EVALUATION OF BENDING STRENGTH RATIOS FOR EASTERN OAK PALLET LUMBER

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ABSTRACT

Visual stress rating using strength ratios is the only expedient and currently available method of assigning strength design values to pallet shook. In this study, the estimated bending strength ratio (ESR), determined from ASTM D245, and the actual bending strength ratio (ASR), determined through testing, were compared for over two thousand two hundred pieces of eastern oak pallet lumber. The ESR generally underestimated the ASR for stringers and deckboards with knots and slope of grain. The ESR increasingly underpredicted the ASR as knot size increased. The ESR consistently underpredicted the ASR throughout the range of severity of slope of grain. If assigners of design stresses for pallet shook use ASTM strength ratios, then conservative strength estimates will result; this is particularly true for low quality material.

Keywords: Strength ratio, pallet lumber, lumber defects, visual stress rating, modulus of rupture.

INTRODUCTION

The principal objective of the cooperative Pallet Research Program (PRP), involving Virginia Tech, the USDA Forest Service, and the National Wooden Pallet and Container Association (NWPCA), was the development of a rational design procedure for wood pallets. A major input to the design procedure is an estimate of the strength of the pallet shook (cut-to-size pallet lumber). Studies of yellow-poplar (McLain and Holland 1982) and eastern oak (McLain et al. 1986) cut-to-size pallet parts, or shook, provided in-grade test data for these species. However, almost all species of lumber, hardwoods and softwoods, are used in pallet construction, and there is no standard grading scheme for pallet parts. Therefore, a method of estimating the strength of pallet shook of any species and quality is required.

Strength design values for structural lumber have been and are currently based on the methods of ASTM D2555 and D245 (ASTM 1986). Strength values for small, clear, green specimens of a single species or mix of species are obtained using the methods outlined in ASTM D2555. Adjustment factors from ASTM D245 modify the properties obtained by tests of small, clear, green specimens to obtain design values for full-size structural lumber of any grade and use condition.

One adjustment factor is the strength ratio, which is defined as the ratio of the strength of a structural member, containing knots, cross-grain, splits, checks, or other strength-reducing defects to the estimated strength of a defect-free member of comparable dimensions. Strength ratios modify the estimated clear wood strength value to account for the reduction in strength due to the presence of defects. Strength ratios could theoretically be used to estimate strength of any species and quality of pallet shook. However, the ratios were originally developed for softwood structural lumber and have only recently been used with hardwoods. Their ac-
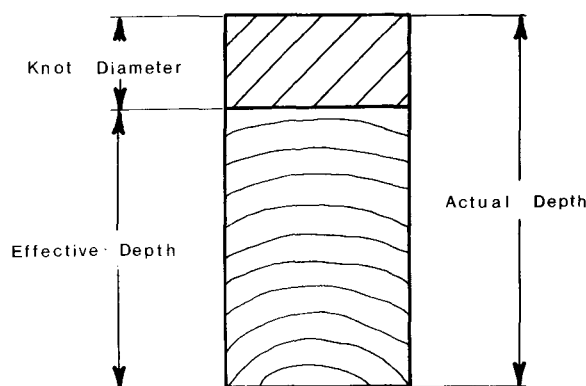
FIG. 1.   A schematic of an edge knot used to calculate strength ratio. Cross-section view of piece of lumber.

curacy in estimating the strength of hardwood dimension lumber has been questioned (Koch 1981; Rousis and Koch 1976; Walters et al. 1971). Their usefulness in estimating the strength of relatively small, cut-to-size hardwood pallet parts has not been evaluated.

The objective of this paper is to examine the use of ASTM strength ratios for estimating the influence of defects on the bending strength of green, eastern oak pallet shook. This information will be used to determine the best way to use strength ratios for establishing pallet shook design values. As a starting point, strength estimates for green material are required since pallets are typically built and first used in the green condition. This strength ratio evaluation is, therefore, based on green lumber.

LITERATURE

Wilson (1934) first published strength ratio tables in his guide to the grading of structural timbers. The methods of ASTM D245, which use the strength ratio approach, are based upon this guide. The influence of a defect on lumber strength depends on the type of defect and kind of loading to which the piece is subjected. Strength ratios for bending members with knots were derived as the ratio of moment-carrying capacity of a member with its cross section reduced by the largest knot to the moment-carrying capacity of the member of full cross section. For simplicity, all knots in the wide face are treated as either edge knots or centerline knots. The strength ratios for bending members with edge knots were derived assuming the effective section modulus is reduced by the knot diameter, with the member used on edge as a beam. The bending strength ratio is approximately equal to the square of the ratio of the effective depth to the actual depth, as illustrated in Fig. 1 and by the following equation.

$$SR \cong \left[\frac{D_{effective}}{D_{actual}} \right]^2 \tag{1}$$

where:

SR = bending strength ratio for edge knots
D_{actual} = actual depth of member
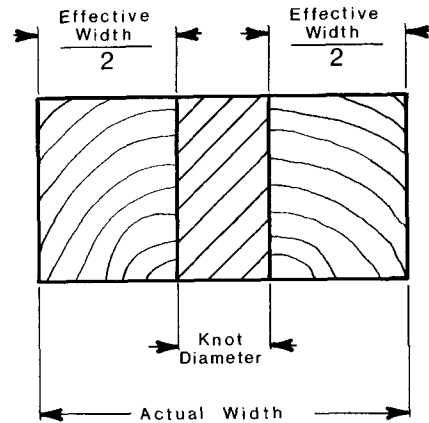$D_{effective}$ = effective depth of member.

