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ORIGINAL ARTICLE

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Influence of knot area ratio on the bending strength of Canadian Douglas fir timber used in Japanese post and beam housing

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Abstract A study was conducted to establish the engineering properties and the influence of knot area ratio (KAR)-based grading rules on the bending strength properties of full-size Canadian Douglas fir timber used in Japanese post and beam building construction. In-grade tests were conducted on lumber selected at random from coastal mills in British Columbia, Canada, that manufacture products for the Japanese post and beam housing market. Bending strength and modulus of elasticity test results and KAR-based out-turn information on the 105 × 105 mm and 45 × 105 mm specimens are presented in this article. The in-grade test results indicate that KAR-based grading rules can be successfully applied to Canadian Douglas fir timber to meet strength property requirements.

Key words Knot area ratio · Grading rules · Bending strength · Modulus of elasticity · Post and beam housing

Introduction

Japan has a strong tradition of using timber as a structural material in buildings. One of the common methods of construction for Japanese single-family residences is the post and beam construction technique. From the coastal regions in British Columbia (BC), Canada, Douglas fir (*Pseudotsuga menziesii*) is one of the major Canadian structural timber species used in the Japanese housing market.

Building code authorities and many countries other than Japan are adopting performance-based design criteria. A key feature of these new codes is the derivation of engineering design properties based on full-size tests of in-grade materials. This type of test data provides the most reliable and equitable basis for assigning design properties for wood-based structural materials. Recently, Japan has also adopted performance-based codes that may incorporate full-size test data for establishing lumber design properties.

The Canadian wood products industry developed an extensive in-grade database on the engineering properties of light frame dimension lumber graded to the Canadian National Lumber Grades Authorities (NLGA) grading rules.[1] In Japan, strength properties of post and beam lumber are also available, although most of the data are not based on systematic in-grade testing. Recently a comprehensive in-grade database has been developed at the University of British Columbia on the structural properties of Canadian hem-fir (N) (*Tsuga heterophylla* and *Abies amabilis*) post and beam products graded to the new Japanese Agricultural Standard for Structural Softwood Lumber (JAS 143) grading standard.[2] However, there are no comparable technical data on the structural properties of Canadian Douglas fir post and beam products graded either to the JAS 143 grading standard or the knot area ratio (KAR)-based grading rules.

JAS 143 provides standards for grading structural lumber used in post and beam construction. Although some homebuilders in Japan are using JAS 143-graded lumber, for the most part the sawn lumber components of post and beam housing are not structurally graded. Considering this situation, the most recent revision of the Japanese Building Standard Law (BSL)[3] continues to permit the use of "ungraded" structural lumber and the BSL has introduced new material strength properties for ungraded lumber.

JAS 143 provides for three grades (JAS 1, 2, and 3) in type A and type B products.[4] Type A products are intended primarily for horizontal applications and type B for vertical applications. Studies of Canadian lumber producers demonstrate that the knot-size limitations are unnecessarily restrictive, given typical consumer requirements. Consequently, individual suppliers have tended to develop in-house grades matched to individual consumer require-

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ments. Generally, these in-house grades correspond approximately to a JAS no. 2 or 3 structural quality level. Canadian lumber producers have developed and implemented in-house grades, based on the KAR concept, that meet the stringent quality requirements of Japanese builders. The in-house grading rules adopted by BC coastal companies have the advantage of increasing lumber recovery from the BC coastal forest resource and thereby provide cost-competitive sawn timber products for the Japanese market that can meet the structural requirements of the Japanese Building Standard Law.

In Canada and the United States, the NLGA rules,[5] are used to grade structural lumber used in wood frame housing construction. These rules provide graded lumber that is closely matched to the resource profile and end-user requirements for strength and appearance characteristics. For the most part the knot size limitations are based on a maximum KAR. The philosophy of KAR-based grading rules is that the structural or stress grades of the material are established on the basis of the strength-reducing features such as the KAR that can be related to mechanical properties. This study examines the influence of KAR-based grading on the engineering design properties and out-turns of Douglas fir timber used for Japanese post and beam construction.

Materials and methods

Douglas fir specimens were sampled from production for all BC coastal mills that produced post and beam products for the Japanese market. The sampling was proportional to the production volume of the mills. The material was sampled before drying and selected during mill visits where preliminary visual grading was conducted to ensure an adequate sample size (>300 pieces) was available for each JAS grade and size of interest. A detailed sampling report is available from the Council of Forest Industries of BC.[5]

Approximately 1800 pieces of Douglas fir, 900 with dimensions of 105 mm × 105 mm × 4 m long and 900 with dimensions of 45 mm × 105 mm × 4 m long, were sampled from representative BC coastal mills. The matrix of material evaluated in the test program is shown in Table 1.

