PREDICTED AND ACTUAL PERFORMANCE OF TWO LABORATORY STRESS-GRADING MACHINES EMPLOYING DIFFERENT SUPPORT CONDITIONS

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ABSTRACT

Actual performance data were developed on two laboratory stress-grading machines differing only in support conditions for comparison with theoretical predictions from a finite element model developed previously. Performance was assessed on the basis of the ability of the grading machines to measure modulus of elasticity on lumber containing natural bow and one ideal defect (notch). Theory and observation were in good agreement in showing that performance of grading machines is dependent on support conditions, especially regarding their ability to identify zones of lower stiffness along the lumber. Practical implications of the results on future machine stress-rating procedures are discussed.

Keywords: Machine stress-rating, grading machines, lumber, modulus of elasticity, low-point modulus of elasticity.

INTRODUCTION

Most of the lumber stress-grading machines in operation today are based upon determining modulus of elasticity (E) of lumber using the concept of the laboratory bending machines. These so-called bending-type machines have emerged from the first phase of development of machine grading, approximately from 1958 to 1962 (Glos and Schutz 1980). Perhaps because of the apparent simplicity of the bending principle, basic research on bending-type machines has been limited after industrial implementation of the first machines in the mid-sixties. A recent study by Samson (1985) aimed at modelling grading machines provided a deeper insight into the principles of measuring E. Computer simulations carried out with the model developed indicated that machine performance was largely dependent on support conditions, an unexpected finding that could impact significantly on the design of future machines.

Conclusions reached by Samson on the effect of supports on machine performance were based solely upon theoretical considerations. The present study was intended as a more thorough investigation of this support effect by providing both actual and predicted performance data on two machines utilizing different types of supports. The specific objectives of the study were to assess the validity of the model proposed and to examine the practical implications of this support effect on future machine stress-rating procedures.

BACKGROUND

Accuracy and reliability of machine stress-rating of lumber depend on a number of factors, some pertaining to the material graded and others to the type of grading machine used. Effects of factors pertaining to lumber, such as moisture content, temperature, dimensional tolerances, and species, have received constant atten-

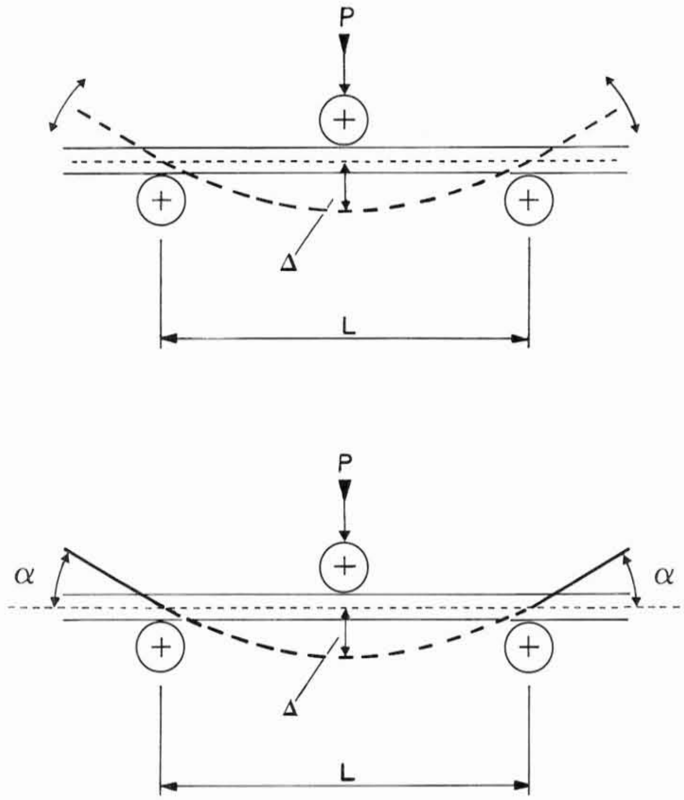

FIG. 1. Testing schemes studied by Samson (1985).

tion in the literature since the early stages of development of machine grading (Hoyle 1961, 1968; Hilbrand and Miller 1966; Golyakov 1977; Houldsworth 1979; Ogurtsov 1982). Investigations of machine-related factors are more recent and have focused on the identification of low-point E, the lowest E value along the length of each piece of lumber graded. In fact, early research on determination of E over short spans (Corder 1965; Orosz 1969) had indicated that assessment of low-point E would largely depend on the testing geometry employed by the machines. Since then, some aspects of testing geometry, including span length and method of loading have been investigated (Thunell 1969; Kass 1975; Orosz 1976). These studies, however, could not be used to examine the effect of supports on machine performance since only simple supports were considered.