FIG. 2. A schematic of a centerline knot used to calculate strength ratio. Cross-section view of piece of lumber.

The strength ratios for bending members with centerline knots, as well as one-inch nominal boards with knots anywhere in the wide face, were derived assuming the effective section modulus is reduced by the knot diameter, with the piece used flatwise as a plank. The bending strength ratio is approximately equal to the ratio of the effective width to the actual width, as illustrated in Fig. 2 and by the following equation.

$$ SR \cong \left[\frac{W_{effective}}{W_{actual}} \right] \qquad (2) $$

where:

SR = bending strength ratio for centerline knots
W_{actual} = actual width of member
$W_{effective}$ = effective width of member.

Shakes, splits, and checks are assumed to affect only horizontal shear in bending members. Strength ratios for these defects were derived by assuming that a critical cross section is reduced by the amount of the shake, split, or check (ASTM 1986). The bending strength ratios for members with slope of grain were derived based on values Wilson (1921) experimentally determined for small, dry specimens of several species. However, the ASTM strength ratios for full-size lumber with slope of grain are substantially lower than those reported by Wilson. The ASTM ratios allow for drying defects and conservatism in full-size lumber.

Several researchers (e.g., Doyle and Markwardt 1966; Walters et al. 1971) have checked the accuracy of estimated strength ratios (ESR) by testing a full-size piece of lumber to obtain an MOR and then testing a small, clear specimen taken from the undamaged portion of the full-size piece. The ratio of the MOR of the full-size piece to the MOR of the small, clear specimen (after adjusting for depth) is the actual strength ratio (ASR). The ESR and ASR are then compared.

Doyle and Markwardt (1966) used the small, clear specimen method to determine the ASR of 2 × 4 and 2 × 8 kiln-dried southern pine dimension lumber of various grades. The ESR was determined using strength ratios given in ASTM

D245. A correlation coefficient of 0.678 was found between ESR and ASR, indicating a moderately strong relationship. Average ASR was less than average ESR for all sizes and grades, and the ASR to ESR ratio decreased with increased depth. ASR decreased with increased depth more for low quality grades than high quality grades.

ASTM D245 strength ratios were originally developed for deriving design values for softwood structural lumber. Their use has been extended to estimate the strength of hardwood structural lumber for yellow-poplar, cottonwood, and aspen species.

Walters et al. (1971) compared ESR and ASR of red oak and cottonwood lumber. The coefficients of determination (r^2) ranged from 0.12 to 0.44, indicating a low degree of correlation between ESR and ASR; ASR for the 2 × 8 beams with centerline knots became increasingly lower than ESR as knot size increased. The ASR was greater than ESR for small edge knots in the 2 × 8's, but became increasingly lower than ESR as knot size increased; ASR was consistently 15–20% higher than ESR throughout the range of severity for slope of grain.

Rousis and Koch (1976), in a study of yellow-poplar 2 × 4's, found a higher degree of correlation between ASR and ESR than Walters but less than that from the southern pine study (Doyle and Markwardt 1966). Later, Koch (1981) again examined the prediction of bending strength of yellow-poplar 2 × 4's using strength ratios and found that ESR underpredicted ASR for large knots and overpredicted ASR for small knots. Koch states that this may be due to disproportionately greater grain disorientation as knot size decreases.

Despite criticism of the strength ratio approach, it is the only available method of estimating the strength of visually graded lumber when full-size in-grade test data are unavailable. This is likely to remain the case for most species of pallet lumber for the foreseeable future.

MATERIALS AND METHODS

The source of data for this study was the eastern oak pallet lumber data (McLain et al. 1986) involving over 2,800 green stringers and deckboards. Stringers were nominal 2 × 4 × 48 inch, deckboards nominal 1 × 4 × 40 inch and 1 × 6 × 40 inch dimension. This lumber was randomly sampled from mills in sixteen states in the eastern U.S. States were chosen on the basis of their percentage of total eastern U.S. oak timber volume and on whether they maintained an oak pallet shook producing industry. Mills that purchased shook as well as those that produced it were sampled.

Each piece was graded according to the scheme proposed by Sardo and Wallin (1974), which defines four grades (2&BTR, 3, 4, and Cull). For each piece of shook, all significant defects were measured in accordance with ASTM D245, and their location was recorded. A code used to identify and characterize each defect within a piece was entered and stored on computer.

