DEVELOPMENT OF A METHOD TO PREDICT THE BENDING STRENGTH OF LUMBER WITHOUT REGARD TO SPECIES USING X-RAY IMAGES

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Abstract. Several models have been developed for predicting bending strength of lumber using X-rays, but most require species-specific classifications. However, the classification is very difficult because logs or cants can arrive without leaves or bark. This study was carried out to develop an alternative bending strength prediction model that does not lose precision when the species is unknown. The study proposes an Equivalent Density Model (EDM), in which a cross-section is quantified as equivalent density. Because the relationship between density and strength of small clear specimens is not affected by species, the EDM was expected to correlate to strength regardless of species. This model predicted the modulus of rupture in two species with $R^2 = 0.73$, although the two were mixed. Therefore, it may be possible to predict bending strength using X-rays without classifying lumber by species.

Keywords: Knot depth ratio, X-ray, Equivalent Density Model, species independence.

INTRODUCTION

To optimize the use of wood in structural applications, the mechanical properties, particularly the stiffness and strength, must be determined. The wood should fall within a desirable set of ranges in relation to these properties. Stiffness can be quantified using various nondestructive techniques such as measurement of wave speed (eg ultrasonic and stress wave), natural frequency, and flatwise bending tests. On the other hand, failure of the wood is required to measure strength. Therefore, when using lumber for structural purposes, it is desirable to determine the strength of lumber by nondestructive evaluation.

Several characteristics affect the strength of lumber: modulus of elasticity, density, knot, slope of grain, cracks/checks, and so on. Among these

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characteristics, knots are known to be the most important variable, because they can greatly reduce the lumber strength (Schniewind and Lyon 1971). The knot area ratio (KAR), which is defined as the ratio of knot area to cross-sectional area, has been generally used to quantify the influence of knots on strength. In practice, it is difficult to evaluate KAR relying only on the naked eye and information obtained from the surface of the lumber. However, X-rays can pass through nontransparent objects, providing a means to evaluate knot area in a cross-section. In previous research (Oh et al 2009b), the knot depth ratio (KDR) method was proposed for quantitative evaluation of knots in a cross-section. This method is based on the relative density of knots and clear wood.

Several methods of predicting bending strength using X-ray radiation have been developed. Oh et al (2008, 2009a) also reported that X-ray analysis based on the KDR value can predict the bending strength of lumber. However, the prediction model requires classifying lumber by species as well as the use of a regression curve for each species. Schajer (2001) also reported that the bending strength of lumber can be predicted by X-ray analysis. However, the Schajer (2001) method also requires the use of a regression curve that is species-specific. Previous models for predicting bending strength similarly require the use of a species-specific regression curve and knowledge of the strength of a defect-free specimen. The determination of a regression curve for each species requires many specimens. However, in practice, several species may grow together in naturally biodiverse landscapes. Also, harvested material is often supplied as sawn cants without bark or leaves that can provide species identification. Moreover, there is wide variation in mechanical properties not only between species, but even within samples of the same species. Mechanical properties vary within species depending on factors such as the climatic effects, age of the tree, and many more. Gathering data about all possible variables makes it less feasible to create an accurate regression curve for each

species. The complexity makes misclassification likely because of human error, and this ultimately lowers the precision of strength prediction. To be feasible, a strength prediction model should be applicable without regard to species, even if the tradeoff lowers the precision of prediction.

It is well known that density is an important factor in determining wood strength. In the case of small clear specimens, density is strongly related to strength. Markwardt and Wilson (1935) carried out static bending, impact bending, and compression tests of small clear specimens for species grown in the United States. They provided a regression curve that can be used irrespective of species. However, in the case of structural lumber, the correlation between density and strength is very low with ranges of R^2 of 0.16 – 0.40 (Thelandersson and Larsen 2003). The low correlation occurs from effects of characteristics such as knots and slope of grain.

Although the relationship between strength and density in structural lumber is weak, there is a possibility to develop a species-independent model for strength prediction because the relationship between density and strength is independent of species for small clear specimens.

In the previous study (Oh et al 2009a), we modified the KDRA algorithm to take adjacent knots into consideration. The modified KDRA model was more accurate than the KDRA method, especially for bending strength predictions in red pine, which has large knots. This modified KDRA model improved the predictive precision of bending strength of $R^2 = 0.60$ for Japanese larch and 0.56 for red pine without requiring the cross-sectional interval as an input variable.

