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Using Transverse Vibration Nondestructive Testing Techniques to Estimate Stiffness and Strength of Southern Pine Lumber

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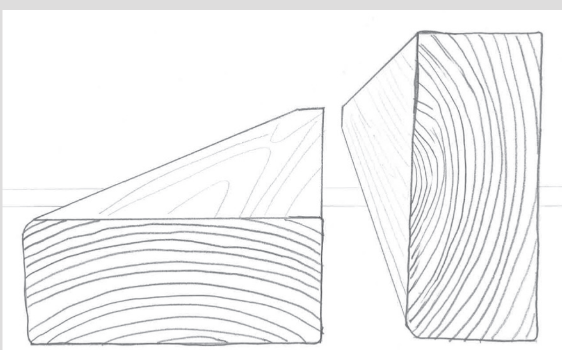

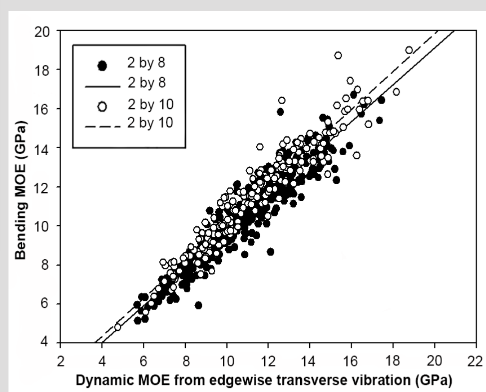

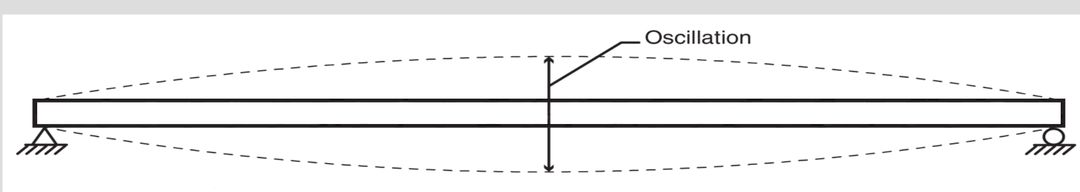

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Abstract

This research focused on evaluating the bending stiffness and strength of structural lumber with transverse vibration nondestructive testing techniques. A random sample of nominal 2-in.- (standard 38-mm-) thick Southern Pine dimension lumber was obtained from several mills in southeastern United States. After conditioning, the lumber specimens were nondestructively tested using transverse vibration techniques. Modulus of elasticity (MOE) was determined using the frequency of oscillation and density. Static bending MOE and strength were then determined for each specimen. Statistical analyses were then performed to examine the relationships between transverse vibration modulus values and bending MOE and strength. Excellent relationships were observed between transverse vibration and static bending MOE values. Strong relationships were found between transverse vibration MOE and bending strength.

Keywords: transverse vibration, nondestructive, bending strength, modulus of elasticity

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Nominal lumber size (in.)	Standard lumber size (mm)
2 by 4	38 by 89
2 by 6	38 by 140
2 by 8	38 by 184
2 by 10	38 by 235

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Using Transverse Vibration Nondestructive Testing Techniques to Estimate Stiffness and Strength of Southern Pine Lumber

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Introduction

Transverse vibration techniques have received considerable attention for nondestructive evaluation applications (Ross 2015). Figure 1 illustrates a typical free transverse vibration test setup. Note that the specimen is simply supported at both ends.

A slight deflection is introduced at the specimen's midspan and is then allowed to freely oscillate in the vertical (transverse) direction. Frequency of oscillation is determined and, along with the specimen weight and dimensions, used to compute modulus of elasticity (MOE). This measurement of MOE is referred to as transverse MOE (MOE_{tv}) and is sometimes referred to as dynamic MOE to differentiate it from static MOE. MOE_{tv} is calculated from the following formula:

$$MOE_{tv} = f^2\, WS^3/2.46Ig$$

where f is resonant frequency (Hz), W weight of the specimen (N), S span (m), I moment of inertia (m^4), and g acceleration due to gravity (9.81 m/s^2).

ASTM D6874-12, "Standard Test Methods for Nondestructive Evaluation of Wood-Based Flexural Members Using Transverse Vibration," outlines important aspects for using transverse vibration nondestructive testing (NDT) techniques to evaluate the MOE of wood materials (ASTM 2012). This standard outlines three elements that are essential when using this type of technique: the support apparatus, excitation system, and measurement system. A detailed discussion of these elements is beyond the scope of this report but is provided in the standard and in Ross (2015). It is important to note that this standard recommends transverse vibration testing of lumber specimens flatwise; this results in a low frequency vertical vibration with few modes. Testing edgewise complicates the test, because a specimen may vibrate in several modes, specifically vertically and horizontally, which could lead to erroneous results.

