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ORIGINAL ARTICLE

Yield analysis of Hem-Fir (N) lamina for Japanese visual and machine grade standards

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Abstract The grade yields of Hem-Fir (N) (*Tsuga heterophylla* and *Abies amabilis*) laminas were compared for visual and machine grades based on the Japanese Agricultural Standard (JAS) for glued laminated timber. The main objective of this study was to assess technical and material benefits when a glued laminated timber is manufactured using machine-graded laminas rather than visually graded. Total 1000 pieces of Hem-Fir (N) lamina were tested for modulus of elasticity (E) and tensile strength. Also, the E's measured by two different test equipment (vibration and continuous bending) were compared. The test data showed that if the laminas were machine graded, 54 % of the lamina would achieve a modulus of elasticity of 12.5 GPa or higher, which are above the average 11 GPa assigned to JAS visual Grade 1 of the wood species group D. It was concluded that the machine grading method was able to derive higher mechanical properties leading to a yield benefit for the lamina production.

Keywords Lamina · Glued laminated timber · Visual grading · Machine grading · Hem-Fir (N)

Introduction

The use of glued laminated timber products in Japanese post and beam housing has grown dramatically in the last decade. This leads to a growing market for wood lamina which is a prior product for manufacturing glued laminated posts and beams in Japan. The Japanese Agricultural Standards (JAS) for glued laminated timber and structural glued laminated timber are dictated by the Ministry of Agriculture, Forestry and Fisheries (MAFF) Notification 1152 [1] and MAFF Notification 235 [2] respectively. This notification provides visual and machine grading requirements for various wood species of lamina. Manufacturers of the glued laminated timber have the option of visually or machine graded lamina on which the strength grades of glued laminated timber are based. The choice of the grading methods will often depend on the yields that can be achieved in visual grades as compared to the machine grades [3]. If the actual structural properties of the lamina in a particular species are higher than those visually graded, then there are technical and material benefits to be achieved by machine grading the laminae.

The MAFF Notification 1152 [1] assigns visually graded laminas to the six species groups of A, B, C, D, E, and F, which are classified by wood species and their mechanical properties. The wood species groups are linked to a set of lamina layups and associated with structural properties for glued laminated members that can be manufactured from each species. Consequently, once a visually graded lamina is assigned to a wood species group the structural properties of glued laminated members are predetermined. Western hemlock, called Beitsuga in Japan is assigned to the wood species group D that has the ranges of average bending modulus of elasticity of 9–11 GPa, average bending strength of 39–45 MPa and average tensile strength of 23.5–26.5 MPa in the visual grade requirements for laminae with end-joints. Hem-Fir (N) is a species group including Western Hemlock (*Tsuga heterophylla)* and Amabilis Fir (*Abies amabilis*) which shows similar strength behavior.

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Previous studies of the mechanical properties of Hem-Fir (N) show that the design values of the wood species group D are conservative for Hem-Fir (N) lamina if visually graded and should be put into the group classification [4–6]. The highest visual grade requirement of the wood species group D lamina has an assigned modulus of elasticity of 11 GPa. Higher modulus of elasticity ratings of Hem-Fir (N), however, can be achieved by machine grading. Therefore, the objectives of this study were to compare the grade yields in the visual and machine grades references in the JAS glued laminated timber standard, and to assess the benefits that could be achieved by machine grading.

Materials and methods

Machine grades of the MAFF Notification 1152 [1]

The MAFF Notification 1152 [1] also provides criteria of 14 machine grades for laminas. According to the bending and tensile properties of lamina, grades have a range of the highest L200 and the lowest L30. In the notification, the visual grades of Hem-Fir (N) lamina could be assigned to the wood species group D that corresponds to machine grades between L90 and up to L110 when they compares to only the range of requirements for average and 5th percentile bending and tensile strength of laminae with end-joints. The structural properties requirements for machine graded and visually graded lamina of the wood species group D are summarized in Table 1. If it can be demonstrated that Hem-Fir(N) lamina have the mechanical properties greater than those assigned to the highest visual grade (JAS 1) then lamina producers may want to consider introducing machine grading to derive higher structural and market values for the lamina. Furthermore, if various choices of equipment for machine grading are given it would be more helpful for the consideration. In this study, pilot evaluations were made on the modulus of elasticity and tensile strength of Hem-Fir (N) visually graded and machine graded lamina using two different test equipment for MOE measurements.