The lumber was tested to failure in bending, using third-point loading and methods similar to those in ASTM D198 (1986), with the exception of loading rate. Stringers were tested at a crosshead travel rate of 1 in./min over a 45-inch span; deckboards were tested at a crosshead travel rate of 2 in./min over a 36-inch span. After testing, moisture content and specific gravity (O.D. weight and volume basis) were determined for each piece, and modulus of rupture (MOR),

TABLE 1. *Properties of those pieces of pallet shook visually clear of defects.*

Size	N	Specific[1] gravity	Modulus of rupture		Modulus of elasticity[2]	
			Mean (psi)	Cov (%)	Mean (million psi)	Cov (%)
Stringers	115	0.58	8,930	20.3	1.409	23.2
4-in. deckboards	120	0.58	8,040	20.0	1.467	26.4
6-in. deckboards	47	0.57	8,420	16.8	1.547	22.4

[1] Based on oven-dry weight and volume.
[2] Adjusted for shear effects assuming E/G = 16.

modulus of elasticity (MOE), and stress at proportional limit (SPL) were computed. Stringer MOEs were corrected for shear using the procedures of ASTM D2915 (1986).

A computer program was written to calculate the strength ratio associated with each defect according to the equations and tables in ASTM D245 for knots, checks, shakes, and slope of grain. The estimated strength ratio (ESR) of the piece was taken to be the lowest strength ratio associated with any defect within the piece. Pieces having defects for which strength ratios do not exist (e.g., wane, decay) could not be assigned an ESR and were deleted from this study.

To calculate the actual strength ratio (ASR), the MOR of the full-size piece is typically divided by the strength of a small, clear specimen taken from the full-size piece. However, this procedure was not feasible in this study because of the number of pieces tested and the resulting size of the destroyed full-size pallet lumber. Instead, the clear wood strength was estimated by the average MOR of the clear, straight-grained pieces, having an ESR of 100, within a particular size class (stringers, 4-inch deckboards, and 6-inch deckboards). A reasonable estimate of clear wood strength was possible because of the large number of clear pieces available. Table 1 shows the properties of the clear pieces of each size.

The ASR of each piece was calculated as the ratio of the actual MOR of the piece to the average clear wood MOR determined for the respective size. By comparing ASR with ESR, the effectiveness of the strength ratio approach in predicting MOR can be determined.

RESULTS AND DISCUSSION

The method of determining small clear MOR from remains of full-size lumber has the advantage of producing a clear wood strength value that is representative of the particular piece from which it came. The alternative clear wood strength values used in this study are averages and therefore underestimate the true clear wood strength of some pieces while overestimating others. This results in wider variation of ASR, with values well over 100% possible. Nevertheless, the average ASR for a particular size or grade should be fairly accurate. It is this average that we are most interested in for input to the pallet design procedures, which are cast in a load and resistance factor type format.

A regression relationship between MOR and specific gravity of the clear pieces could have been used to predict an individual clear wood MOR for each piece. However, the relationship between MOR and specific gravity of the clear pieces was very poor, with r^2 values of less than 0.3.

The clear sample properties in Table 1 are within the range of those given in

TABLE 2. *Comparison of actual and estimated strength ratios for cut-to-size eastern oak pallet parts.*

Size	Grade	N	Minimum estimated strength ratio (%)	Average strength ratio		Ratio (actual/ estimated)
				Actual (%)	Estimated (%)	
Stringers	2 & BTR	332	61	95	85	1.12
	3 & BTR	627	50	90	77	1.17
	4 & BTR	889	26	86	72	1.20
	All shook	1,131	0	82	66	1.24
	3	295	50	84	67	1.25
	4	262	26	77	59	1.31
	Cull	242	0	68	48	1.42
4-in. deckboards	2 & BTR	231	61	99	93	1.06
	3 & BTR	407	53	96	84	1.14
	4 & BTR	526	40	93	79	1.18
	All shook	695	0	89	73	1.22
	3	176	53	92	73	1.26
	4	119	40	84	62	1.35
	Cull	169	0	76	53	1.43
6-in. deckboards	2 & BTR	127	61	97	93	1.04
	3 & BTR	260	53	91	85	1.07
	4 & BTR	336	40	90	80	1.12
	All shook	426	0	86	75	1.15
	3	133	53	86	78	1.10
	4	76	40	84	63	1.33
	Cull	90	0	73	55	1.33

ASTM D2555 (1986) for red and white oak species. It is surprising that the MOR of the 3½-inch-deep stringers is greater than that of the ¾-inch-deep deckboards. On the basis of the well known depth effect (Bohannan 1966), clear deckboards would be expected to have greater bending strength than stringers. An explanation for this trend likely involves the "failure" of the green pieces tested as a beam versus as a plank. While stringers typically failed in splintering tension, deckboard failure was often due to compression or excessive deflection. Since the latter is not a brittle failure, the weak link theory may not be operable. In the excessive deflection case, the deflection limit of the test apparatus (5 inches) was exceeded before the piece had failed to sustain a load. The MOR was computed from recorded maximum load. It should be noted that at deckboard "failure," load did not appreciably increase with additional deflection.

Table 2 compares average ASR and ESR for each size of the oak pallet lumber. These strength ratios are presented for single grades and for grade mixes. The minimum ESR associated with the worst defect permitted in each grade is also presented. Average ESR is less than average ASR for all sizes and grades. The ratio of ASR to ESR is smaller for the higher quality grades than the lower quality grades, indicating that ESR increasingly overpredicts the strength reduction for more severe defects.