Pellerin (1965b) used this technique to evaluate the properties of several large, glued-laminated (glulam) timbers in an edgewise orientation. Using three Douglas-fir glulam timbers, he was able to obtain accurate

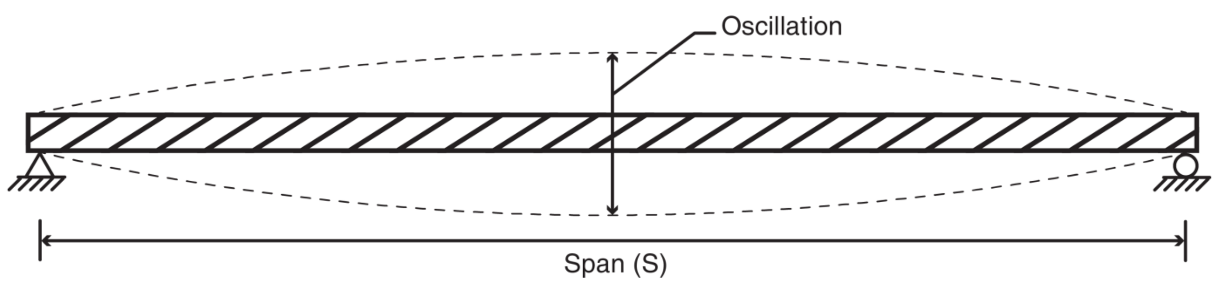

Figure 1. Typical free transverse vibration test setup.

measurements of natural frequency, dynamic MOE, and the decay of transverse vibrations and use them to predict the relative strength of the timbers. It was important to test the timbers in an edgewise orientation, because each timber had a unique layup pattern, which significantly affected its flexural stiffness and strength. Yang and others (2015) used this technique to evaluate southern yellow pine lumber in edgewise and flatwise orientations, with both yielding good results.

Pellerin (1965a) and O'Halloran (1969) reported on the use of transverse vibration techniques to evaluate the strength and stiffness of structural lumber. Pellerin's research focused on predicting the bending MOE and strength of inland Douglas-fir dimension lumber. O'Halloran's efforts focused on the use of the techniques to evaluate lodgepole pine dimension lumber. Both reported excellent empirical relationships between static and dynamic MOE values and strong relationships with strength. Wang and others (1993) also reported on the use of these techniques to evaluate the MOE of a sample of Spruce–Pine–Fir dimension lumber; they noted that excellent correlative relationships were obtained.

The objective of the research study summarized in this report was to investigate the relationships between transverse vibration characteristics, measured in flatwise and edgewise orientations, and the flexural MOE and strength of Southern Pine dimension lumber.

Materials and Methods

Table 1 summarizes a breakdown of the lumber sample used. More than two thousand (2039) lumber specimens, all visually graded as No. 2, were used. The specimens were randomly selected from the southeastern region of the United States. All specimens were conditioned (temperature 22°C; relative humidity 61%) for approximately 90 days to equilibrate to an estimated 12% moisture content prior to testing.

Table 1—Summary of the sample of lumber used in this study

Nominal size	Thickness (mm)	Width (mm)	Length (m)	Number of samples	
				By length	Total
2 by 4	38	89	2.4	121	630
			3.1	152	
			3.7	206	
			4.3	49	
			4.9	102	
2 by 6	38	140	3.1	85	613
			3.7	265	
			4.3	137	
			4.9	102	
			6.1	24	
2 by 8	38	184	3.7	145	483
			4.3	202	
			4.9	136	
2 by 10	38	235	4.3	204	313
			4.9	109	

The MOE_{tv} was measured for each specimen using a Metriguard Model 340 Transverse Vibration E-Computer (Metriguard Inc., Pullman, Washington, USA). Each specimen was initially tested in flatwise orientation. Actual dimensions and weight were used in the computation of the transverse vibration MOE in flatwise orientation ($dMOE_{flat}$). A similar procedure was used in the measurement of the dynamic MOE in edgewise orientation ($dMOE_{edge}$), with special care taken to ensure that horizontal vibration was minimized.