Experiment

A sample of 1000 pieces of 3.65 meter long, kiln-dried lamina grade Hem-Fir (N) in a Japanese 30 mm × 110 mm size were sampled from a British Columbia coastal mill in Canada. Hem-Fir (N) species group includes Western Hemlock (Beitsuga) and Amabilis fir that have similar physical and mechanical properties [7]. Each lamina was graded to the Japanese standards for visually graded lamina (JAS 1, JAS 2, JAS 3 and JAS 4) specified in the MAFF Notification 1152 [1]. The grading was conducted by the senior visual grader of the Canadian Mill Services Association. Non-destructive flat-wise modulus of elasticity (E) measurements was made on all laminas using the Metriguard E 340 Transverse Vibration E-Computer. The Metriguard E 340 E-Computer (see Fig. 1) uses the natural frequency, dimensions and weight to compute the transversely vibrating flexural modulus (E_{340}) of a lamina [8]. The modulus of elasticity derived in this test meets the requirements of span-to-depth ratio (1:21) and shear-free bending (four-point loading) specified in the Test method C of Notification 1152 [1]. Moisture meter readings were taken at the time of test using an electrical resistance-type Delmhorst® moisture meter. Density was determined based

Table 1 Structural properties requirements for the wood species group D

Grading method	Grade	Modulus of elasticity (GPa)		Bending strength (MPa)		Tensile strength (MPa)	
		Average	5th percentile	Average	5th percentile	Average	5th percentile
Visual grades	JAS 1	11.0	9.5	45.0	34.0	26.5	20.0
	JAS 2	10.0	8.5	42.0	31.5	24.5	18.5
	JAS 3	9.0	7.5	39.0	29.5	23.5	17.5
	JAS 4	Unspecified					
Grading method	Grade	Modulus of elasticity (GPa) Not less than		Bending strength (MPa)		Tensile strength (MPa)	
				Average	5th percentile	Average	5th percentile
Machine grades	L140	14.0		54.0	40.5	32.0	24.0
	L125	12.5		48.5	36.5	28.5	21.5
	L110	11.0		45.0	34.0	26.5	20.0
	L100	10.0		42.0	31.5	24.5	18.5
	L 90	9.0		39.0	29.5	23.5	17.5
	L80	8.0		36.0	27.0	21.5	16.0

This table is excerpted from the Ministry of Agriculture, Forestry and Fisheries Notification 1152 [1] on the weight and the actual dimensions of each specimen at the time of test.

A second flat-wise modulus of elasticity profile was measured on a sub-sample of 200 specimens using a Cook-Bolinders grading (see Fig. 2). The sample was selected using a ranking method which picks every 5th specimen from the full sample of 1000 sorted in descending order of *E*. This method preserves the *E* distribution of the full sample. The Cook-Bolinders grading machine is a board bending-type machine that measures the local flat-wise *E* over a span of 910 mm continuously while a board is passing through the machine. The *E* profile is measured in a 2-pass system that determines the *E*'s two times with the change of the loading face of a specimen. The individual pass *E* values are averaged to produce an *E* profile along the full length of each specimen that eliminates the effects of bow in the member. A typical Cook-Bolinders *E* profile is shown in Fig. 3. For this study the average of the complete profile was computed for each specimen.

A sub-sample of 100 tensile strength test specimens was selected for the grades JAS 1, 2 and 3, respectively. Only 73 specimens were available for tension tests in the grade JAS 4. The tension specimens were selected from the population of available material for each JAS grade using the ranking method described previously. The tension tests were conducted in a Metriguard Tension Proof Tester Model 304. The specimens without end-joints were tested full-length on a test gauge length of 2.44 m. Moisture content was measured at the time of test using an electrical resistance-type Delmhorst® moisture meter.

Fig. 1 Metriguard E 340 E-computer

Fig. 2 Cook-Bolinders stress grader

Results and discussion

Modulus of elasticity relationships

The average of measured moisture contents of lamina specimen was 9.5 % (max. 15.7 %, min. 7.2 % and SD 1.29). Modulus of elasticity data was adjusted to 12 percent moisture content according to ASTM D 1990 procedures [9]. The cumulative probability distribution of the transversely vibrating flexural modulus (E_{340}) for the 1000 full sample of lamina is shown in Fig. 4. This distribution shows that more than 70 % of the laminas have an E_{340} value greater than $E = 11.0$ GPa specified for JAS visual grade 1 in the wood species group D. This result demonstrates that higher *E* grades could be extracted from Hem-Fir (N) lamina production by producing the machine grades rather than that of the wood species group D. The relation between the average of the flat-wise Cook-Bolinders modulus of elasticity profile (E_{CB}) and the Metriguard transverse vibration modulus of elasticity measured on the sub-sample of 200 Hem-Fir (N) lamina is shown in Fig. 5.