The first contribution towards assessing the effect of supports can be attributed to Korneev (1980) in a theoretical investigation aimed at identifying the optimum testing scheme for grading machines. Two machines employing both center-point loading but different support conditions were compared. One machine used simple supports, while the other used the fixed-end condition maintaining the lumber in the horizontal position at supports. Simulations revealed that low-point E was more accurately measured with the scheme employing simple supports. Although Korneev's work showed the existence of a support effect on machine accuracy, there were limitations in its general applicability. His simulations were based on closed-form solutions of beam flexure problems, thereby limiting the investigation to very few support types. Furthermore, his models did not account for initial deviation from straightness of lumber (e.g., natural bow), a factor that could significantly affect machine accuracy.

A more general approach was followed by Samson (1985) for comparing testing geometries. Using the concept of finite elements, a model was derived for predicting E measured by grading machines employing any possible testing geometries on nonuniform and initially deformed lumber. To illustrate machine sensitivity to supports, Samson used the model to simulate lumber grading with two testing schemes differing only in support conditions (see Fig. 1). In each instance, the indicating parameter of E was the force P necessary to maintain a constant deflection Δ in the middle of the span L. This approach permitted comparison of simple and fixed end conditions as did Korneev (1980). However, while Korneev employed the conventional fixed ends with zero slope at supports, Samson considered fixed ends with slopes maintained to an angle $\alpha = 3\Delta/L$, i.e., the angle at which a simply supported beam, initially straight and of uniform stiffness, would lie in the machine. Simulations revealed that the ability to detect low-point E was better with fixed supports set to $\alpha = 3\Delta/L$ than with simple supports, a conclusion opposed to that obtained by Korneev for $\alpha = 0$. This analysis threw new light on the effect of supports, especially of the support angle, on grading machine performance. Another advantage of the fixed-angle over the free-angle situation was revealed in simulating machine grading of bowed lumber. As both machines deflect the lumber in only one direction, both were expected to require two passes to compensate for bow. While this proved to be necessary over simple supports, the machine using fixed ends was found so insensitive to bow that a second pass appeared unnecessary. The validity of this result relied on the assumption that bow could be represented by a parabola. This assumption has since been ascertained by Simpson and Gerhardt (1984) in their study of crook development in lumber.

While the effects of machine-related factors on the accuracy of machine stress-rating have been the object of a few studies, these studies were essentially theoretical, without experimental verification. They do, however, suggest that a better understanding of the bending principle in its appplication to the measurement of E could lead to improvements in the design of grading machines. The present investigation is aimed at providing experimental data on the performance of two grading machines as an attempt to substantiate this claim.

METHODS

Equipment and test material

Testing was conducted with the two laboratory machines referred to as Machines A and B and schematically illustrated in Fig. 2. These were built to simulate the conditions of the two schemes showed in Fig. 1. To constrain the support angles in Machine B, the lumber was clamped between a series of pinch and datum rollers inclined to an angle $\alpha = 3\Delta/L$. Spans and deflections were set to 35.82 in. (910 mm) and 0.157 in. (4 mm), respectively, resulting in an angle of 0.755° on the roller assembly at each support in Machine B. Both machines were designed to deflect the lumber on the flat.