The edgewise bending test was conducted according to ASTM D198-15 (2015) via four-point loading, using a span-to-depth ratio of 17:1. The bending span was selected to match prior in-grade testing programs (Green and others 1989). The tension face of each specimen was randomly selected, and specimens were loaded randomly to better represent actual end use. Load and deflection were continuously monitored until failure. Static bending MOE and strength (modulus of rupture (MOR)) were calculated for each specimen from their corresponding load–deflection diagram.

All statistical analyses of static bending (MOR and MOE) and dynamic MOE values obtained from transverse vibration tests were conducted using SAS 9.4 (SAS 2013). Single variable linear regression analyses ($\alpha = 0.05$) were built for each cross section and length lumber group to correlate the NDT outputs to bending MOE and MOR values. The linear regressions were conducted given the independent variables (x, which can be represented by density, $dMOE_{edge}$, and $dMOE_{flat}$) and the dependent variable (MOE, MOR). Coefficient of correlation (r), which measures the strength of the relationships between variables, was the main focus.

Results and Discussion

Table 2 presents a summary of several basic properties of the lumber tested. Note the following: (1) each lumber group had comparable density values, (2) moisture content values for the groups were consistent, (3) the transverse vibration MOE values were consistent between cells, and (4) strength (MOR) values showed the most variability.

The mathematical regression models between the nondestructive test parameters (density, $dMOE_{edge}$, and $dMOE_{flat}$) and static properties (MOE and strength (MOR)) were assumed to be linear and of the following form:

$$\text{Static property} = \text{slope} \times (\text{nondestructive test parameter}) + \text{intercept} + \text{error}$$

Table 2—Summary of properties from the lumber evaluated (coefficients of variation (%) in parentheses)

Nominal size	Density (kg m^{-3})	Moisture content (%)	Transverse vibration MOE flatwise (GPa)	Transverse vibration MOE edgewise (GPa)	Modulus of elasticity (MPa)	Modulus of rupture (MPa)
2 by 4	548	11.45	11.51	11.61	10,855	55.39
	(11.1)	(8.47)	(26.1)	(25.2)	(25.8)	(37.5)
2 by 6	548	11.04	11.31	11.19	10,414	45.88
	(10.8)	(11.6)	(25.3)	(23.9)	(23.0)	(39.1)
2 by 8	542	11.68	11.06	10.92	10,519	38.92
	(9.9)	(14.2)	(25.3)	(21.2)	(22.1)	(36.1)
2 by 10	560	12.15	10.96	10.68	11,059	42.90
	(10.5)	(18.7)	(26.6)	(22.7)	(24.0)	(38.3)

After a statistical analysis of each combination of size and length, summaries of which are included in the Appendix, it was deemed appropriate to combine 2 by 4 and 2 by 6 data sets for purposes of examining statistical relationships between transverse vibration MOE and static bending properties. Similarly, we combined 2 by 8 and 2 by 10 data sets.

Tables 3 and 4 provide summaries obtained from these statistical analyses. Figure 2 shows plots of static bending MOE values predicted using transverse vibration MOE values. These plots show that strong correlative relationships exist. In this case, the coefficients of determination for MOE and $dMOE_{flat}$ were 0.839 and 0.794, respectively. For MOE and $dMOE_{edge}$, they were 0.874 for 2 by 4 and 2 by 6 and 0.887 for 2 by 8 and 2 by 10. The correlative relationships we developed were comparable with those reported in the literature (Table 5) (Pellerin 1965a; O'Halloran 1969; Wang and others 1993; Yang and others 2015; Green and McDonald 1993a, 1993b).

Figure 3 shows several plots of bending strength (MOR) values predicted by transverse vibration MOE. Results obtained from the corresponding statistical analyses are summarized in Tables 3 and 4. Between MOR and $dMOE_{flat}$, the coefficients of determination were 0.377 for 2 by 4 and 2 by 6 and 0.213 for 2 by 8 and 2 by 10. For MOR and $dMOE_{edge}$, they were 0.425 for 2 by 4 and 2 by 6 and 0.289 for 2 by 8 and 2 by 10.

Table 3—Results of linear regression analyses relating static bending modulus of elasticity (MOE) and strength to transverse vibration MOE for 2 by 4 and 2 by 6 Southern Pine dimension lumber

Variable	MOE[a]				MOR[a]			
	Slope (m)	Intercept (b)	Coefficient of determination (r^2)	Standard error of estimate	Slope (m)	Intercept (b)	Coefficient of determination (r^2)	Standard error of estimate
Density	30.02	–5712.26	0.469	1906.58	0.192	–54.09	0.331	16.26
$dMOE_{flat}$	817.41	1307.07	0.839	1048.48	4.18	3.01	0.377	15.79
$dMOE_{edge}$	869.64	721.35	0.874	925.55	4.63	–2.10	0.425	15.16

[a]The coefficients m and b are used in the generalized model static property = m (transverse vibration MOE) + b.