For a visual comparison of ESR and ASR for different types of defects, line-plots of ESR versus defect size were superimposed on scatter-plots of ASR versus defect size. These plots were made separately for the various types of defects and shook sizes using the eastern oak shook data and are presented in Figs. 3 through
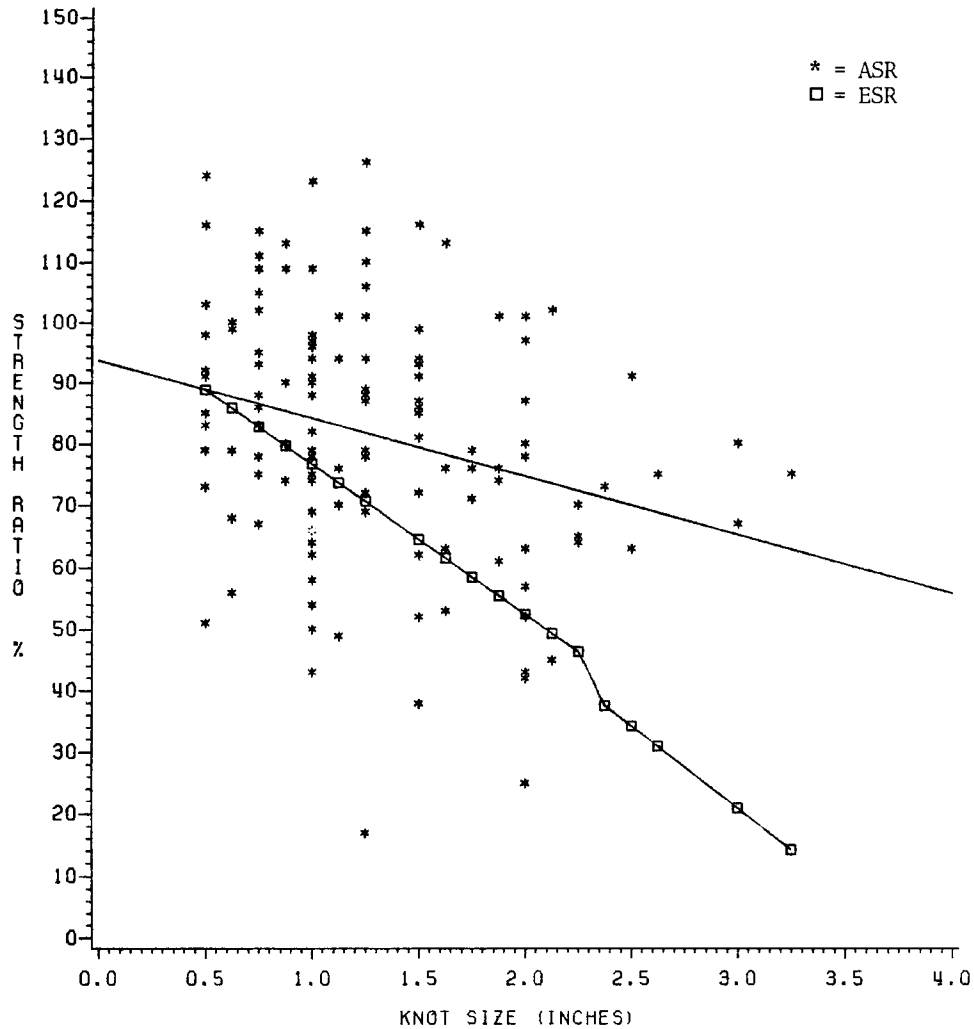
FIG. 3. Strength ratio as a function of knot size for centerline knots in oak stringers. Regression line for ASR vs. knot size superimposed.

7. To be included in a plot for a particular type of defect, a shook piece had that defect as its only or worst defect (i.e., the defect resulted in the lowest ESR for the piece). However, failure of the piece was not necessarily caused by that particular defect.

Immediately noticeable from these plots is the wide variation in ASR for a given defect size. This is due in part to the use of an average clear wood strength value in determining ASR, which also explains why some ASRs exceed 100. Note that the ESR line-plot for knots is based on knot size and the average actual dimensions for all shook pieces in the particular size class. The general trend of conservatism in ESR is obvious. A linear regression analysis showed the degree of correlation between ASR and ESR to be quite low, with r^2 values ranging from 0.06 (slope of grain in four-inch deckboards) to 0.21 (compression edge knots in stringers).

Also superimposed on each strength ratio plot is a least squares regression line for ASR versus defect size. The r^2 values were quite low, ranging from 0.08 (centerline knots in stringers) to 0.26 (compression edge knots in stringers). They are included on the plots only to aid the visual comparison of the trend between ESR and ASR versus defect size. While the relationship between strength ratio and defect size may not be linear, for visual purposes a linear regression was felt to be most appropriate given the wide variation in ASR.