The test specimens were kiln-dried to an average equilibrium moisture content of approximately 18% using a mild kiln schedule. Following delivery to the Timber Engineering and Applied Mechanics Laboratory at the University of British Columbia, the material was further conditioned to an equilibrium moisture content of approximately 15%. Each piece was visually graded according to JAS 143 Standards for Structural Lumber Type AII and Standards for Structural Lumber Type B.[4]

Table 1. Test material matrix

Specimen size (mm)	Sample size (n)
105 × 105	932
45 × 105	913

During grading, the maximum strength-reducing defect (MSRD) was identified for each specimen. The MSRD is the defect that was estimated to provide the lowest strength if tested in bending. Visual inspection of the kiln-dried material indicated that drying splits might result in downgrading of some otherwise on-grade specimens. Therefore, it was decided to also visually grade each piece without consideration of the drying splits. The characteristics determining the grade and the MSRD were recorded. The location of the MSRD was measured and recorded with respect to the

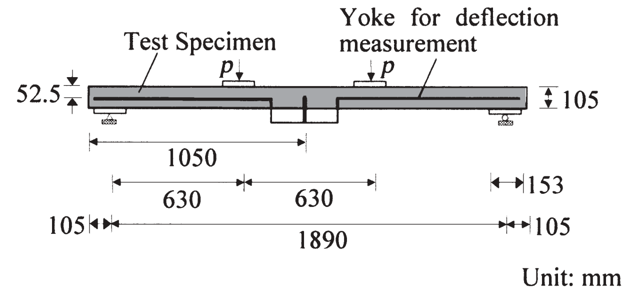

Fig. 1. Long span modulus of elasticity (MOE) (E_L) test configuration

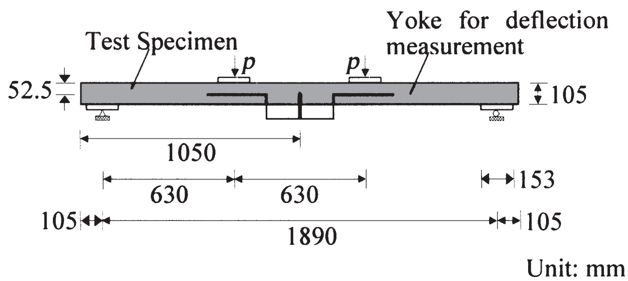

Fig. 2. "Shear-free" MOE (E_{true}) test configuration

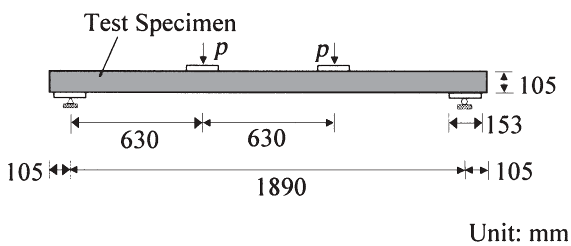

Fig. 3. Third-point bending test configuration

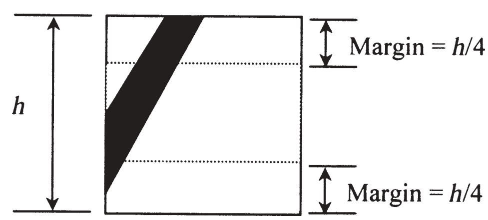

Fig. 4. Knot area ratio (KAR) concept. Note that total knot area ratio (TKAR) = total knot area / total area of cross section, and margin knot area ratio (MKAR) = knot area occupying the margin / total area of cross section

numbered end of each piece. The physical dimensions of each piece were also measured and recorded.

The selection of the tension face of a bending specimen can have a significant effect on the bending strength of a specimen.[7] In accordance with accepted international practice, the tension face of the specimen was chosen at random. In cases where significant drying splits were observed in the 105 × 105 mm specimens, the specimen was oriented such

Table 2. Preliminary Douglas fir in-grade based MOR allowable stresses for JAS 143 grades

Grade	Design stress (MPa)[a]	In-grade data (MPa)[b]	
		105 × 105 (*n*)	45 × 105 (*n*)
JAS type A			
No. 1	12.54	16.70 (309)	15.79 (304)
No. 2	8.36	13.06 (311)	12.92 (304)
No. 3	6.38	10.18 (312)	9.54 (304)
JAS type B			
No. 1	9.90	13.90 (546)	11.93 (498)
No. 2	6.60	11.24 (218)	11.46 (188)
No. 3	5.06	9.29 (168)	10.12 (226)

MOR, modulus of rupture; JAS, Japanese agricultural standard
[a] Ministry of Construction, notification no. 1452, 2000, Tokyo, Japan
[b] Numbers in parentheses are the sample size

Table 3. Preliminary Douglas fir in-grade based MOE allowable stresses for JAS 143 grades