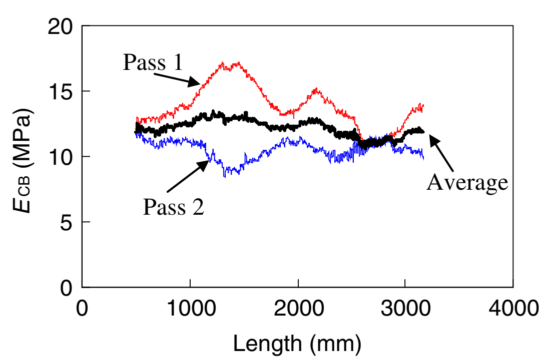

Fig. 3 Cook Bolinders modulus of elasticity (E_{CB}) profile

Regression lines fitted through the data indicate that the E_{CB} and the E_{340} are essentially equivalent. These results agree very closely with comparisons of E_{CB} and E_{340} obtained in a larger sample study of several sizes of

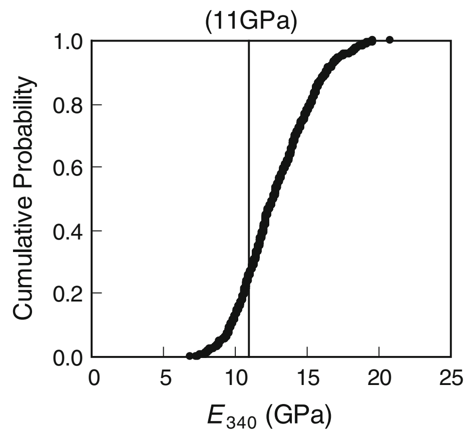

Fig. 4 Distribution of transverse vibration modulus of elasticity (E_{340}) ($n = 1000$)

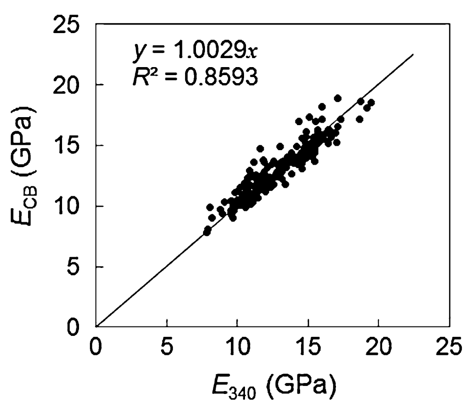

Fig. 5 Relation between Cook Bolinders modulus of elasticity (E_{CB}) and transverse vibration modulus of elasticity (E_{340}) for Hem-Fir (N) lamina ($n = 200$)

Hem-Fir (N) lumber, done by Barrett et al. [6]. The plot of the relation shows an almost perfectly linear relation between the two E values.

Therefore, the transverse vibration E_{340} can be taken to be essentially equivalent to the average of the Cook Bolinders flat-wise bending E profile taken along the length of a lamina. These results confirm that the lamina could be graded effectively with the transverse vibration E_{340} which is relatively low-cost equipment.

The summary of flat-wise modulus of elasticity results for the JAS visually graded lamina is given in Table 2 for the 978 specimens that met the JAS visual grade requirements, out of 1000 specimens (excluding the rejected 22 specimens). The results show that 77.5 % of the lamina specimen has E equal to, or higher than 11 GPa which is assigned to JAS visual grade 1 of wood species group D for the average E requirement. Assumed that the usage of JAS visual grades is limited by the E requirement, the degree of

Table 2 Summary of transverse vibration E_{340} of Hem-Fir (N) laminas (GPa)

Visual grade	Count	Average	Standard deviation	5th percentile	Min.	Max.
JAS 1	424	14.7	2.4	10.5	8.7	20.2
JAS 2	248	12.5	2.0	9.4	7.9	21.7
JAS 3	226	11.4	1.9	8.5	7.4	16.7
JAS 4	80	11.9	2.4	8.1	7.4	19.3

utilization of Hem-Fir (N) can be improved if the lamina products are machine graded. The transition of lamina products from visual grades to machine grades may also increase economic benefits to lamina producers as reported by Erikson [10].

