. This efficiency is appraised by considering the magnitude of the associated coefficients of determination. Although UK scaffold board suppliers have made it clear that the final rules for knots must be based on surface knot dimensions and not knot area ratios, it is generally recognised that knot area ratio rules set the benchmark to which alternative knot measures should aspire and knot area ratio is, therefore, included in Table 3. The following observations are made with respect to the effectiveness of the various surface knot dimension measures recorded in Table 3:

a) All the surface knot dimension measures have a lower coefficient of determination than the value of 0.22 attributable to knot area ratio.

b) Not surprisingly the greater the proportion of the total surface dimension of the board included in the knot measure, the better its coefficient of determination. The best 'surface knot dimension' coefficient of determination of 0.16 being that for all four surfaces.

c) The coefficients of determination for 'both faces' or even a 'single face' do not diminish greatly below that appertaining to all four surfaces.

d) Not surprisingly there is virtually no correlation between board strength and cumulative surface knot dimensions on edge as a 'stand-alone' parameter.

The importance of the relationships outlined in points 1-4 should not be over-emphasised in view of the fact that all the knot measures, including knot area ratio, have a lower coefficient of determination than that of rate of growth.

Table 3. Coefficients of determination of various knot measures

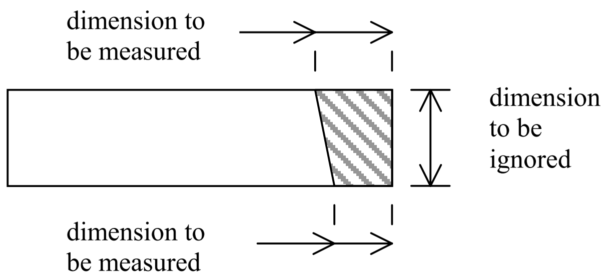
Description of knot measure	Coefficient of determination
Knot area ratio	0.22
Cumulative knot dimension on four surfaces	0.16
Cumulative surface knot dimension on both faces	0.15
Cumulative surface knot dimension on single face	0.14
Cumulative surface knot dimension on both edges	0.04
Cumulative surface knot dimension on single edge	0.05

The second category of regression analysis treats face and edge knot dimensions as separate variables in a multi-variate analysis. In fact the regression analyses are based on surface cumulative 'clear wood' dimensions (SCCD) which are evaluated by deducting the associated surface cumulative knot dimension (SCKD) from the relevant nominal board dimension. This step was taken so that modulus of rupture increases with an increase in the grade-predicting parameter, thereby facilitating comparisons between linear and power regressions for the parameter. The coefficients of determination for these regressions are summarised in Table 4.

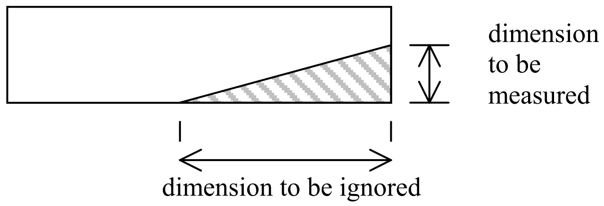
Table 4. Coefficients of determination of multi-variate regression analyses for knots

Description of knot measure	Description of associated 'clear wood' dimension	Coefficient of determination
1.SCKD for both faces 2.SCKD for both edges	1.SCCD for both faces 2.SCCD for both edges	0.16
1.SCKD for both faces modified in line with Fig.2 2.SCKD for both edges modified in line with Fig.2.	1.SCCD for both faces modified in line with fig.2 2.SCCD for both edges modified in line with fig.2.	0.21

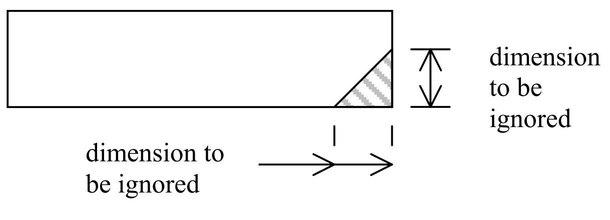
From the top row of Table 4 it can be seen that treating face and edge knot dimensions as separate variables in the regressions results in only modest improvements to the coefficients of determination. The final row of Table 4 relates to the method of measurement for knots outlined in Figure 2, which was developed when it was observed that the influence of small knots around board corners on the surface cumulative knot dimensions was not in proportion to their influence on the MOR of the board. Consequently the method of measurement of Figure 2 allows the surface knot dimensions of these small corner knots to be discounted when evaluating the cumulative surface knot dimensions on edge and on face. From Table 4 it can be seen that this step has a beneficial effect on the coefficient of determination, bringing it up to broadly the same magnitude as that appertaining to knot area ratio.