Grade	Design MOE (GPa)[a]	In-grade data (GPa)	
		105 × 105 (*n*)	45 × 105 (*n*)
JAS type A			
No. 1			
Upper	10.78	14.85 (309)	16.55 (301)
No. 2			
Normal	9.80	14.16 (311)	15.45 (304)
No. 3		12.77 (312)	14.19 (303)
JAS type B			
No. 1			
Upper	10.78	14.53 (546)	15.94 (495)
No. 2			
Normal	9.80	13.43 (218)	15.20 (188)
No. 3		12.60 (168)	14.37 (225)

MOE, modulus of elasticity
[a] Architectural Institute of Japan, 1973, standard for structural design of timber structures, Tokyo, Japan. Note that the Architectural Institute of Japan (AIJ) MOE values do not correspond to those of the JAS grade. However, as there is no authorized data for MOE values other than the ones shown in the AIJ design manual, the MOE (E_L) values of the AIJ design manual was used to represent the MOE (E_L) values for the JAS grade

Table 4. Possible knot area ratio (KAR)-based grading rules

	KAR boundaries	Grade
TKAR only	TKAR < 0.25	1
	0.25 < TKAR < 0.33	2
	0.33 < TKAR < 0.5	3
TKAR and MKAR	TKAR < 0.25 and MKAR < 0.25	1
	(TKAR < 0.25 and 0.25 < MKAR < 0.33) or (0.25 < TKAR < 0.33 and MKAR < 0.33)	2
	(TKAR < 0.33 and 0.33 < MKAR < 0.5) or (0.33 < TKAR < 0.5 and MKAR < 0.5)	3
MKAR and TKAR case 1	(MKAR < 0.5 and TKAR < 0.25) or (MKAR > 0.5 and TKAR < 0.2)	1
	(MKAR < 0.5 and 0.25 < TKAR < 0.33) or (MKAR > 0.5 and 0.2 < TKAR < 0.25)	2
	(MKAR < 0.5 and 0.33 < TKAR < 0.5) or (MKAR > 0.5 and 0.25 < TKAR < 0.33)	3
MKAR and TKAR case 2	(MKAR < 0.5 and TKAR < 0.2) or (MKAR > 0.5 and TKAR < 0.2)	1
	(MKAR < 0.5 and 0.2 < TKAR < 0.33) or (MKAR > 0.5 and 0.2 < TKAR < 0.25)	2
	(MKAR < 0.5 and 0.33 < TKAR < 0.5) or (MKAR > 0.5 and 0.25 < TKAR < 0.5)	3
MKAR and TKAR case 3	(MKAR < 0.5 and TKAR < 0.25) or (MKAR > 0.5 and TKAR < 0.2)	1
	(MKAR < 0.5 and 0.25 < TKAR < 0.5) or (MKAR > 0.5 and 0.2 < TKAR < 0.5)	2

TKAR, total knot area ratio; MKAR, margin knot area ratio that the face of the specimen with the drying split was under compression during a bending test. This procedure is consistent with procedures followed in Japan.

The test program followed ASTM D 4761,[8] Standard Method for Testing Mechanical Properties of Lumber and Wood-Based Structural Material, to establish the modulus of elasticity (MOE) and modulus of rupture (MOR) values of each specimen. The strength of bending specimens varies depending on the location of the MSRD within the test span. For these studies, the MSRD was located randomly within the total test span (simple supports and third point loading at a span-to-depth ratio of 18 to 1). Excess material, outside the test span, was cut from the test specimen prior to testing. Moisture content and specific gravity blocks were cut from each test specimen. The tests were conducted with displacement control at a rate of loading of 21.2 mm/min.

Following ASTM D 4761,[8] each piece was nondestructively tested in bending to a maximum load of 5.34 kN. Long span MOE (E_L) (Fig. 1) and "shear-free" MOE (E_{true}) (Fig. 2) were measured for each specimen. The data allowed the relationship between E_{true} and E_L to be established for these timber sizes in a separate study. The applied load, machine stroke deflection, and specimen deflection relative to a yoke (either supported at full span for E_L estimate or supported at loading points for E_{true} estimate) were continuously monitored and recorded. Following ASTM D 4761[8] procedures, the material was then tested to failure in third-point loading to establish its bending strength (Fig. 3). The applied load and machine stroke deflection were continuously monitored and recorded. The strength of each specimen was derived based on the peak load.

Specific gravity and moisture content blocks were tested to confirm the moisture content and specific gravity of each test specimen (ASTM D 2395).[8] The MOE data were adjusted to standard moisture content of 15% during data analysis according to ASTM D 2915,[8] Standard Practice for Evaluating Allowable Properties for Grades of Structural Lumber. The MOR data were adjusted to standard moisture content of 15% following a linear surface model moisture adjustment method.[2] The characteristic moisture-adjusted mechanical properties for each specimen grade were established for the material following procedures of ASTM D1990, Standard Practice for Establishing Allowable Properties for Visually Graded Dimension Lumber from In-Grade Tests of Full-Size Specimens.