Tensile strength

The tensile strength was measured for a total of 373 specimens of JAS visual grades. The goal of this test sampling was to obtain data of 100 tension specimens per grade. However, only 73 specimens were available in the JAS visual grade 4. The average of measured moisture contents of tension lamina specimen was 9.6 % (max. 14.0 %, min. 7.5 % and SD 1.22). The tensile strength data were adjusted to 12 % moisture content according to ASTM D1990 [9]. The relations between tensile strength and E_{340} for the JAS visual grades are shown in Fig. 6. Power law regressions fitted through the data show that overall the higher JAS visual grades have a higher tensile strength for a given E which reflects the effects of the visual grading criteria.

The cumulative probability distributions of tensile strength for the JAS visual grades are shown in Fig. 7. The corresponding summary of tensile strength statistical results is given in Table 3. The average tensile strength for JAS 1 (42.37 MPa) and JAS 2 (24.80 MPa) grades exceeds the requirements for JAS graded lamina as listed in Table 1. The 5th percentile tensile strength results, however, show much lower values than the minimum requirements except for JAS 1 grade. This may be because the specimens were tested full length [11]. Notification 1152 [1] permits a minimum gauge length of 600 mm with end-joint centered. In this study, the test specimen did not have any end-joints. The method of selecting the test zone is not stated explicitly for a specimen without end-joints, therefore the decision was made to test specimens full-length with the major strength reducing defect (MSRD) located in the test span whenever possible. The location of MSRD for the tensile test could explain partly why the 5th percentile strength requirements of JAS 1 grade were not fulfilled.

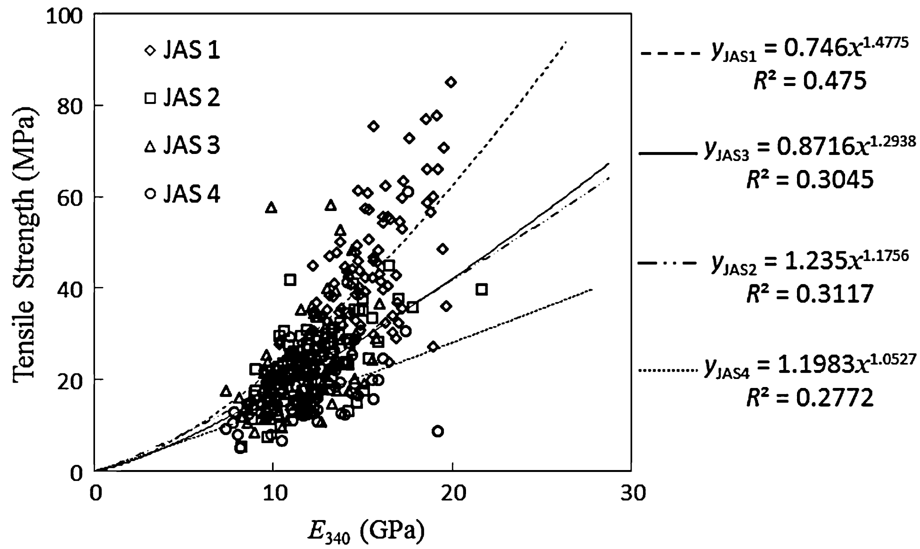

Fig. 6 Relation between tensile strength and transverse vibration modulus of elasticity (E_{340}) for visually graded Hem-Fir (N) lamina

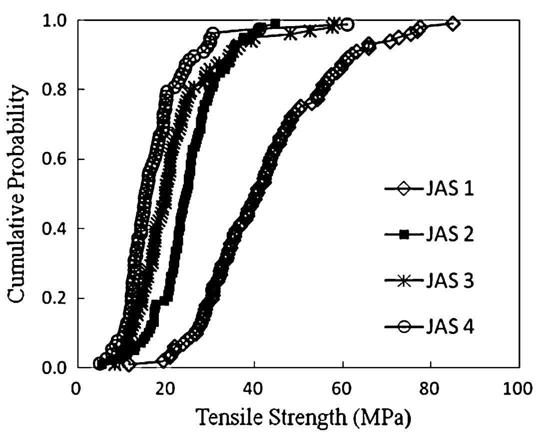

Fig. 7 Cumulative probability distributions of tensile strength of Hem-Fir (N) lamina by JAS grades

Table 3 Summary of tensile strength statistics of Hem-Fir (N) lamina (MPa)

Visual grade	Count	Average	Standard deviation	5th percentile	Min.	Max.
JAS 1	100	42.37	14.45	21.85	11.58	84.85
JAS 2	100	24.80	7.27	12.82	5.32	44.76
JAS 3	100	21.59	9.62	10.84	8.44	58.15
JAS 4	73	17.34	8.05	7.79	5.03	61.02