Figures 3 and 4 show strength ratio plots of centerline knots and edge knots, respectively, in oak stringers. While ASTM strength ratios for centerline knots are applicable throughout the length of the piece, the strength ratios for edge knots apply only to those knots within the middle one-third of the length. Therefore, only those edge knots within the middle one-third of the length of the oak stringers are plotted in Fig. 4. For both centerline and edge knots in oak stringers, the ESR predicts the average ASR fairly well for small knot sizes. As the knot size increases, however, the ESR becomes increasingly conservative. The ASR and ESR for a ½-inch knot are approximately equal for both centerline and edge knots, judging from Figs. 3 and 4. However, for a 2½-inch knot the ASR is twice the ESR for centerline knots and four times the ESR for edge knots. It appears that the ESR for edge knots becomes even more conservative than for centerline knots as knot size increases.

The ASTM D245 strength ratio equations for edge knots make no differentiation as to which edge (compression or tension) the knot occupies. However, the strength reduction assumed is based on a tension edge knot (Wilson 1934). Edge knots in tension can be expected to reduce strength much more than in compression because of the more severe effect of grain orientation on tensile strength. Indeed, separate strength ratio plots for tension and compression edge knots revealed that the ESR underpredicts the ASR of compression edge knots more than for tension edge knots (see McLeod 1985).

The formula for calculating the ESR changes below a value of 45% for all sizes of members and all types of knots. This can be seen as a sudden shift of the ESR line at the 45% point in Figs. 3 and 4, as well as the remaining plots comparing ASR and ESR for members containing knots. This may be an artificial adjustment to the strength ratio based on the assumption that larger defects will have more than a proportional effect on strength.

Figure 5 shows the plot of strength ratio versus slope of grain in oak stringers. As with knots, the ESR is fairly conservative in predicting strength. However, this conservatism is fairly constant over the range of grain deviation with ASR approximately 50% greater than ESR for stringers.

The strength ratio plot for knots in four-inch deckboards is shown in Fig. 6. The ESR calculated from ASTM D245 applies to knots anywhere in the wide face of boards with one-inch nominal thickness. A trend similar to that found for centerline knots in stringers is seen; the ESR predicts the average ASR fairly well for small knot sizes but becomes increasingly conservative as the knot size increases. For a ¼-inch knot, the ASR is approximately equal to ESR, but for 2½-inch knots, the ASR is over 80% greater than ESR. Similar trends were noted with the six-inch deckboards.

The effect of slope of grain on strength in four-inch oak deckboards is seen in Fig. 7. The grain deviation ESR underpredicts the comparable ASR for deckboards
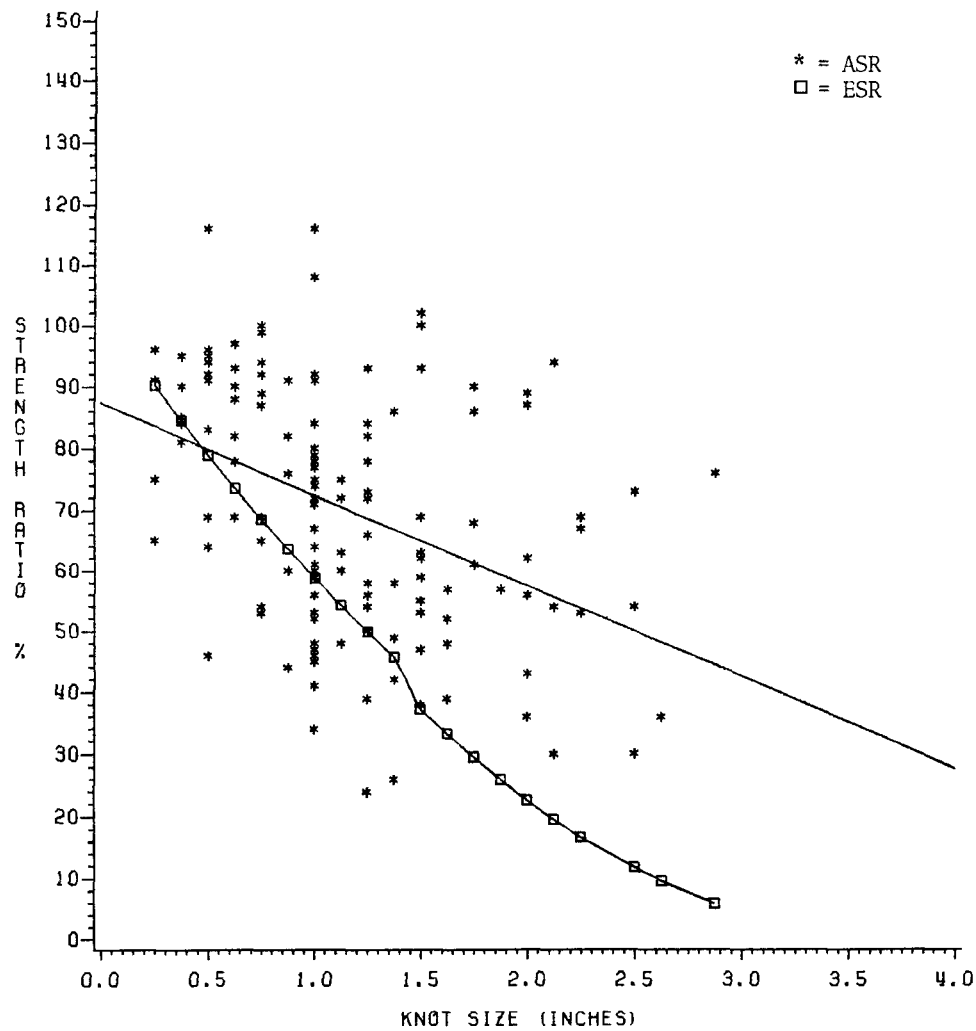
Fig. 4.   Strength ratio as a function of knot size for edge knots in oak stringers (knots within central third of length only). Regression line for ASR vs. knot size superimposed.