Each broken specimen was also examined in detail to assess the knots by the concept of KAR projected on a plane. Total knot area ratio (TKAR) and the margin knot

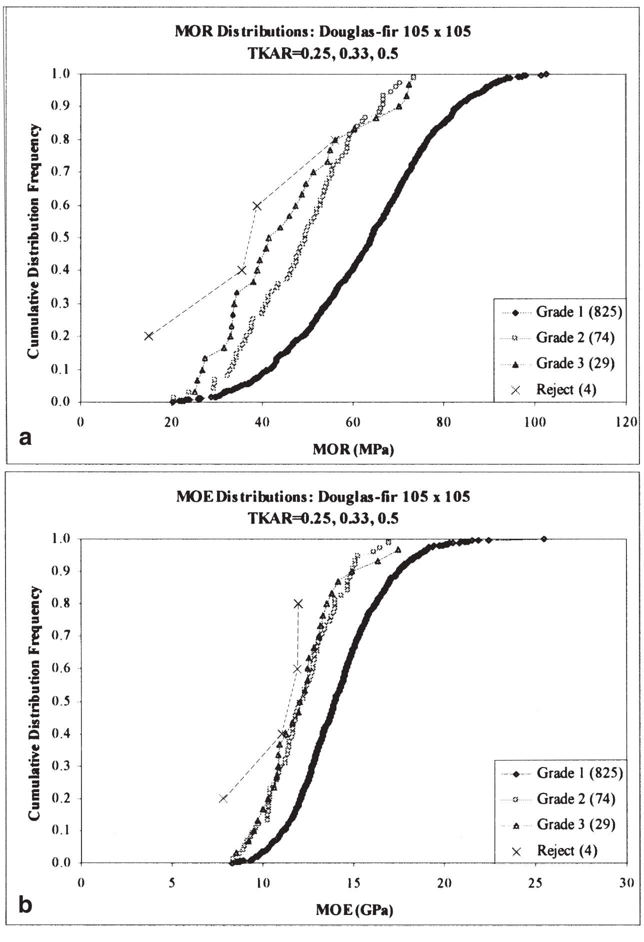

Fig. 5. Modulus of rupture (*MOR*) (**a**) and MOE (**b**) cumulative distributions for 105 × 105-mm Douglas fir with the TKAR only grading rule

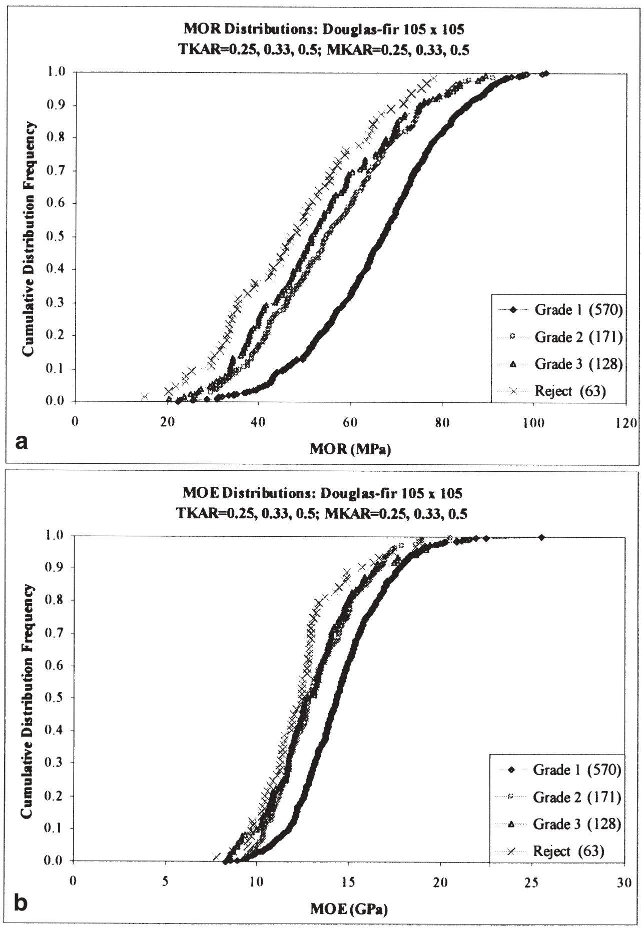

Fig. 6. MOR (**a**) and MOE (**b**) cumulative distributions for 105 × 105-mm Douglas fir with the TKAR and MKAR grading rule

area ratio (MKAR) can be established at a cross section where the margin is defined as one quarter of the specimen width measured from either the top or bottom face (see Fig. 4). Knots were considered part of the same cross section if any parts of the knots or the grain disturbances overlapped along the length of the piece. In each specimen, the TKAR and MKAR values were measured at the location of failure and the location of worst defect.