The E_{340} data for the 978 specimens was used to sort the lamina to meet modulus of elasticity properties requirements for the machine grades. The grade yields in corresponding machine grades are summarized in Table 4 by JAS visual grades. A total of 54 % of the specimens met the E requirements for the L140 or higher (37.52 %) and the L125 (16.46 %) machine grades which are higher grades than 11 GPa (L110) of JAS visual grade 1 for the wood species group D. It should be noted that the visual grade requirement of 11 GPa is an average value of E, while, the machine grade requirements of L110 is a cut-off value which determine the machine grade of lamina by checking whether a measured E is equal or higher than 11 GPa or not. However, both E requirements are the representative E of the respective grade which should be considered in structural applications.

Table 4 Machine grade yields based on E_{340} ($n = 978$)

Visual grade	Machine grade					
	L140 or higher	L125	L110	L100	L90	L80 or lower
JAS 1	271	61	65	16	9	2
JAS 2	56	56	74	42	12	8
JAS 3	24	32	66	46	39	19
JAS 4	16	12	25	10	8	9
Total	367	161	230	114	68	38
Percentage	37.52	16.46	23.52	11.66	6.95	3.89

A total of 373 specimens which had been selected for tensile strength tests were examined for the machine grade requirements of E and tensile strength. These specimens were sorted into the machine grades from L140 or higher, to L80 or lower. Also, the numbers of each JAS visual grade included in each machine grade were counted as shown in Table 5. The reasonable trend was found that the higher machine grades have more the higher visual grades. In the Notification 1152 [1] the tensile strength requirements for the machine grades stipulate an average and the minimum values (5th percentile strength) based on statistics, rather than cut-off values. The results show that most

Table 5 Machine grade yields based on E_{340} and tensile strength criteria ($n = 373$)

Machine grade[a]	L140 or higher	L125	L110	L100	L90	L80 or lower
Average tensile strength (MPa)	39.8	27.8	22.1	19.7	17.4	12.1
5th percentile tensile strength (MPa)	16.3	12.7	12.5	9.5	7.7	5.0
Counts of JAS visual grades included[b]						
JAS 1	**67**	14	15	2	2	0
JAS 2	22	**20**	**33**	15	5	3
JAS 3	10	16	26	**18**	**20**	8
JAS 4	15	12	24	10	7	**9**
Tensile strength only-based machine grade	L80	L50	L50	L30	Reject[c]	Reject

[a] Based on bending modulus of elasticity requirements only

[b] The highest counts are bold

[c] Out of the range of machine grade

machine grades could not meet the requirements except for L140 or higher. If the specimens are re-graded according to tensile strength requirements only, the machine grades fall a much lower range from L80 to L30 including rejects (see the last row in Table 5). Large gap between *E*-based grades and tensile strength-based grades was found. In fact, it appears that the tensile strength requirements were established based on bending strength requirements in Notification 1152 [1]. Uniformly for all machine grades, 60 % of the bending strength requirements are assigned to average tensile strength requirements and 40 % of that to the 5th percentile tensile strength requirements. These non-fulfillment results for tensile strength requirements seem to come from the disparity between actual test data distribution and the prescriptive requirements, and the location of MSRD in the tension tests as well. In this study, therefore, the investigation for tensile strength requirements was excluded. A further study on practical tensile strength requirements is needed because a tensile strength of lamina. in service cannot be guaranteed without destructive tests as this study shows.

Conclusions

Hem-Fir (N) lamina is allocated to the wood species group D in the JAS structural glued laminated timber standard. The highest visual grade requirement of lamina has an assigned modulus of elasticity of 11 GPa in the wood species group D, which is conservative for the actual modulus of elasticity of Hem-Fir (N). Higher modulus of elasticity ratings can be achieved by machine grading. Therefore, this study focused on comparing the grade yields in the visual and machine grades references in the JAS glued laminated timber standard. The main conclusions for this investigation are:

1. 77.5 % of the laminas tested shows equal to or over the modulus of elasticity (*E*) of 11 GPa which is the JAS 1 visual grade requirements of wood species group D.
2. Hem-Fir (N) laminas can be machine graded using either the bending type mechanical grading machine, or a vibration measurement machine which is a relatively low-cost equipment.
3. Overall Hem-fir (N) lamina did not meet the tensile strength requirements for visual and machine grades simultaneously.
4. Further investigations should be undertaken to confirm the opportunity to extract higher value by machine grading of Hem-Fir (N) lamina.

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