The objective of this study was to develop an alternative bending strength prediction model independent of species. The prediction model was expected to be useful for lumber in which little species information is known. Therefore, a new bending strength prediction model was proposed and tested.

Materials

As reported previously (Oh et al 2009a), 121 specimens of Japanese larch (*Larix kaempferi*) and 145 specimens of red pine (*Pinus densiflora*) were obtained from production Korean mills. Each specimen was 38 mm thick by 140 mm wide and 3.6 m long. All specimens were kiln-dried to an approximate 18% average MC.

Experiments

X-ray. An image intensifier (Thales image intensifier TH9429) was used to take digital X-ray images. The image was taken through the thickness of 38 mm with a resolution of 2.7 pixels/mm.

Bending test. Data from Oh et al (2009a) were used in this study. As discussed previously, center-point loading was used for Japanese larch and third-point for red pine. Although third-point loading would have been ideal, both knot sizes and locations in Japanese larch are highly varied and dispersed, making it very difficult to identify the location of failure. The test span was 2.4 m for Japanese larch and 3.0 m for red pine. Cross-head speed was 10 mm/min for both species. Modulus of rupture (MOR) was calculated from the test data. Because only data from specimens that failed at the knot of interest were considered, 97 pieces of Japanese larch and 133 pieces of red pine were analyzed.

Analysis

Prediction of bending strength using the previous model. Raw X-ray images were divided into two categories, the knot and clear areas. KDR values were calculated for each pixel of the knot image using Eq 1 (Oh et al 2009b) and the knot geometry for each cross-section was predicted as the simplified knot geometry of Fig 1:

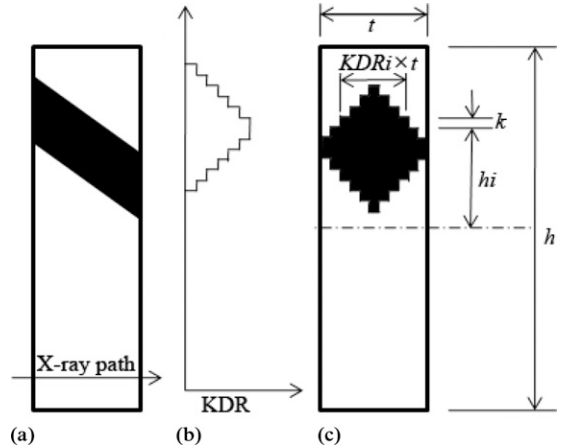$$KDR = \frac{\rho - \rho_c}{\rho_k - \rho_c} \qquad (1)$$

Figure 1. Simplified knot geometry by the knot depth ratio (KDR) method (Oh et al 2009b). (a) Geometry of an actual knot. (b) KDR value by X-ray. (c) Simplified knot geometry.

where

KDR = Knot depth ratio

ρ = Average density for a pixel of knot X-ray image

ρ_c = Average clear wood density determined by X-ray

ρ_k = Average knot density (Japanese larch: 950 kg/m^3; red pine: 930 kg/cm^3, experimentally determined)

The previous study introduced a method to predict bending strength using X-ray (Oh et al 2009a) based on the KDR method, but added the influence of adjacent knots on strength. This is termed KDRA (KDR including adjacent knots). The values of adjacent knots within 150 mm were multiplied by a weighting function. The weighted values were added to the KDR values of the cross-sections of interest (Fig 2). Simplified knot geometry was reconstructed by adding the KDR values. The moment of inertia for this reconstructed simplified knot geometry, I_k, was calculated as was the moment of inertia for the gross cross-section. Finally, the moment ratio was calculated (Eq 2; Oh et al 2008):