Results and analysis

The calculated design strength properties of Canadian Douglas fir for JAS 143 visually graded lumber shown in Tables 2 and 3 are compared with the allowable stresses published in Japan prior to June 2000.[3] Analysis of the MOE values is based on the E_{true} data. Based on the strength property data from the current test program, new design strength properties of the Canadian Douglas fir can be approximated using the following formula:

$$\text{Allowable unit stress} = \left(\frac{\text{Standard strength}}{\text{Safety factor}}\right) \times 1.1 \qquad (1)$$

Where Standard strength = $\text{MOR}_{5\%\ \text{tolerance limit}}$
= 5% lower tolerance limit of $\text{MOR}_{0.05}$

Safety factor = 3.0

$\text{MOR}_{0.05}$ = fifth percentile bending strength

The 5% lower tolerance limit on the fifth percentile MOR can be estimated conservatively by Eq. 2,[9]

$$\text{MOR 5\% tolerance limit} = \text{MOR}_{0.05}\left(1 - \frac{2.7V}{\sqrt{n}}\right) \qquad (2)$$

wher V = coefficient of variation,
n = number of specimens in each cell.

In general the calculated design values for Canadian Douglas fir meet or exceed the published allowable stresses in the current Japanese building code. For Canadian Douglas fir, the allowable stresses of 105 × 105 mm material are underestimated by 33.2%–59.6% and 40.4%–83.6% for type AII and type B grades, respectively. Because the design strengths of timber in JAS 143 are referenced to a wide range of cross sections, it may not be appropriate to extend the conclusions from these results to other untested sizes. Further research may be required to determine if the strength properties of Douglas fir vary with member size.

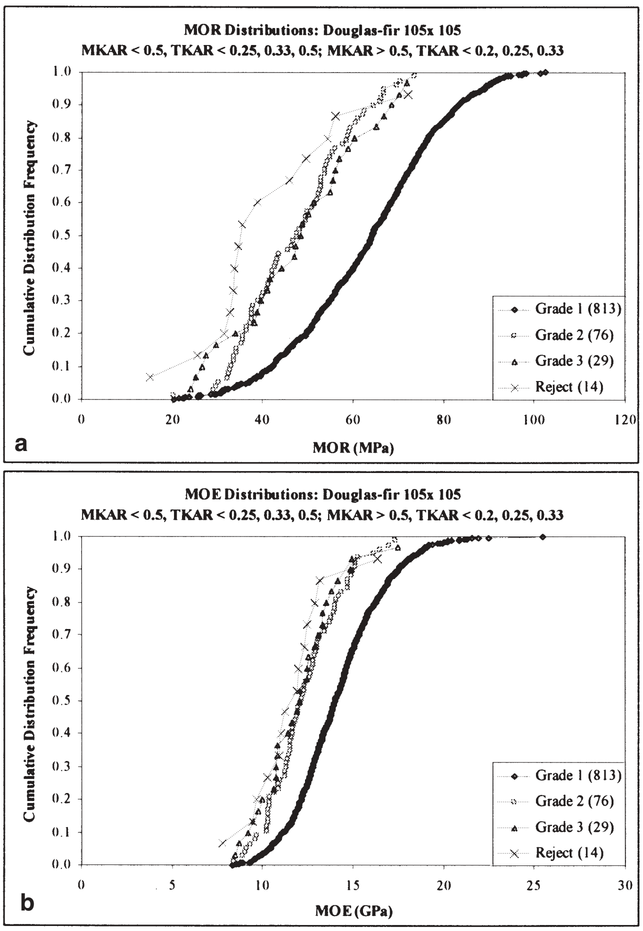

Fig. 7. MOR (**a**) and MOE (**b**) cumulative distributions for 105 × 105-mm Douglas fir with the MKAR and TKAR grading rule (case 1).