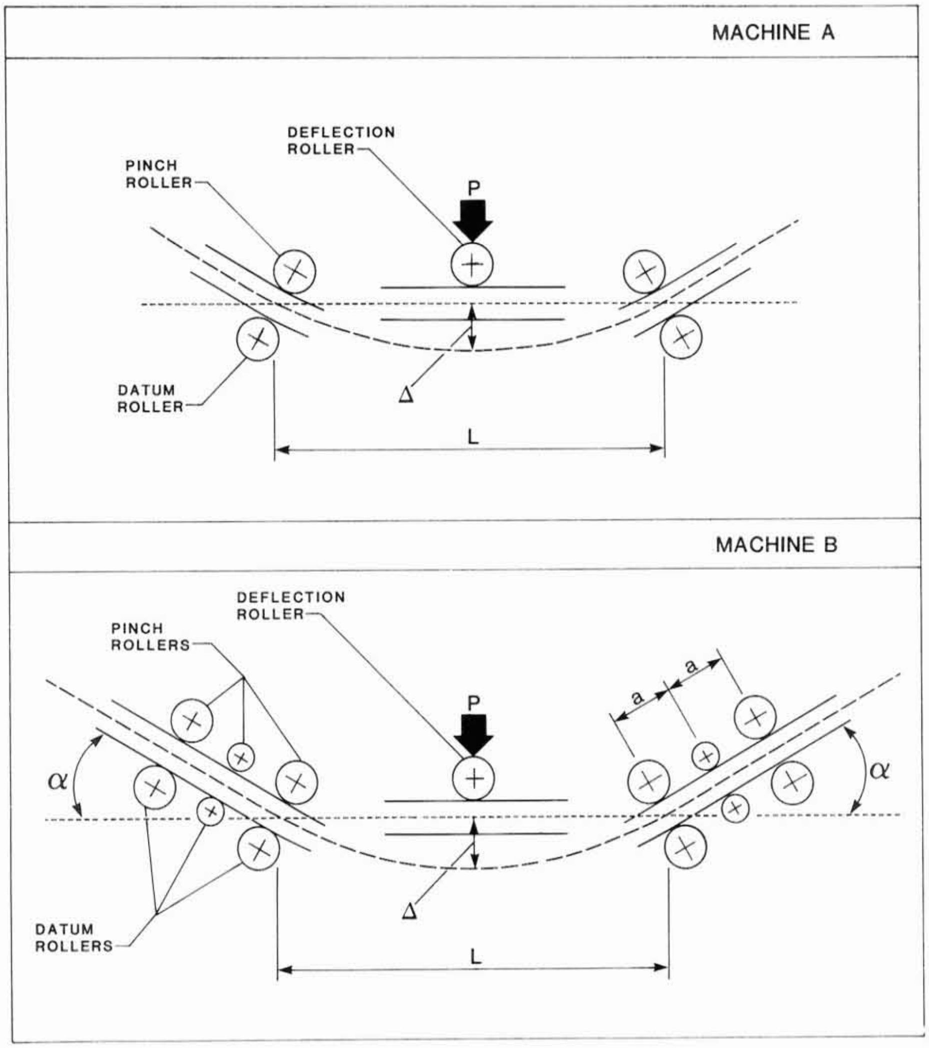

FIG. 2. Testing geometries employed by Machines A and B (a = 13.082 in., $\alpha = 0.775°$, $\Delta =$ 0.157 in., L = 35.826 in.).

Test material was selected from a lot of kiln-dried 2- × 4-in. by 13-ft (38 mm × 89 mm × 3.96 m) white spruce dimension lumber free of knots, wane, and any possible forms of warp with the exception of natural bow. The aim was to obtain a final sample with minimal variation in E, both within and between specimens, and segregated into two lots on the basis of the severity of bow (light and severe).

First, all pieces in the lot were E-rated with a commercial Cook-Bolinders grading machine using a 910-mm span and a midspan deflection of 4 mm. The E data developed along the length of each piece were visually examined to select from the sample only those pieces showing reasonably uniform stiffness profiles. The pieces selected were subsequently examined to determine bow, defined for convenience in this study as the ratio of the deviation measured over machine span to machine deflection.