$$I_k/I_g = \frac{\sum_{i=1}^{n}\left(\frac{KDR_i \times t \times k^3}{3} + KDR_i \times t \times k \times h_i^2\right)}{\frac{t \times h^3}{12}} \qquad (2)$$
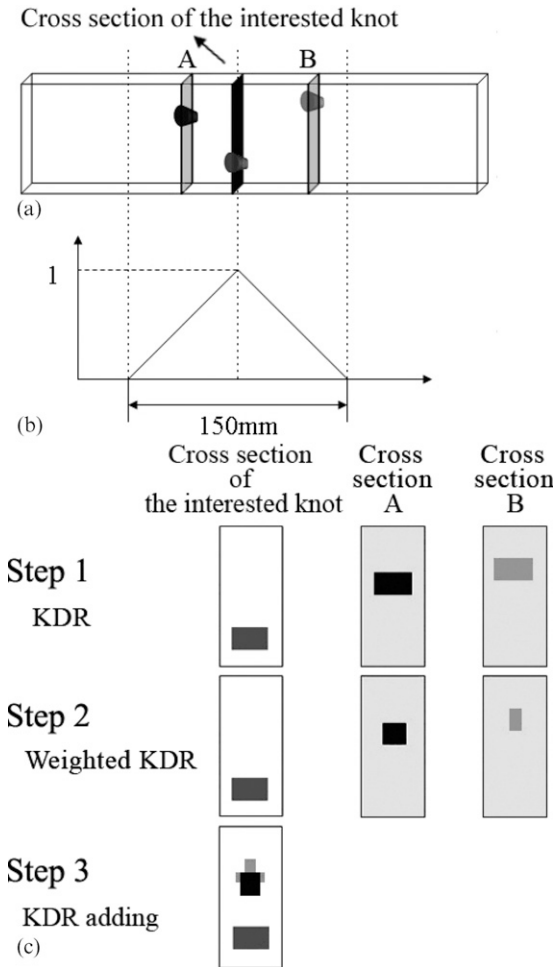
Figure 2.   Consideration of adjacent knots using the previous model (Oh et al 2009b). (a) Example of lumber containing adjacent knots. (b) Weighting function for considering spacing between knots. (c) Example of the work flow of the previous model.

where

I_k = Moment of inertia for the simplified knot geometry
I_g = Moment of inertia for gross cross-section
KDR_i = KDR value of ith cell
h = Width of lumber
t = Thickness of lumber
n = Number of cells in the width of lumber
k = Width of a cell
h_i = Distance between center line and bottom of ith cell

The relationship between MOR and I_k/I_g, as computed by the previous model, was investigated.

Prediction of bending strength using the Equivalent Density Model. To predict bending strength independent of species, we proposed an Equivalent Density Model (EDM).

X-ray images of both knotted and clear areas were also generated using a knot detection algorithm (Oh et al 2009b). KDR values were also calculated for each pixel of the knot X-ray image using Eq 1. In the previous model, knot density was experimentally measured for each species and it was used as an input variable in the KDR calculation. However, because the species of lumber was not known, knot density could not be measured. It is well known that the density of knots is double that of clear wood (Sahlberg 1995). That method was used as the input variable of knot density in the KDR calculation.

To consider the influence of adjacent knots on bending strength, every KDR value was regenerated by adding the KDR values of any adjacent knot. Then, all cells of the X-ray image were divided into three types of areas based on the reconstructed KDR value (Fig 3d).

The fully knotted area (A_{knot}) was defined as any area with a KDR value of 1.0. The fully clear area (A_{clear}) was defined as any area with a KDRA value of 0.0. Intermediate areas ($A_{Intermediate}$) were defined as any area between the fully knotted area and the fully clear area.

The local density of each area was modified using the following assumptions (Fig 3e):

1. The local density of fully knotted areas was assumed to be zero.
2. The local density of fully clear areas was calculated by converting the lightness of each cell in the X-ray image of the clear part into density.
3. The intermediate areas have both the knotted areas and the clear areas in the X-ray image. The density of clear parts in the intermediate areas was assumed to be the same as the
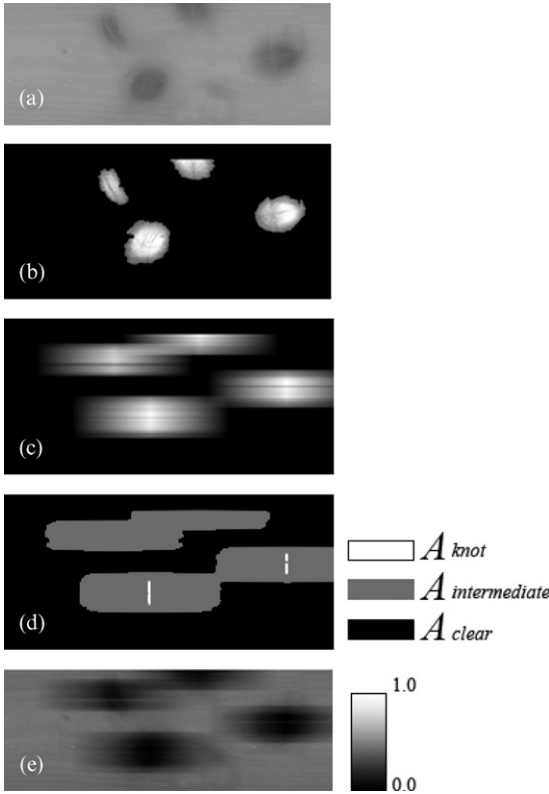
Figure 3.   Example of a density array calculation that considers both knot and local density. (a) Raw X-ray image. (b) Knot depth ratio (KDR) array. (c) KDR array modified by the previous model. (d) Classification of the X-ray image into fully knotted areas, intermediate areas, and fully clear areas. (e) Density array recalculated based on knot and local density information.
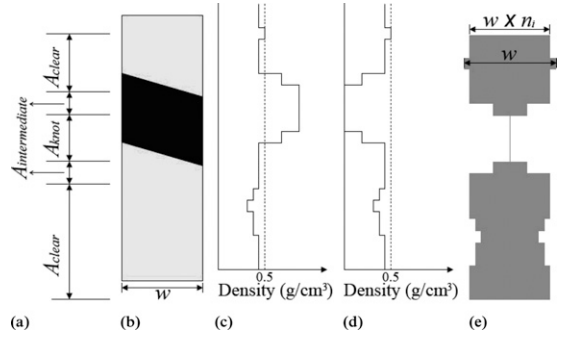