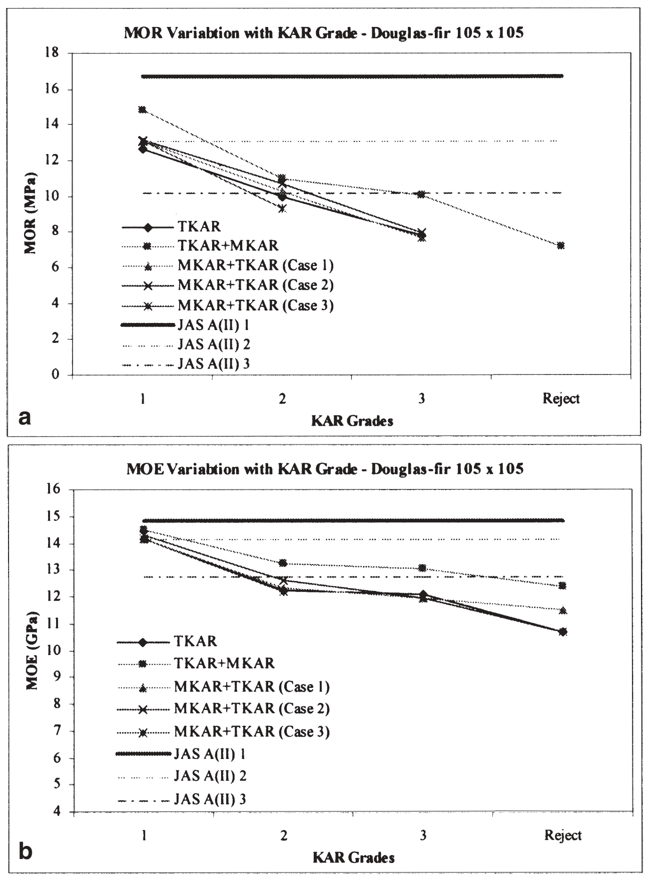

Fig. 8. MOR (**a**) and MOE (**b**) distributions for 105 × 105-mm Douglas fir for various grades based on different KAR grading rules

Because the TKAR and MKAR values were obtained in the MSRD in each specimen, the test material can be graded on the basis of KAR to estimate the yield and the design properties of the KAR-based grades. Various combinations of provisional KAR grading rules were evaluated to establish the relations between strength and stiffness properties for Canadian Douglas fir timber. The KAR grading rules provide limits on the MKAR and TKAR permitted in a specific grade. As an illustration of KAR-based grading, the test material was sorted into different grades following a possible set of grading rules given in Table 4. The grading can be based by considering TKAR only. Alternately a grade can be assigned on the basis of meeting the TKAR requirements first and then the MKAR requirements (TKAR and MKAR). Finally, the piece can be checked against MKAR requirements first and then TKAR requirements (MKAR and TKAR cases 1–3). In most cases, three grades can be generated from these KAR-based grading rules. However, for MKAR and TKAR case 3, only two grades were established for the resource.

Figures 5–7 show the cumulative property distributions of the MOR and MOE for 105 × 105 mm Canadian Douglas fir timber for the TKAR, TKAR and MKAR, and MKAR and TKAR case 1 grading rules, respectively. The TKAR and MKAR rule tends to yield higher "characteristic properties" for grade 1 and grade 2 materials as compared with the other KAR-based grading rules. The associated yields for these grades based on TKAR and MKAR are lower than those from the other KAR-based rules.

Summarized information on the fifth percentile MOR and mean MOE values for the various grade and size combinations are shown in Figs. 8 and 9. Based on Eq. 1, approximate MOR design stresses can be obtained for the various grades. Approximate MOE design stresses can also be obtained from the mean MOE values of the various grades. Summarized results are shown in Tables 5 and 6. Clearly, KAR-based rules can be used to establish grades for Canadian Douglas fir timber with a set of reasonable design stresses.