TABLE 1. *Natural bow within each bow category expressed as a percentage of machine deflection* $\Delta = 4.0$ *mm.*

Light bow category		Severe bow category	
Specimen	Bow %	Specimen	Bow %
L-1	5.0	S-1	8.5
L-2	3.0	S-2	11.0
L-3	5.0	S-3	7.0
L-4	5.0	S-4	11.0
L-5	4.0	avg.	9.4%
L-6	3.0		
avg.	4.2%		

A total of ten specimens, segregated into six lightly and four severely bowed pieces, were retained to form the final sample. Cross-sectional dimensions and moisture content were recorded at three locations along the length of each specimen. Average values of these parameters within each specimen werre calculated and retained for further calculations.

Measurement of E

All ten specimens were run at a speed of 50 ft/min (15.2 m/min) through Machines A and B, recording the force P at 0.311 in. (7.9 mm) intervals within the middle 7-ft (2.13-m) portion of each specimen. Tests were carried out in two passes, alternating the faces loaded.

At mid-length on each specimen, a V-shaped notch, 0.875 in. (22.2 mm) deep with a 163° opening, was cut in from each edge to create a localized zone of lower stiffness. At the narrowest point, the notch reduced the width of the specimen to half of its original value. The notched specimens were tested with Machines A and B, following the procedure used for the specimens in their original unnotched condition.

Each individual load reading was processed to determine a machine-measured E value (E_{mach}) using the conventional deflection formula for center-point loading

$$E_{mach} = \frac{L^3}{48I\Delta}P \tag{1}$$

where I is the moment of inertia about the neutral axis calculated for each individual specimen from its average cross-sectional dimensions. These data were used to construct profiles of E_{mach} values along the length of each specimen, both in the original unnotched and notched conditions.

After testing, bow was remeasured on all specimens. Very little change was observed in bow as a result of notching and testing. The average of bow data measured prior and after tests was calculated for each specimen and used as the characteristic value of bow in subsequent analysis. Characteristic bow for the individual specimens within each bow category is given in Table 1.

Prediction of E

Simulations were carried out with the model derived by Samson (1985) to develop predicted E_{mach} profiles for comparison with the observed profiles. The

TABLE 2. *Two-pass average E data for original unnotched specimens.*

Specimen	Average E (million psi)	
	Machine A	Machine B
L-1	2.009	2.049
L-2	1.993	1.975
L-3	2.007	2.057
L-4	2.106	2.012
L-5	1.983	1.956
L-6	1.984	2.049
S-1	1.780	1.787
S-2	1.818	1.838
S-3	2.039	2.030
S-4	1.979	2.048
Mean	1.977	1.980
Stand. dev.	0.103	0.095

model, based on a finite element solution of a beam flexure problem, is designed to predict the apparent E measured by a grading machine (E_{mach}) on a given piece of lumber from the inherent E, the cross-sectional dimensions and the initial bow of the piece. Testing geometry of the machine is specified by imposing proper boundary conditions on the equilibrium equations for the beam. A detailed account of the predicting procedure of E_{mach} and the computation of the predicted E_{mach} profiles can be found in Samson (1985).

Input data for the simulations are of two types: those pertaining to the lumber tested and those pertaining to the machine modelled. Machine-related input data are given in Fig. 2, for the two machines investigated. Input data pertaining to the lumber include nodal values of modulus of elasticity (E_i), nodal values of moment of inertia (I_i) and natural bow.

The present simulations were intended to predict the mean E_{mach} characteristics for the entire test sample. Therefore, lumber-related input data were assigned values representing best the sample. E_i was given a constant value $\bar{E} = 1.978 \times 10^6$ psi based on the experimental E_{mach} data collected on the specimens before notching. As can be seen in Table 2, this value is the general average of the two-pass average E data measured by both machines on the original unnotched specimens. I_i was also assigned a constant value $\bar{I} = 0.984$ in.^{4} based on average thickness and width calculated for all specimens, except when simulating machine grading of notched lumber. Over the notch, I_i varied proportionally with specimen width taking a low value of $\bar{I}/2$ at the narrowest point. Initial deviation from straightness $w_0(x)$ was prescribed by fitting a parabola through the three points

$$
\begin{array}{ll}
x = -L/2 & w_0(x) = 0 \\
x = 0 & w_0(x) = b \\
x = L/2 & w_0(x) = 0
\end{array}
$$

where x is the machine axis originating at midspan and b the value of bow at midspan. Nodal values w_{0_i} were calculated at regular increments using the resulting parabolic relation. Either of the two following values of b (see Table 1) were used in the simulations: $b = 0.042\Delta$ when simulating the light bow category or $b = 0.094\Delta$ when simulating the severe bow category.