Table 4—Results of linear regression analyses relating static bending modulus of elasticity (MOE) and strength to transverse vibration MOE for 2 by 8 and 2 by 10 Southern Pine dimension lumber

Variable	MOE[a]				MOR[a]			
	Slope (m)	Intercept (b)	Coefficient of determination (r^2)	Standard error of estimate	Slope (m)	Intercept (b)	Coefficient of determination (r^2)	Standard error of estimate
Density	29.24	–5,273.40	0.444	1,885.48	0.188	–52.93	0.309	16.16
$dMOE_{flat}$	783.22	2,443.24	0.794	1,131.91	2.599	14.09	0.213	14.15
$dMOE_{edge}$	983.65	302.82	0.887	840.10	3.60	3.35	0.289	13.45

[a]The coefficients m and b are used in the generalized model static property = m (transverse vibration MOE) + b.

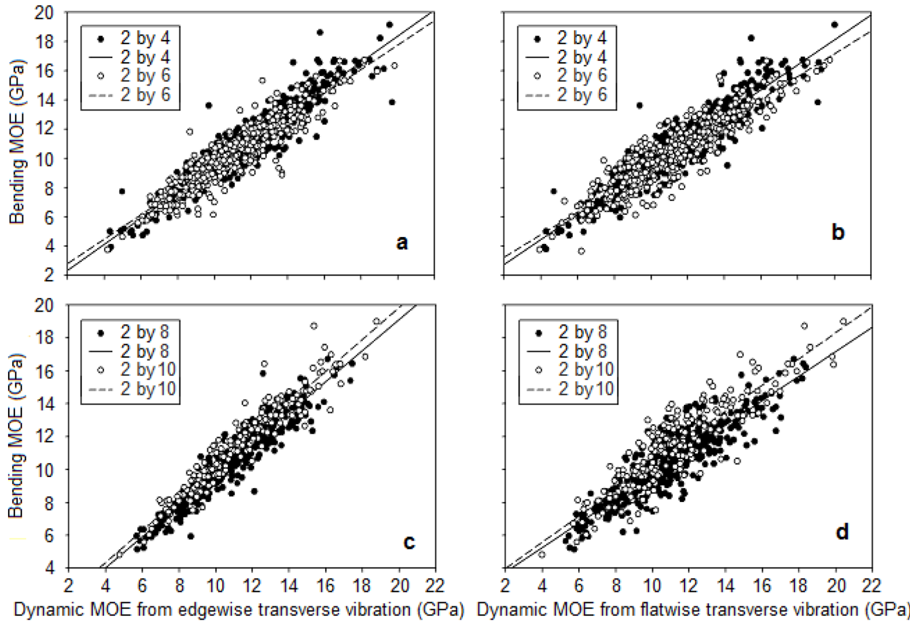

Figure 2. Linear regression plots for each lumber size: bending modulus of elasticity (MOE) versus dynamic MOE from (a) edgewise transverse vibration on 2 by 4 and 2 by 6; (b) flatwise transverse vibration on 2 by 4 and 2 by 6; (c) edgewise transverse vibration on 2 by 8 and 2 by 10; and (d) flatwise transverse vibration on 2 by 8 and 2 by 10.

Table 5—Summary of research conducted to examine the relationship between transverse vibration modulus of elasticity and static bending properties (modulus of elasticity (MOE) and modulus of rupture (MOR)) of structural lumber

		Comparison of transverse vibration parameters and properties (correlation coefficient, r)	
Reference	Material	MOE	MOR
Pellerin (1965a)	Inland Douglas-fir dimension lumber	0.98	0.67–0.93
O'Halloran (1969)	Lodgepole pine dimension lumber	0.98	0.89
Wang and others (1993)	Spruce–Pine–Fir dimension lumber	0.96–0.98	NA[a]
Yang and others (2015)	Southern Pine dimension lumber	0.86–0.97	NA
Green and McDonald (1993a)	Northern red oak lumber	0.92	0.58
Green and McDonald (1993b)	Red maple lumber	0.85	0.42

[a]NA, not available.