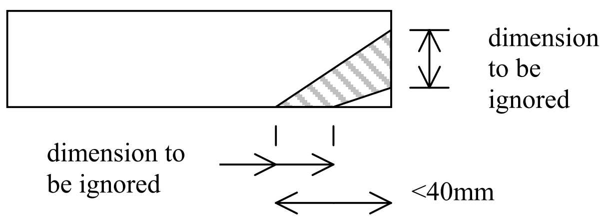
a) Edge margin knot



b) Large splay knot
(knot extends >40 mm along face from corner)



c) Small splay knot
(knot extends <40 mm along face from corner)



d) Small through edge knots
(knot extends <40 mm along face from corner)

Figure 2 Proposed method of measurement for knots - surface dimensions to be ignored

Note: with the exception of the four types of knot shown in Figures 2a-d, the dimensions of all knots shall be measured when determining whether a board satisfies limits for knots.

Overall it can be concluded that the effectiveness of knot measures as parameters for predicting modulus of rupture is poor, having a maximum coefficient of determination of 0.22 compared with the coefficient of determination found for rate of growth of 0.33 and for machine grading of scaffold boards of 0.71.

Relationship between modulus of rupture and slope of grain

As mentioned earlier, only 9% of boards had a slope of grain over 1 in 10. So it was not considered instructive to attempt a regression analysis of slope of grain against modulus of rupture. Instead it was decided to compare the moduli of rupture of these 'high slope of grain' boards against the mean modulus for all the boards tested. For this exercise to be meaningful account had to be taken of the other defects present in the 'high slope of grain' boards, which might in themselves have explained a decrease in board strength. Table 5 summarises a comparison made between the strengths of each 'high slope of grain' board and the strengths predicted for that board by the optimum multi-variate regression analysis involving both knots and rate of growth derived above.

Table 5. An appraisal of the moduli of rupture of 'high slope of grain' boards taking into account the other visual defects present in the boards

Slope of grain range	No. of specimens	Actual modulus of rupture / MOR predicted by regression		
		Minimum	Maximum	Mean
1:10 to 1:6	19	0.65	1.26	0.97
>1:6	5	0.76	1.17	1.02

The evidence of Table 5 was inconclusive in respect of whether the strength of boards decreases at slopes of grain over 1 in 10 and further investigations are planned in this area. However it is reassuring to note that failure to implement this most difficult of grading procedures does not appear to result in seriously under-strength boards.

Multi-Variate Regressions of MOR against Rate of Growth and Knot Measures

Multi-variate regression analyses have been undertaken of rate of growth and the knot measures of Table 4, together with knot area ratio. The coefficients of determination of these various options are given in Table 6.

Table 6. Coefficients of determination of multi-variate regression analyses involving both rate of growth and knot measures with MOR

Description of visual defect measures	Coefficient of determination
1. Number of growth rings per 25mm 2. Knot area ratio	0.47
1. Number of growth rings per 25mm 2. SCKD for both faces 3. SCKD for both edges	0.43
1. Number of growth rings per 25mm 2. SCKD for both faces modified in line with Fig.2 3. SCKD for both edges modified in line with Fig.2.	0.46

It is clear from Table 6, in comparison with Tables 3-4, that regression analyses involving both rate of growth and knots are a substantial improvement over regression analyses considering either parameter in isolation with coefficients of determination being above 0.4 in all cases. However, again it can be seen that the highest coefficient of determination appertaining to knot surface dimension rules is that associated with the scheme of Figure 2, which can be seen to again almost match the coefficient of determination appertaining to knot area ratio.

A power multi-variate regression analysis was also undertaken on the knot rules of Figure 2 combined with rate of growth and yielded a similar magnitude of coefficient of determination at 0.45. This type of regression, which by definition has to pass through the origin at all percentile levels, thereby avoiding the negative MOR offset which usually occurs for linear regressions at the 5th-percentile level, was used to derive the visual grading rules for scaffold boards used in the UK. This multi-variate regression equation is given as equation 2.

$$MOR_m = 0.309 \times (NOR)^{0.458} \times (SCCD_{edge})^{0.323} \times (SCCD_{face})^{0.378} \quad (2)$$

where:

MOR_m	=	Mean modulus of rupture
NOR	=	Number of growth rings per 25mm
$SCCD_{edge}$	=	Surface cumulative 'clear wood' edge dimension (mm)
	=	76 - $SCKD_{edge}$
$SCKD_{edge}$	=	Surface cumulative knot dimension measured on both edges in line with Figure 2.
$SCCD_{face}$	=	Surface cumulative 'clear wood' face dimension (mm)
	=	450 - $SCKD_{face}$
$SCKD_{face}$	=	Surface cumulative knot dimension measured on both faces in line with Figure 2.

CONCLUSIONS

1. Flatwise modulus of elasticity, as measured by flatwise bending machines, was found to be far more accurate in predicting the bending strength of scaffold boards (R^2 = 0.71) than any of the visual defect measures or combinations thereof.

2. The effectiveness of knot measures as parameters for predicting bending strength of scaffold boards is poor, having a maximum coefficient of determination of 0.22 compared with that found for rate of growth of 0.33.

3. The above coefficients of determination relate to visual defects measured under laboratory conditions and the difference in accuracy between the output of machine and visual grading is likely to increase further in a commercial grading environment.

REFERENCES

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