TABLE 3. *Two-pass average and low-point E for notched specimens. All data in million psi.*

Specimen	Average E		Low-point E	
	Mach. A	Mach. B	Mach. A	Mach. B
L-1	1.943	1.946	1.518	1.412
L-2	1.907	1.873	1.467	1.356
L-3	2.018	1.938	1.542	1.383
L-4	2.028	1.869	1.526	1.269
L-5	1.887	1.826	1.480	1.297
L-6	1.866	1.872	1.438	1.275
S-1	1.693	1.681	1.299	1.211
S-2	1.721	1.718	1.332	1.234
S-3	1.924	1.904	1.484	1.391
S-4	1.879	1.893	1.479	1.348
Mean	1.887	1.852	1.457	1.318
Predicted	1.888	1.893	1.505	1.266

Boundary conditions imposed on the deflected shape w(x) were, for Machine A (3 conditions)

$$x = \pm L/2 \qquad w(x) = 0$$
$$x = 0 \qquad w(x) = \Delta$$

and for Machine B (7 conditions)

$$x = \pm(L/2 + 2a) \qquad w(x) = -2a\alpha$$
$$x = \pm(L/2 + a) \qquad w(x) = -a\alpha$$
$$x = \pm L/2 \qquad w(x) = 0$$
$$x = 0 \qquad w(x) = \Delta$$

where a is the distance between adjacent rollers.

All simulations were conducted using an element length H = L/22 or 1.63 in. (41.4 mm). Predicted E_{mach} values were calculated, at every increment H, over the middle 7-ft portion of the simulated pieces. Each simulation run yielded two profiles, one for each pass. In order to model all situations tested experimentally, simulations were conducted under any combination of the following conditions: light or severe bow categories, unnotched or notched specimens, Machine A or Machine B.

RESULTS AND DISCUSSION

Moisture content readings ranged from 9 to 14%. This variation was considered too small to require moisture content adjustment of the experimental E data developed.

Prior to analysis, all stiffness profiles, either experimental or predicted, were processed as follows. An average profile was calculated for each set of first and second pass profiles by averaging individual E_{mach} data at corresponding locations. Then, the mean (average E) and the minimum (low-point E) of the E_{mach} data were calculated for the first, the second and the average pass. The difference in average E and in low-point E between the first and the second pass was also calculated for each run.

TABLE 4. *Difference in E values between passes. All data in million psi.*

	Original unnotched		Notched			
	Average E		Average E		Low-point E	
Specimen	Mach. A	Mach. B	Mach. A	Mach. B	Mach. A	Mach. B
			Light bow specimens			
L-1	0.192	0.008	0.184	0.025	0.343	0.202
L-2	0.377	0.004	0.099	0.006	0.209	0.175
L-3	0.292	0.066	0.181	0.033	0.085	0.281
L-4	0.116	0.075	0.218	0.053	0.065	0.163
L-5	0.105	0.014	0.149	0.005	0.017	0.095
L-6	0.007	0.033	0.009	0.029	0.160	0.013
Mean	0.182	0.033	0.140	0.025	0.147	0.155
Predicted	0.166	0.007	0.158	0.007	0.126	0.037
			Severe bow specimens			
S-1	0.396	0.036	0.319	0.032	0.281	0.046
S-2	0.488	0.020	0.385	0.016	0.261	0.217
S-3	0.266	0.008	0.260	0.043	0.305	0.014
S-4	0.514	0.101	0.470	0.126	0.548	0.124
Mean	0.416	0.042	0.359	0.054	0.349	0.100
Predicted	0.373	0.016	0.355	0.013	0.282	0.083

Original unnotched specimens

Two-pass average E data obtained from both machines on the original unnotched specimens are given in Table 2, along with the mean and standard deviation values for this parameter in the sample. Comparison of the means and standard deviations calculated for both machines reveals that Machines A and B gave the same assessment of two-pass average E on uniform lumber, thereby showing no influence of support conditions. This result was expected in theory, since support rollers in Machine B were inclined to the precise angle at which a uniform beam lies in Machine A. Had the support rollers been inclined to a different angle, Machine B readings would have been biased with respect to the E values measured on simple supports in Machine A. The fact that no bias was found suggests that Machine B was properly set for the tests.