Table 5. KAR-based MOE and MOR design stresses of 105 × 105-mm Douglas fir

	TKAR		TKAR and MKAR		MKAR and TKAR case 1		MKAR and TKAR case 2		MKAR and TKAR case 3	
	MOE (GPa)	MOR (MPa)	MOE (GPa)	MOR (MPa)	MOE (GPa)	MOR (MPa)	MOE (GPa)	MOR (MPa)	MOE (GPa)	MOR (MPa)
Grade 1										
Design stress	14.2	12.6	14.5	14.8	14.2	13.1	14.3	13.2	14.2	13.1
Count	825	825	570	570	813	813	740	740	813	813
Average	14.2	62.9	14.5	66.0	14.2	63.2	14.3	64.2	14.2	63.2
Minimum	8.32	20.3	8.32	22.4	8.32	20.3	8.32	20.3	8.32	20.3
Maximum	25.5	103	25.5	103	25.5	103	25.5	103	25.5	103
SD	2.47	15.9	2.40	14.7	2.47	15.8	2.45	15.6	2.47	15.8
COV	17.5%	25.3%	16.6%	22.3%	17.4%	24.9%	17.2%	24.3%	17.4%	24.9%
Fifth percentile	10.3	35.3	10.8	41.5	10.4	36.6	10.4	36.8	10.4	36.6
Grade 2										
Design stress	12.3	9.98	13.3	11.0	12.4	10.2	12.6	10.7	12.2	9.34
Count	74	74	171	171	76	76	149	149	115	115
Average	12.3	48.8	13.3	55.9	12.4	47.5	12.6	50.5	12.2	47.0
Minimum	8.40	20.4	9.45	23.0	8.40	20.4	8.40	20.4	8.40	20.4
Maximum	17.0	73.5	20.5	97.6	17.4	73.5	20.0	88.5	17.5	73.5
SD	1.97	12.1	2.27	15.5	1.96	11.7	2.12	13.4	1.98	12.6
COV	16.1%	24.8%	17.1%	27.7%	15.9%	24.7%	16.8%	26.5%	16.2%	26.7%
Fifth percentile	9.02	29.5	10.1	31.7	9.11	30.2	9.55	31.0	9.11	27.3
Grade 3										
Design stress	12.1	7.82	13.1	10.0	12.0	7.67	12.0	7.97	–	–
Count	29	29	128	128	29	29	39	39	–	–
Average	12.1	44.7	13.1	53.0	12.0	47.8	12.0	46.2	–	–
Minimum	8.49	25.1	8.40	20.4	8.49	24.0	8.49	24.0	–	–
Maximum	17.5	72.3	21.3	89.3	17.5	71.8	17.5	72.3	–	–
SD	2.07	14.0	2.60	15.8	2.04	14.1	2.02	14.2	–	–
COV	17.1%	31.4%	20.0%	29.7%	17.1%	29.4%	16.9%	30.7%	–	–
Fifth percentile	8.86	25.3	8.93	29.5	8.61	24.5	8.73	25.1	–	–
Reject										
Design stress	10.7	–	12.4	7.19	11.5	–	10.7	–	10.7	–
Count	4	4	63	63	14	14	4	4	4	4
Average	10.7	36.3	12.4	47.3	11.5	39.9	10.7	36.3	10.7	36.3
Minimum	7.80	15.1	7.80	15.1	7.80	15.1	7.80	15.1	7.80	15.1
Maximum	12.0	56.0	18.8	77.8	16.3	72.3	12.0	56.0	12.0	56.0
SD	1.96	16.8	2.20	15.6	2.02	14.5	1.96	16.8	1.96	16.8
COV	18.4%	46.3%	17.8%	32.9%	17.5%	36.3%	18.4%	46.3%	18.4%	46.3%
Fifth percentile	–	–	9.46	22.1	–	–	–	–	–	–

SD, standard deviation; COV, coefficient of variation

The estimated design stresses for the in-grade tested JAS grade material are shown in Figs. 8 and 9, respectively. In the KAR-based grading case studies, it can be seen that most of the KAR-based material have lower design strength properties compared with the JAS A(II) 1 material. This is because the JAS grading method is more restrictive and therefore yielded higher design strength properties for the top grades. The KAR-based rules, on the other hand, have the economic advantage of yielding high-grade out-turns comparing the results shown in Tables 5 and 6 with those in Table 2. Furthermore, the KAR-based grading rules have the flexibility to be tailored to effectively approach or exceed the JAS grade properties.

Conclusions

An in-grade evaluation of the bending properties of Canadian Douglas fir timber produced in the sizes and grades used for Japanese post and beam was conducted. Based on the resulting database, the influence of KAR-based grading on the bending strength and MOE of Canadian Douglas fir timber was investigated.

Allowable bending stress estimates for Canadian Douglas fir in the KAR-based grades met or exceeded the allowable design properties currently published in the Japanese building codes. Similarly the KAR based MOE exceeded the MOE assigned for Douglas fir by the Architectural Institute of Japan.

This in-grade database can be used to support revisions to the design properties for Canadian Douglas fir used in Japan. Acceptance of these new data would allow architects, engineers, and builders to specify Canadian Douglas fir products with more reliable design properties. This will also allow consumers to utilize the resources more effectively in their applications.

The in-grade database also provides technical information on the relationships between knot size and MOR and MOE that can be used to develop and assess new KAR-based grading rules for Canadian Douglas fir lumber. Adapting these new grading rules can lead to increased