Figure 4.   Construction of a transformed section based on local density. (a) Area classified by knot depth ratio. (b) Actual knot geometry. (c) Density profile. (d) Local density modified by considering strength reduction resulting from knot. (e) Transformed section based on local density.

average density of clear parts in that specimen of lumber. The local density of intermediate areas was calculated as described in Eq 3:

$$\rho = \rho_{clear} \times (1 - KDR) \qquad (3)$$

where

ρ_{clear} = Average density of the clear areas of the lumber

KDR = Knot depth ratio value

The one-dimensional density array for the section of interest was prepared under the previously mentioned assumptions, and it was transformed into a beam of material with a density of 500 kg/m^3. The modular ratio (n_i) for each cell was calculated using local density information. The modular ratio was defined as shown in Eq 4:

$$n_i = \frac{\rho_i}{500} \qquad (4)$$

where

n_i = Modular ratio of ith cell

ρ_i = Modified local density for i^{th} cell of X-ray image

In a cross-section, the width of each cell was transformed by multiplying the modular ratio (Fig 4e). The moment of inertia of the transformed section was calculated.

The equivalent density ($\rho_{equivalant}$) was calculated as follows:

$$\rho_{equivalant} = \frac{I_{tranformed}}{I_{gross}} \times 500 \qquad (5)$$

where

$I_{transformed}$ = Moment of inertia of the transformed section

I_{gross} = Moment of inertia of the gross beam cross-section

The resistance of a cross-section was quantified as the equivalent density. The relationship between the MOR and the equivalent density computed by the EDM was investigated.

Comparison between the Equivalent Density Model and the KDRA model. The two species have significantly different characteristics with respect to knot size and density. To investigate if the precision of bending strength predictions varies by species, these two species were mixed and the predictive precision of the two mixed species by the EDM was compared with the previous model.

When the bending strength was predicted using the previous model, it was assumed that the species information such as strength of defect-free specimens was known. The strength ratio was calculated as follows (Eq 6):

$$R_{strength} = \frac{MOR}{MOR_{defect-free}} \tag{6}$$

where

$R_{strength}$ = Strength ratio
MOR = Modulus of rupture for each specimen (MPa)
$MOR_{defect-free}$ = Modulus of rupture for defect-free specimen (Japanese larch: 58.7 MPa, red pine: 45.9 MPa, experimentally measured)

Ultimately, we investigated the relationship between the strength ratio and I_k/I_g with the previous model. Using the EDM, we investigated the relationship between equivalent density and MOR. The two correlations were compared.

RESULTS AND DISCUSSION

Effect of Species on Strength Prediction

The EDM converted the X-ray image for a certain cross-section into the equivalent density value. Because the correlation between density and strength does not depend on species in the case of small clear specimens, the equivalent density was also expected to correlate with the strength of the lumber regardless of species.