Notched specimens

Two-pass average and low-point E data obtained from both machines on the individual specimens after notching are presented in Table 3. Mean values of these parameters are also provided, together with predicted values from the simulations. Comparison of mean and predicted values shows that a good agreement exists between theory and observation both in average and low-point E. In fact, the largest difference between mean and predicted values is 0.052×10^6 psi, an error of less than 4%. Although relatively small in all cases, the discrepancy between theory and observation is larger for the low point. This may be due to the fact that factors responsible for noise on machine readings such as surface roughness and variations in cross-sectional dimensions of the specimen, out-of-round of rollers, and presence of pinch rollers were not taken into consideration in the model. This noise, which is filtered out when averaging, will have very

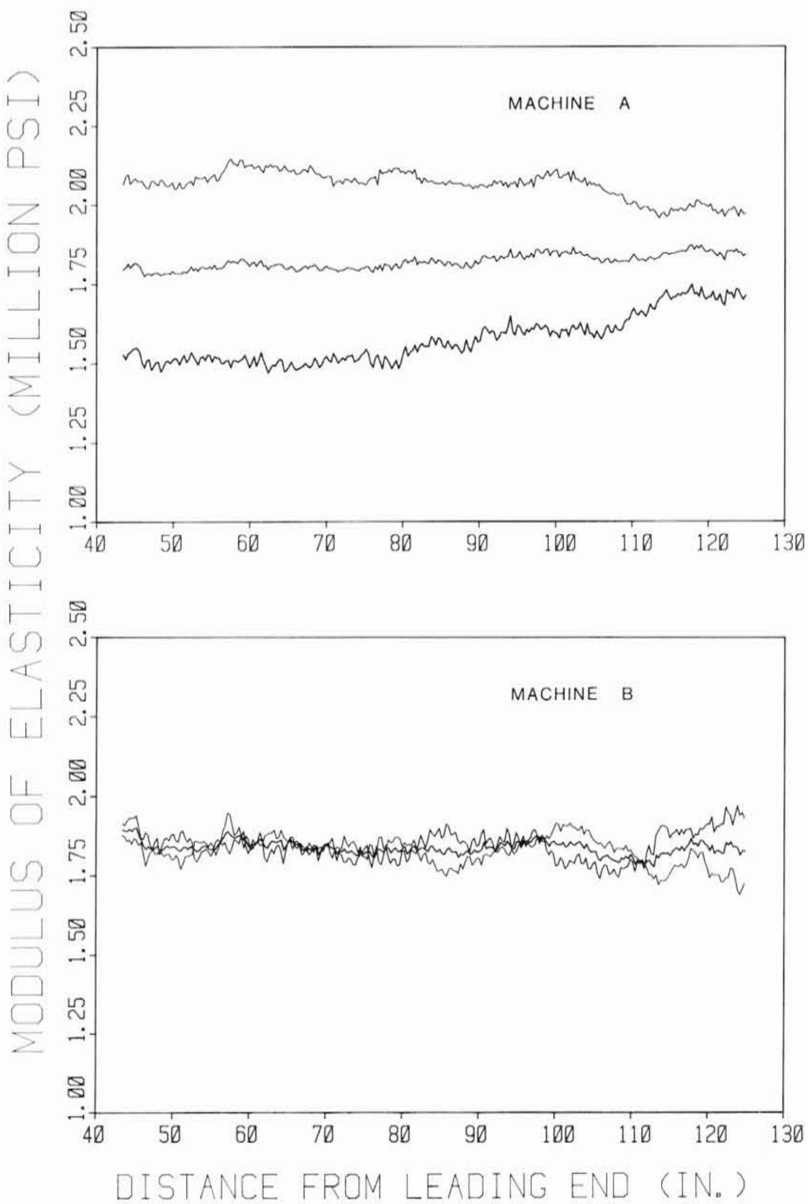

FIG. 3. Stiffness profiles measured by both machines on specimen S-2 in the original unnotched condition. Outer profiles correspond to individual passes; median profile is the two-pass average.

little effect on average E. Its influence, however, will be much larger on individual readings such as low-point E, explaining the larger discrepancy between actual and predicted values for this parameter.