with overall greater conservatism than for stringers. However, as with stringers, the level of conservatism does not increase with the severity of the grain slope. The ASR is approximately 60% greater than ESR in deckboards. Similar trends were also found with 6-inch deckboards.

The ESR for centerline knots in oak stringers and all knots in oak deckboards is valid for knots located throughout the length of the piece. However, the shook was tested in third-point loading and the section between load points was subjected to the maximum bending moment. The data in Figs. 3 and 6 were reexamined to determine how the knots outside the load points affected the strength ratio relationship for stringer centerline knots and all knots in deckboards. The variation in ASR was slightly reduced, and some of the outlying points were eliminated. There was no significant shift in position of data relative to the ESR line.
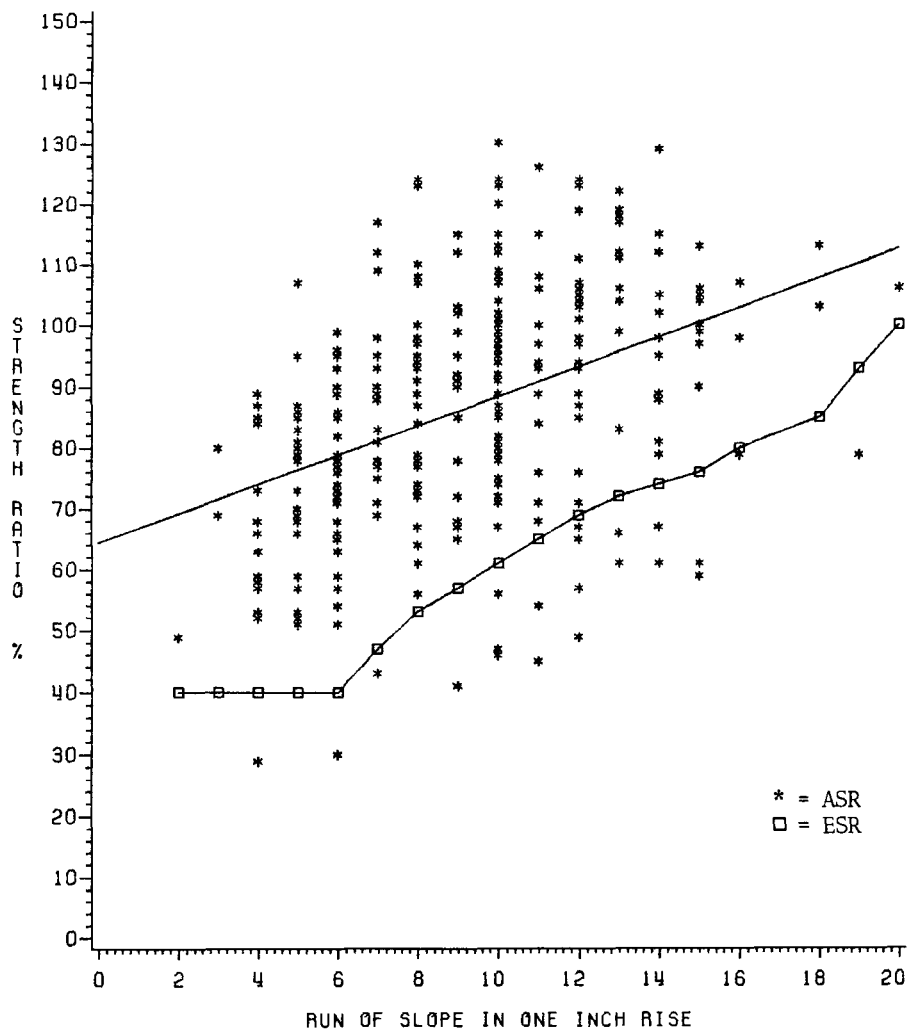
FIG. 5. Strength ratio as a function of degree of slope for slope of grain in oak stringers. Regression line for ASR vs. degree of slope superimposed.

Unfortunately, a comparison of ASR and ESR for narrow face knots in stringers could not be made because narrow face knots were not measured according to ASTM D245 and could not be assigned an ESR. ASTM D245 strength ratios for splits apply to bending capacity governed by shear strength. Since very few pieces failed in shear, no meaningful comparison can be made.