Conclusions and Recommendations

This study investigated the ability of flatwise and edgewise transverse vibration NDT techniques to estimate the static bending MOE and strength (MOR) values of Southern Pine dimension lumber. Results revealed the following:

- Commercially available transverse vibration NDT equipment was able to capture the vibration characteristics for a variety of sizes (cross sections) and lengths frequently used in the construction industry.
- It was possible to obtain adequate measurement of frequency of vibration data for dimension lumber, tested in both flatwise and edgewise orientations.
- Flatwise and edgewise transverse vibration MOE values were strongly correlated with static bending MOE values for Southern Pine dimension lumber.
- Useful correlative relationships were observed between transverse vibration MOE and corresponding strength values.
- Edgewise transverse vibration MOE values showed slightly higher correlative relative relationships with both static bending MOE and strength values. This was exhibited most strongly with larger lumber sizes (2 by 8 and 2 by 10).

These results revealed that transverse vibration NDT techniques can be used successfully as part of an automated structural lumber grading system. Lumber should be tested in a flatwise orientation because an edgewise orientation has the potential to vibrate in additional modes. which would complicate the design of in-line equipment.

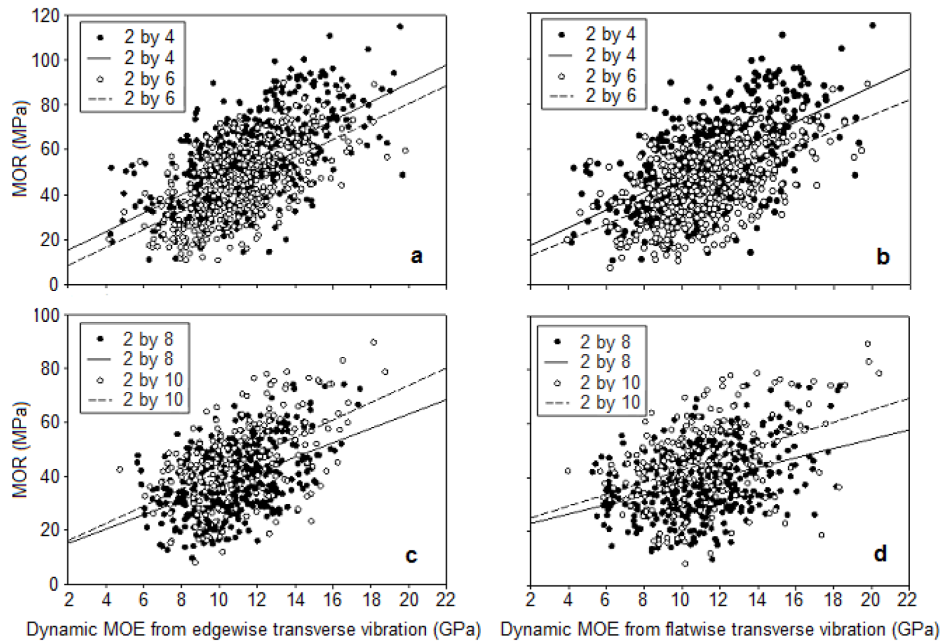

Figure 3. Linear regression plots for each lumber size: modulus of rupture (MOR) versus dynamic modulus of elasticity (MOE) from (a) edgewise transverse vibration on 2 by 4 and 2 by 6; (b) flatwise transverse vibration on 2 by 4 and 2 by 6; (c) edgewise transverse vibration on 2 by 8 and 2 by 10; and (d) flatwise transverse vibration on 2 by 8 and 2 by 10.

Literature Cited

ASTM. 2012. D6874-12. Standard test methods for nondestructive evaluation of wood-based flexural members using transversal vibration. West Conshohocken, PA: ASTM International.

ASTM. 2015. D198-15. Standard test methods of static tests of lumber in structural sizes. West Conshohocken, PA: ASTM International.

Green, D.W.; McDonald, K.A. 1993a. Investigation of the mechanical properties of red oak 2 by 4’s. Wood and Fiber Science. 25(1): 35-45.

Green, D.W.; McDonald, K.A. 1993b. Mechanical properties of red maple structural lumber. Wood and Fiber Science. 25(4): 365-374.

Green, D.W.; Shelley, B.E.; Vokey, H.P. 1989. In-grade testing of structural lumber. Proceedings 47363. Madison, WI: Forest Products Society. 110 p.

O’Halloran, M.R. 1969. Nondestructive parameters for lodgepole pine dimension lumber. Fort Collins, CO: Colorado State University. M.S. Thesis.