Figure 5 shows the relationship between the equivalent density and MOR with a coefficient of determinant of 0.73, although the specimens
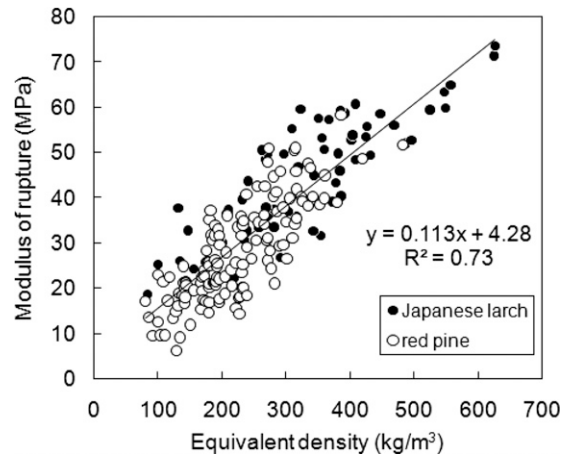

Figure 5. Relationship between equivalent density and modulus of rupture with the two species mixed.

had not been classified by species and no information about the species was used.

However, Fig 5 showed that predictions for specimens having low equivalent density were underestimated. The EDM is fundamentally based on the KDR method, which is the ratio of knot and transition zones in lumber thickness, and also considers the transition zone, that is, the intermediate area between knotted and clear wood (Oh et al 2009b). EDM assumes that the knotted and transition zones do not resist stresses. However, because the resistance of the transition zone is actually not zero, the y-intercept of the regression curve (Fig 5) must be a positive value.

In addition, the underestimation of the density of red pine was somewhat less than that of Japanese larch. This is attributed to different knot characteristics such as size, location, the ratio of knots to transition zone, and so on. For example, red pine trees have several branches at the same height; therefore, several knots can exist at the same location parallel to lumber length. This can lead to brittle failure and to a relatively lower strength compared with Japanese larch.

Although there remain certain differences between strength values of the two species, species-independent values have commercial importance

and therefore the species independence of this model was tested statistically.

First, a species-independent model can predict strength although there is no information on the species. Figure 6 shows the relationship between the strength ratio and I_k/I_g of the previous model, which has a coefficient of determinant of 0.58, although the difference between species was reduced by computing the strength ratio. Figure 5 shows the results of the EDM. Although the specimens were not classified by species, and the bending strength of defect-free specimens was not part of the calculation, the correlation ($R^2 = 0.73$) was greater than for the previous model.

Table 1 shows the predictive precision of the EDM and that of the previous model. The coefficient of determinant showed that the EDM can predict the bending strength of lumber more accurately than the previous model. To investi-

Figure 6. Relationship between strength ratio and I_k/I_g in the previous model.

gate the improvement in precision of predictions of bending strength, a one-tailed t-test was conducted. The null hypothesis was that there would be no difference between the error of prediction by EDM and error in the previous model. Error was defined as the absolute value of the difference between the predicted and measured MOR. The t-test showed that the error of the EDM was smaller than that of the previous model at the 10% significance level (Table 1). This t-test result showed that the predictive precision of the EDM was superior to that of the previous model. The higher coefficient of determinant and the t-test results also pointed to the possibility of predicting the bending strength of lumber of unknown species.

Last, the predictive error of species-independent models should not differ between species. To investigate the difference between two species, bending strength was predicted using the regression curve of two mixed species (Fig 5). A one-tailed t-test for errors of two species groups was carried out at the 10% significance level. The result of the t-test showed that the predictive error when making predictions for two species did not differ from the precision in predictions for a single species (Table 2).

When the previous model was applied, species information was essential to the regression curve to permit the determination of strength of defect-free specimens in advance. The determination of the regression curve or the strength of a defect-free specimen requires a number of specimens and time. Moreover, when pieces of lumber of several species are mixed, the task of identifying the species of each may be very difficult. However, the EDM does not require information on species.
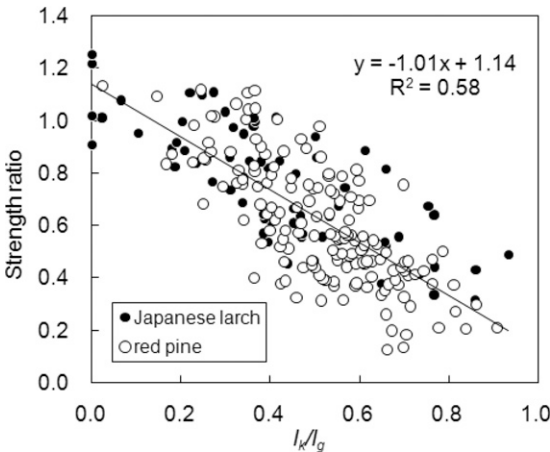
Table 1. *t-test results verifying the EDM's improvement in predictive precision for mixed-species lumber.*

| Prediction model | R^2 | Error[a] | | t-test | | |
		Average	Standard deviation	Test statistic	*p*-value[b]	Result
Previous model[c]	0.58	6.27	4.72			
Equivalent density	0.73	5.72	4.23	1.32	1.29	H_0[d] rejected