Close similarity in the two-pass average E data for both machines suggests that supports had virtually no effect on this parameter. This conclusion, already verified for uniform lumber, seems to apply to nonuniform lumber as well. Supports, however, did affect low-point E, the extent of which is revealed by the predicted values in the table. According to the model, Machines A and B should indicate low-point E values of 1.505 and 1.266 $\times$ 10^6 psi, respectively, while the true low point is $\bar{E}/2$ or 0.989 $\times$ 10^6 psi. Ratios of predicted over true values suggest that low-point E indicated by Machine B would be 24% closer to the true low-point than the low-point indicated by Machine A. Clearly, the model predicts a better performance for Machine B on the basis of the ability to identify low-point E. Ratios of the actual means over the true low-point show that this claim is supported experimentally, although the two machines differ less in practice than in theory. In fact, experimental data indicate that, on average, the low-point measured by Machine B will be 14% closer to the true low-point than low-point E measured by Machine A. An improvement of such magnitude, however, can still be considered important in practice. A more accurate low-point should translate into more accurate grading as a result of better correlations between strength and E.

The usual solution to obtain closer estimates of low-point E has been to shorten machine span (e.g., Orosz 1969; Kass 1975). The present study shows that improvements can be achieved in the assessment of low-point E simply by modifying support conditions. This conclusion applies to lumber containing one dominant defect as well as lumber with several defects along its length, provided that defect spacing is no less than machine span. Effect of supports on machine grading of lumber containing closely spaced defects remains to be investigated.

Difference data

The effect of supports on the ability to overcome the problem of natural bow is studied in Table 4, which gives the difference data in average and low-point E between passes for all specimens. Considering the original unnotched specimens, comparison of the data for both machines reveals that the difference between passes as a result of bow is considerably less in Machine B than in Machine A. Theory and observation are in good agreement in indicating the existence of a support effect. This effect is more clearly visualized in Fig. 3 showing the E_{mach} profiles measured by both machines on specimen S-2, a typical example in the severe bow category. Profiles measured by Machine B for individual passes on this specimen are, for practical purposes, identical.

Regarding the notched specimens, the data developed indicate that supports also affect the mechanism by which bow is overcome in nonuniform lumber. This support effect, however, is less pronounced on low-point E than on average E. For average E, the effect of supports is consistent with the effect already observed for the original unnotched specimens in that fixed supports considerably reduce the difference in average E between passes. Here again, theory and observation are in good agreement in supporting this conclusion. Agreement between measured and predicted differences, however, is not as good in the case of low-point E. As discussed earlier, the fact that low-point E is influenced by parameters not taken into consideration in the model is again a plausible explanation. The difference between passes in low-point E values measured by Machine B cannot be regarded as negligible as it was the case for average E. This is illustrated in Fig. 4, showing the E_{mach} profiles measured on specimen S-2 in the notched condition. The difference between passes in Machine B is much less than in Machine A everywhere along the length of the piece except at the low point, where this difference is about the same as that recorded by Machine A.