In the derivation of the ASTM strength ratios for knots,the knot is assumed to act as a hole which reduces the section modulus of the piece as illustrated in Figs. 1 and 2. The assumed strength reduction is based on the reduced moment-carrying capacity of the piece with the hole. In reality, however, the knot has some intrinsic strength and the decrease in strength of the piece containing the knot is largely due to the grain deviation around the knot rather than the knot itself. The problem then is how to measure the effective size of the "hole" and accurately predict its influence on strength.
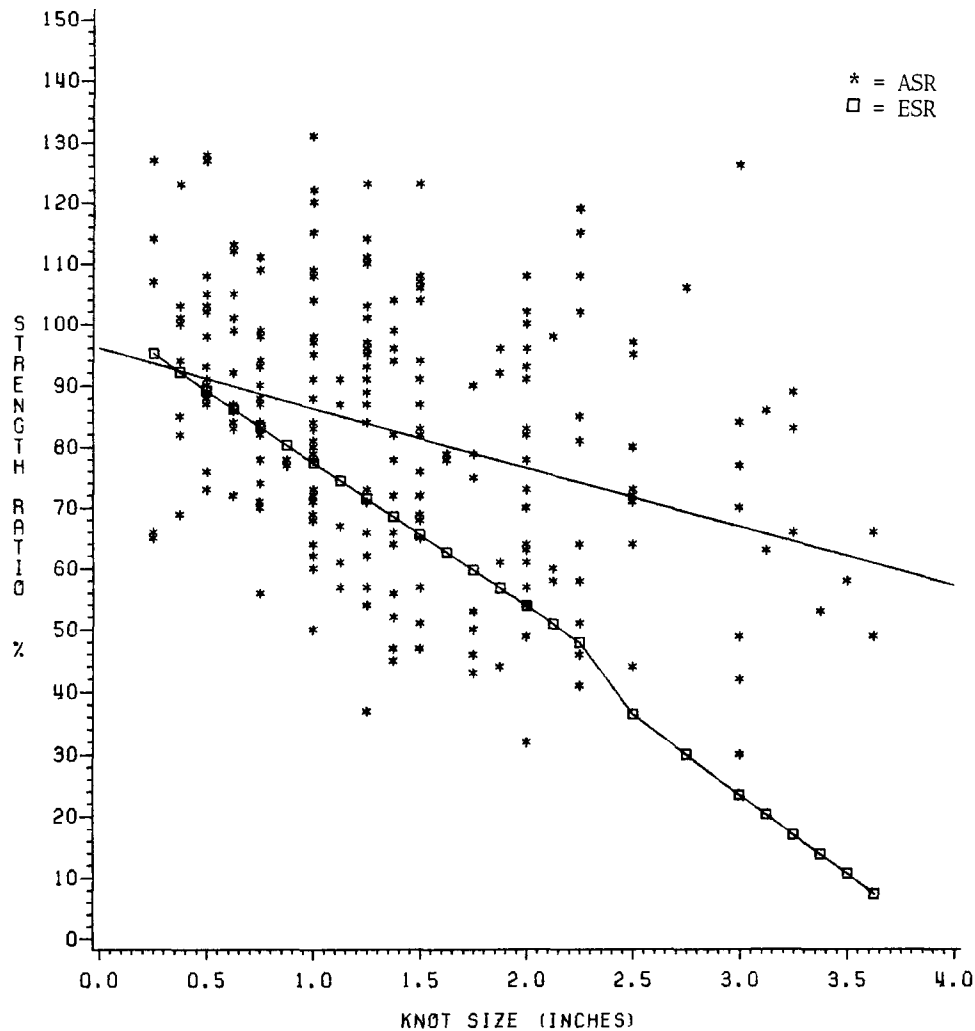
FIG. 6. Strength ratio as a function of knot size for knots in four-inch oak deckboards. Regression line for ASR vs. knot size superimposed.