Table 6. KAR-based MOE and MOR design stresses of 45 × 105-mm Douglas fir

	TKAR		TKAR and MKAR		MKAR and TKAR case 1		MKAR and TKAR case 2		MKAR and TKAR case 3	
	MOE (GPa)	MOR (MPa)	MOE (GPa)	MOR (MPa)	MOE (GPa)	MOR (MPa)	MOE (GPa)	MOR (MPa)	MOE (GPa)	MOR (MPa)
Grade 1										
Design stress	15.8	13.2	16.3	15.5	15.9	14.2	16.1	14.3	15.9	14.2
Count	751	755	370	372	682	686	628	631	682	686
Average	15.8	69.3	16.3	74.5	15.9	70.5	16.1	71.2	15.9	70.7
Minimum	6.18	19.5	7.48	26.2	6.18	25.4	6.18	25.4	6.18	25.6
Maximum	25.3	115	25.3	106	25.3	115	25.3	114.8	25.3	114
SD	2.94	18.0	3.05	16.4	2.95	17.5	2.94	17.5	2.95	17.9
COV	18.7%	26.0%	18.8%	22.0%	18.5%	24.7%	18.3%	24.5%	18.5%	25.4%
Fifth percentile	10.8	37.0	10.8	43.6	10.9	39.7	11.0	40.1	10.9	39.7
Grade 2										
Design stress	13.5	8.78	15.1	11.1	13.9	8.46	14.1	9.39	13.8	8.42
Count	97	97	109	109	124	124	178	179	218	218
Average	13.5	53.5	15.1	66.4	13.9	56.7	14.1	58.5	13.8	53.6
Minimum	6.86	17.2	6.18	24.3	8.14	19.5	7.95	19.5	6.86	17.6
Maximum	19.0	96.4	21.5	101	20.4	97.6	20.4	97.6	22.6	97.1
SD	2.41	16.7	2.77	18.0	2.34	17.9	2.42	17.3	2.51	17.6
COV	17.9%	31.2%	18.3%	27.1%	16.8%	31.7%	17.2%	29.6%	18.3%	32.8%
Fifth percentile	9.16	26.4	11.0	32.5	9.98	25.0	10.1	27.2	9.87	24.4
Grade 3										
Design stress	13.6	6.69	15.0	11.9	13.6	8.67	13.5	7.21	–	–
Count	52	52	194	196	65	65	94	94	–	–
Average	13.6	49.9	15.0	62.9	13.6	50.9	13.5	49.8	–	–
Minimum	8.45	17.6	7.95	26.1	6.86	17.2	6.86	17.2	–	–
Maximum	22.6	87.3	22.8	115	22.6	89.2	22.6	89.2	–	–
SD	2.77	17.1	2.95	17.3	2.87	16.3	2.72	16.8	–	–
COV	20.4%	34.3%	19.7%	27.5%	21.1%	32.0%	20.1%	33.8%	–	–
Fifth percentile	9.71	21.0	10.2	34.3	9.68	26.5	9.71	21.7	–	–
Reject										
Design stress	–	–	14.5	8.39	13.4	5.43	–	–	–	–
Count	0	0	227	227	29	29	0	0	0	0
Average	–	–	14.5	56.4	13.4	47.3	–	–	–	–
Minimum	–	–	6.86	17.2	8.45	17.6	–	–	–	–
Maximum	–	–	21.5	97.6	18.5	87.3	–	–	–	–
SD	–	–	2.66	18.9	2.38	18.0	–	–	–	–
COV	–	–	18.4%	33.6%	17.8%	38.1%	–	–	–	–
Fifth percentile	–	–	10.3	24.4	9.16	18.3	–	–	–	–

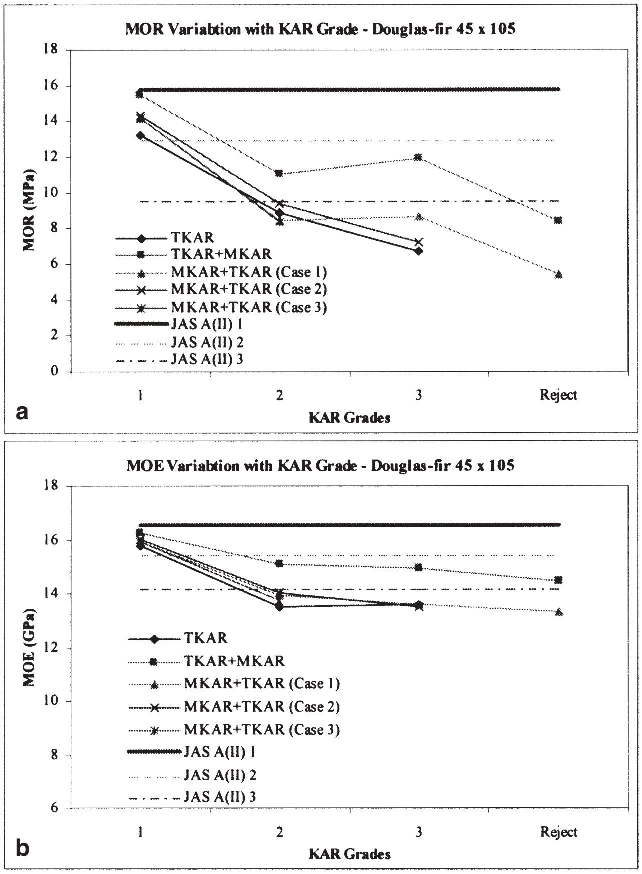

Fig. 9. MOR (**a**) and MOE (**b**) distributions for 45 × 105-mm Douglas fir for various grades based on different KAR grading rules

value recovery from the wood resource, and products that can efficiently match the strength requirements of the markets. Once adapted, such grading rules can be easily applied by certified graders at the sawmills to meet both the strength and visual requirements of the Japanese market.

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