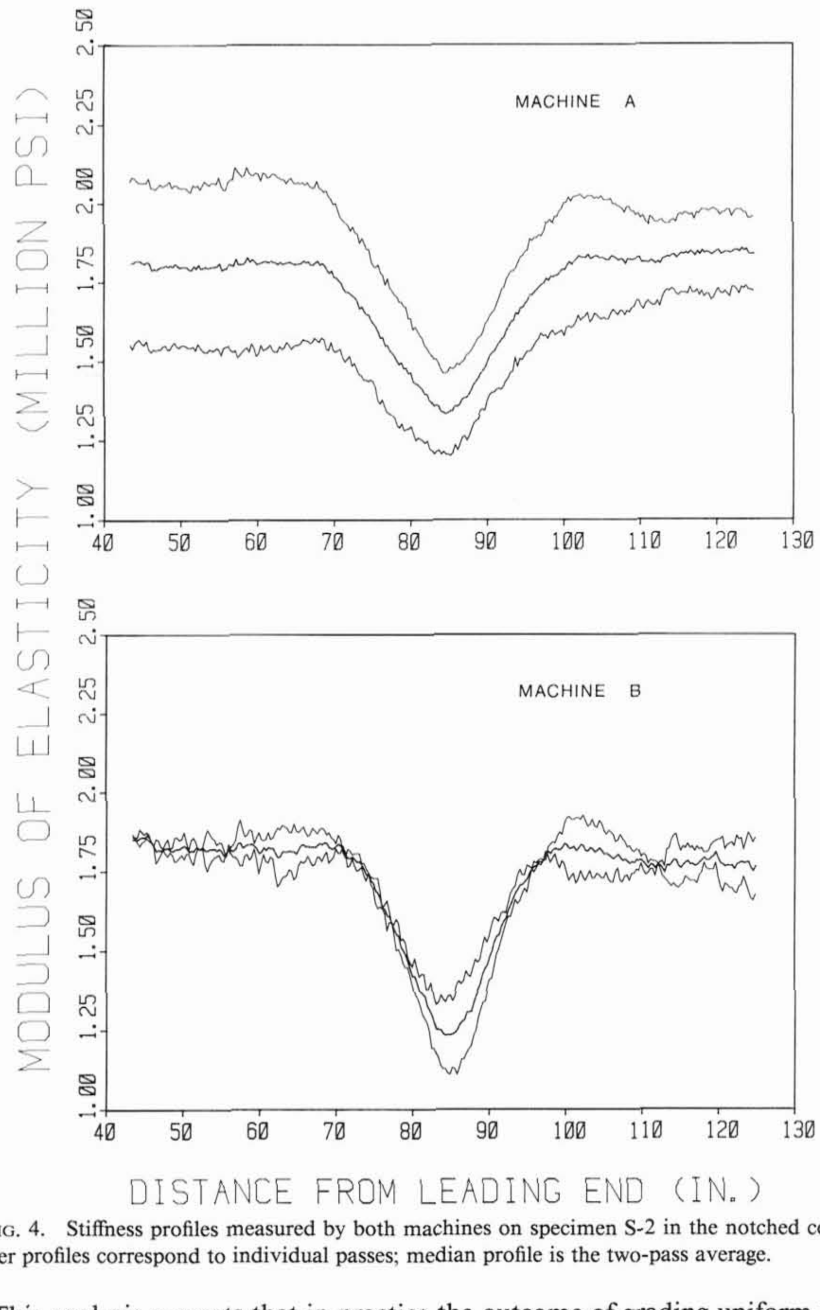

FIG. 4. Stiffness profiles measured by both machines on specimen S-2 in the notched condition. Outer profiles correspond to individual passes; median profile is the two-pass average.

This analysis suggests that in practice the outcome of grading uniform lumber in a machine of type B would not be materially affected if only one pass was used. In this perspective, grading with a machine of type B would be simpler and faster than with a machine of type A as the latter must use either bidirectional bending or a two-pass approach. This situation, however, does not prevail for the grading of nonuniform lumber since large errors would arise in low-point E if only one pass were used, with either of the two machines considered in this investigation. More research is needed to find better testing schemes, possibly showing no difference both in low-point and average E between passes. The finite element model examined in the present study appears to be a potential tool to carry out such research.

CONCLUSION

Actual performances of two laboratory bending-type grading machines have been accurately predicted by a finite element model developed by Samson (1985). Both predicted and experimental data collected on bowed lumber containing one dominant defect confirmed the existence of an effect of supports on the mechanism employed by the machines to compensate for natural bow and on the ability of the grading machines to identify low-point E. On the other hand, average E was virtually independent of support conditions. The agreement between theoretical predictions and actual observations suggests that the model developed is adequate to simulate current grading machines and to explore new designs for future machines.

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