Pellerin, R.F. 1965a. A vibrational approach to nondestructive testing of structural lumber. Forest Products Journal. 15(3): 93-101.

Pellerin, R.F. 1965b. The contributions of transverse vibration grading to design and evaluation of 55-foot laminated beams. In: Proceedings, 2nd nondestructive testing of wood symposium; 1965 April; Spokane, WA. Pullman, WA: Washington State University: 337-347.

Ross, R.J. 2015. Nondestructive evaluation of wood: second edition. Gen. Tech. Rep. FPL-GTR-238. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 169 p.

SAS. 2013. SAS version 9.4. Cary, NC: SAS Institute, Inc.

Wang, Z.; Ross, R.J.; Murphy, J.F. 1993. A comparison of several NDE techniques for determining the modulus of elasticity of lumber. World Forestry Research. 6(4): 86-88. (In Chinese).

Yang, B.Z.; Seale, R.D.; Shmulsky, R.; Dahlen, J.; Wang, X. 2015. Comparison of nondestructive testing methods for evaluating No. 2 southern pine lumber: Part A, modulus of elasticity. Wood and Fiber Science. 47: (4) 375-384.

Appendix—Statistical Analysis

The tables in this Appendix present the complete statistical analysis with the MOE and MOR coefficients of determination for each lumber length group (f is resonant frequency, and d stands for dynamic).

Table A1—Coefficients of determination for 2 by 4

Length	MOE					MOR				
(m)	Density	f_{flat}	$dMOE_{flat}$	f_{edge}	$dMOE_{edge}$	Density	f_{flat}	$dMOE_{flat}$	f_{edge}	$dMOE_{edge}$
2.4	0.301	0.716	0.897	0.762	0.945	0.386	0.130	0.311	0.156	0.368
3.1	0.475	0.728	0.878	0.731	0.924	0.345	0.252	0.386	0.245	0.403
3.7	0.504	0.613	0.826	0.671	0.867	0.298	0.262	0.407	0.325	0.458
4.3	0.542	0.616	0.774	0.681	0.852	0.402	0.206	0.364	0.228	0.406
4.9	0.560	0.564	0.841	0.555	0.832	0.396	0.187	0.397	0.192	0.388
Overall	0.476	—	0.857	—	0.891	0.349	—	0.381	—	0.412

Table A2—Coefficients of determination for 2 by 6

Length	MOE					MOR				
(m)	Density	f_{flat}	$dMOE_{flat}$	f_{edge}	$dMOE_{edge}$	Density	f_{flat}	$dMOE_{flat}$	f_{edge}	$dMOE_{edge}$
3.1	0.286	0.552	0.721	0.726	0.882	0.223	0.045	0.359	0.119	0.266
3.7	0.466	0.599	0.852	0.656	0.912	0.326	0.499	0.423	0.226	0.445
4.3	0.398	0.511	0.760	0.643	0.841	0.227	0.368	0.269	0.253	0.383
4.9	0.563	0.719	0.869	0.656	0.861	0.497	0.692	0.632	0.406	0.610
6.1	0.613	0.658	0.799	0.420	0.762	0.404	0.509	0.393	0.247	0.500
Overall	0.466	—	0.823	—	0.854	0.336	—	0.397	—	0.415

Table A3—Coefficients of determination for 2 by 8

Length	MOE					MOR				
(m)	Density	f_{flat}	$dMOE_{flat}$	f_{edge}	$dMOE_{edge}$	Density	f_{flat}	$dMOE_{flat}$	f_{edge}	$dMOE_{edge}$
3.7	0.500	0.619	0.834	0.554	0.861	0.209	0.112	0.228	0.129	0.283
4.3	0.321	0.624	0.778	0.701	0.889	0.210	0.115	0.221	0.172	0.308
4.9	0.407	0.666	0.806	0.711	0.906	0.162	0.123	0.204	0.116	0.206
Overall	0.413	—	0.797	—	0.878	0.177	—	0.201	—	0.268

Table A4—Coefficients of determination for 2 by 10

Length	MOE					MOR				
(m)	Density	f_{flat}	$dMOE_{flat}$	f_{edge}	$dMOE_{edge}$	Density	f_{flat}	$dMOE_{flat}$	f_{edge}	$dMOE_{edge}$
4.3	0.415	0.615	0.792	0.645	0.867	0.180	0.118	0.219	0.151	0.272
4.9	0.417	0.599	0.755	0.674	0.910	0.343	0.158	0.311	0.196	0.403
Overall	0.412	—	0.767	—	0.876	0.226	—	0.235	—	0.321