The ASR-ESR relationship for oak pallet shook with knots is opposite that reported by Walters et al. (1971) for oak and cottonwood 2 × 8's. Walters found ASR to be increasingly lower than ESR as knot size increased. It was shown in this study of oak pallet shook that ESR was increasingly less than ASR as knot size increased. The ASR-ESR relationship reported by Koch (1981) for yellow-poplar 2 × 4's with knots is the same as found in this study of pallet shook. Given the similarity of size of material, this might be expected. The seemingly opposite trend for 2 × 4's versus 2 × 8's may indicate a depth-lumber quality interaction. Indeed, Doyle and Markwardt (1966) showed a decrease in ASR of southern pine with increased depth. As lumber quality (grade) decreased, there was even greater decrease in ASR with increased depth. The effect of knots on bending strength may be considerably different for pallet shook than full-size 2 × 8's given the
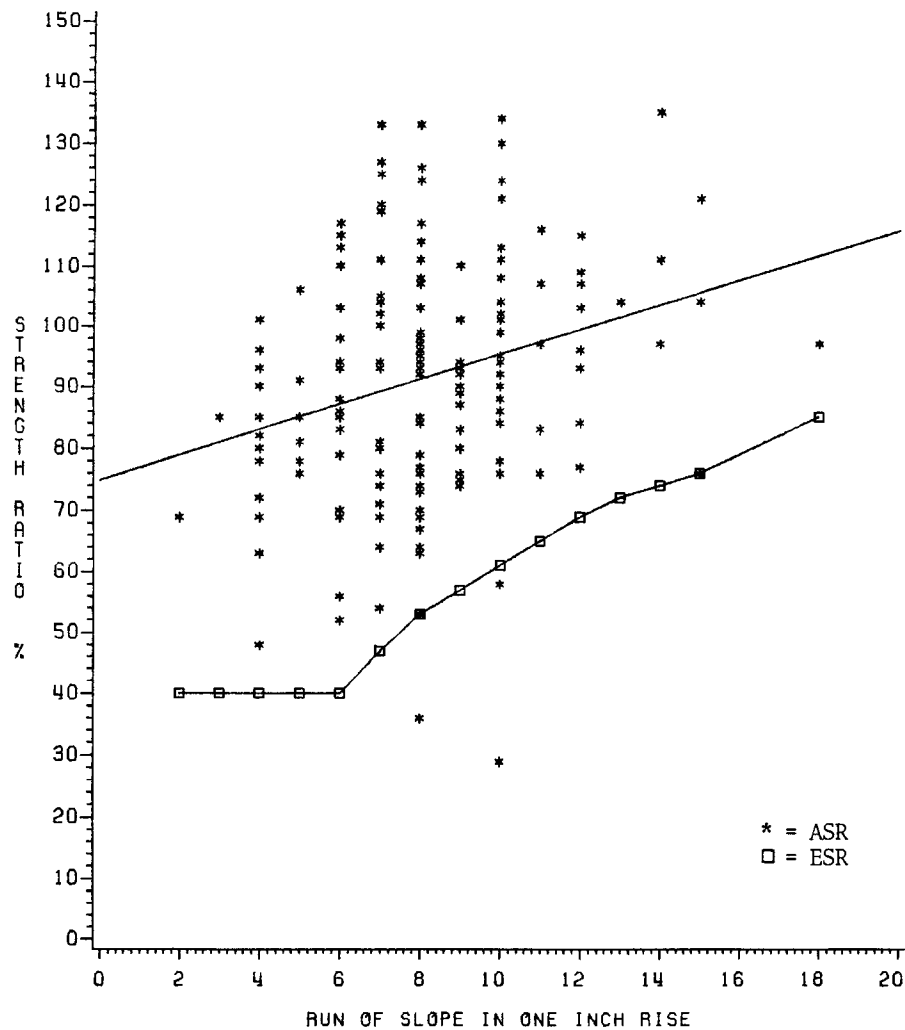
FIG. 7.   Strength ratio as a function of degree of slope for slope of grain four-inch oak deckboards. Regression line for ASR vs. degree of slope superimposed.

considerable difference in size. These dissimilarities in ASR-ESR relationship point to the problem of how to measure the effective knot size and predict the resulting influence on strength. It appears that the current procedures do not accurately or consistently account for the effect of knots on bending strength of hardwood lumber.

The ASTM strength ratios for slope of grain allow for a decrease in strength due to the slope of grain as well as associated drying defects in full-size lumber. However, the shook in this study was in the green condition and had no drying defects. This may explain the conservative ESR. Alternatively, the slope of grain reductions were probably intended to be conservative and should not be expected to approach the average effect.

The ASR-ESR relationship for oak pallet shook with slope of grain is similar

to that reported for oak and cottonwood 2 × 8's: ESR consistently underestimated ASR throughout the range of severity of slope of grain. However, ASR was approximately 15–20% greater than ESR for the 2 × 8's while 50–60% greater in this study. The trend of decreasing ASR with increasing depth may explain this difference.

Given the inaccuracy of the ASTM strength ratios in predicting the bending strength of oak pallet shook, alternative methods of estimating bending strength may be required. One alternative would be to determine how to measure and account more effectively for knot size in relation to its effect on bending strength. Another alternative, the development of a machine stress rating system for pallet shook, would largely do away with the visual stress rating approach. Development of in-grade test data for pallet shook is also an alternative. However, these alternatives represent potential long-term solutions that are not likely to take place in the foreseeable future, at least for the majority of species used.

Assigners of design stresses for pallet shook have two immediately available options. The first is to use the ASTM D245 strength ratios and accept conservative bending strength values for green material. Particularly conservative values should be expected for low quality grades that allow large knots. The second option is to estimate pallet shook strength based on the actual strength ratios observed in this study and reported in Table 2. A future paper will explore these options.

CONCLUSION

The estimated strength ratios of green eastern oak pallet shook, determined according to ASTM D245, generally underestimated the actual strength ratios, determined experimentally. The following specific conclusions can be made:

1) The ESR closely predicts the average ASR for stringers and deckboards with small knots but increasingly underestimates ASR as knot size increases.
2) The conservatism in stringer ESR with increasing knot size is greater for edge knots than centerline knots.
3) The slope of grain ESR consistently underestimates ASR for stringers and deckboards throughout the range of severity of the grain deviation. ESR underestimates ASR more for deckboards with slope of grain than for stringers.

Given the inaccuracy of the ASTM strength ratios in predicting the bending strength of oak pallet shook, alternative methods of estimating bending strength may be required.

ACKNOWLEDGMENTS

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