[a] Error: Absolute value of difference between measured modulus of rupture (MOR) and predicted MOR.
[b] *p*-value: The probability that absolute value is larger than *p*-value is 0.10 in t distribution. $p(|x|>p\text{-value}) = 0.10$.
[c] Oh et al (2009a).
[d] H_0: There is no difference between the error of prediction of the EDM and the error of the previous model.
EDM, Equivalent Density Model.

Table 2.   *t-test results of predictive errors for each species using the EDM without any species information.*

Species	Error[a]		t-test		
	Average	Standard deviation	Test statistic	*p*-value[b]	Result
Japanese larch	6.21	4.98	1.25	1.29	Ho[c] accepted
Red pine	5.45	3.86			

[a] Error: Absolute value of difference between measured modulus of rupture (MOR) and predicted MOR.
[b] *p*-value: The probability that the absolute value is larger than the *p*-value is 0.10 in a t distribution. $p(|x|>p\text{-value}) = 0.10$.
[c] H_0: There are no differences in predictive error between Japanese larch and red pine.
EDM, Equivalent Density Model.

Table 3.   *t-test results verifying the improvement in predictive precision for each species when considering the density variations in the EDM.*

Species	Prediction model	R^2	Error[a]		t-test		
			Average	Standard deviation	Test statistic	*p*-value[b]	Result
Japanese larch	Previous model[c]	0.60	7.20	4.28	2.45	1.29	Ho[d] Rejected
	Equivalent density	0.72	5.71	4.19			
Red pine	Previous model[c]	0.56	5.62	4.35	0.79	1.29	Ho[d] accepted
	Equivalent density	0.64	5.23	3.71			

[a] Error: Absolute value of difference between measured modulus of rupture (MOR) and predicted MOR.
[b] *p*-value: The probability that the absolute value is larger than the *p*-value is 0.10 in a t distribution. $p(|x|>p\text{-value}) = 0.10$.
[c] Oh et al (2009a).
[d] H_0: There are no differences between the predictive error of the EDM and the predictive error of the previous model.
EDM, Equivalent Density Model.

Although further studies are needed to verify the usefulness of the EDM for various species, this model showed that it is possible to predict the strength of these two mixed species without specific species information. The model is expected to be useful for lumber not classified by species or for which no information regarding species is available.

Improvement of Strength Prediction by Consideration of Density Variations

The EDM showed greater precision in predicting the bending strength of two mixed species. In the EDM, the density variation within a cross-section was considered by constructing a transformed section based on local density. This consideration of density variation appears to increase predictive precision.

To investigate the improvement in prediction by considering density variations, the relationship between equivalent density and MOR was investigated for each species. The coefficient of determinant increased significantly from 0.60 and 0.56 to 0.72 and 0.64, respectively, although the EDM did not take into account the bending strength of defect-free specimens. Table 3 also showed that the EDM predicts the bending strength of each species with greater precision than the previous model. A one-tailed t-test of our calculations for Japanese larch also showed that the predictive error of the EDM is smaller than that of the previous model at the 10% significance level (Table 3). It was thought that the consideration of the density variations within a cross-section by constructing the transformed section based on local density would increase the predictive precision. However, red pine did not show an improvement as evidenced by a t-test at the 10% significance level, although the coefficient of determinant increased from 0.56 – 0.64. This was attributed to the larger size of the knot in red pine compared with Japanese larch, making it a much more important factor than density.

CONCLUSIONS

The objective of this study was to develop an alternative prediction model for the bending strength of lumber that has not been sorted by species. The proposed EDM was able to predict bending strength with R^2 of 0.72 and 0.64 for

Japanese larch and red pine, respectively. The predictive precision was improved when density variations within a cross-section were taken into consideration.

Using EDM, a cross-section was quantified as equivalent density. Because the relationship between density and strength in small clear specimens is not affected by species, the equivalent density was expected to predict strength regardless of species. EDM predicted the MOR of the two mixed species with a correlation coefficient of $R^2 = 0.73$.

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