

## Article

# Grading Outcomes of Chinese Fir Laminas Under JAS 1152 and EN 338: Effects of Specimen Size Condition and Grade Alignment

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## Abstract

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) has considerable potential for structural use in China, but wider application is constrained by the lack of standard-linked grading approaches. This study examined the effects of specimen size condition and the two standards, JAS 1152 and EN 338, on the grading outcomes of Chinese fir laminas. Two specimen types were considered: multi-size and single-size specimens were graded under JAS 1152, and the latter were further graded under EN 338. Under JAS 1152, the single-size specimens could be classified into seven grades from L50 to L110, with 30.4% assigned to L80 and above, showing a clearly higher-grade yield than the previously studied multi-size specimens. For the same single-size specimens, JAS 1152 was governed by bending modulus of elasticity (MOE), whereas EN 338 was controlled mainly by density, yielding markedly different grade distributions. The stronger density constraint in EN 338 led to a high Reject ratio (35.3%), whereas no Reject occurred under JAS 1152, suggesting that JAS 1152 may be more favorable for the efficient and fuller utilization of Chinese fir laminas. The two systems remained statistically linked at the bending-MOE level, despite the absence of strict one-to-one correspondence. Specifically, in the JAS 1152-to-EN 338 direction, grades from L50 to L110 corresponded progressively to grades from Reject to C30, whereas in the reverse direction, grades from C14 to C16, from C18 to C22, and from C24 to C30 corresponded to L60, L70, and L80, respectively. These results provide a basis for refined grading of Chinese fir laminas and for cross-standard interpretation of their structural utilization.

**Keywords:** Chinese fir; mechanical grading; resonance frequency method; specimen size condition; JAS 1152; EN 338; grade alignment

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## 1. Introduction

Amid ongoing climate change mitigation efforts and the advancement of carbon neutrality goals, the construction sector is undergoing a transition toward low-carbon materials and greener structural systems [1,2]. Timber construction, owing to its dual role in material substitution and carbon storage, has become an important pathway for reducing emissions from the building industry [3,4]. With the development of engineered wood

products such as glued laminated timber and cross-laminated timber, timber structures have moved beyond traditional low-rise applications and are increasingly being adopted in mid-rise and high-rise buildings [5,6]. As the basic units of engineered wood products, laminas directly influence product strength, stiffness, and quality stability through their mechanical properties and variability [7,8]. Establishing a reliable grading and evaluation system for laminas is therefore a prerequisite for ensuring the structural performance of engineered wood products [9,10]. China has abundant plantation resources, among which Chinese fir, a widely planted and fast-growing softwood species, has considerable potential for structural use. However, it is still used mainly in low-value products, such as particleboard, fiberboard, pulp, and general interior materials, and its structural utilization in modern timber construction remains limited [11–13]. One major constraint is the lack of a mechanical strength grading approach for Chinese fir laminas that can be directly linked to engineering applications, which hinders their stable and standardized use in engineered wood product manufacture.

Previous studies have advanced mechanical grading for structural timber using non-destructive indicating properties (IPs) such as dynamic modulus of elasticity (MOE), density, and defect-related parameters [14–19]. However, in standard-linked grading, the critical issue is not only the predictive ability of these indicators, but also which grade determining property (GDP) becomes limiting for a given species or resource group. In the European strength-class system, timber assignment requires simultaneous compliance with bending strength, bending MOE, and density requirements [9,20]. Thus, a timber population may be downgraded when one of these properties fails to meet the corresponding class limit, even if the others are sufficient. For Norway spruce (*Picea abies* L.), bending strength, bending MOE, and density have been reported to show a relatively balanced fit with the European strength-class system [21]. In contrast, British spruce, a species combination of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and Norway spruce, is mainly stiffness-limited, whereas Scots pine (*Pinus sylvestris* L.) may be more strongly limited by strength [22]. Comparisons among maritime pine (*Pinus pinaster* Ait.), radiata pine (*Pinus radiata* D. Don), and Scots pine have further shown that species-related differences in bending strength, bending MOE, and density can lead to different machine-grading yields and rejection rates [23]. These findings indicate that grading outcomes should be interpreted not only by standard rules, but also by the species-specific balance among stiffness, strength, and density.

In China, current timber strength grading standards have been developed with substantial reference to European, North American, and Japanese systems, forming a framework for structural timber and engineered wood products centered on national standards and supplemented by industry standards. In practice, different product types correspond rather clearly to the European and Japanese grading concepts in terms of grading criteria and controlling properties. For structural sawn timber and mechanically graded laminas used in cross-laminated timber, current Chinese standards generally consider density, bending MOE, and strength simultaneously, and their evaluation logic is therefore closer to that of EN 338 [20,24–26]. By contrast, for glued laminated timber laminas, the current standard is more closely aligned with the product-oriented grading concept represented by JAS 1152 [27,28], in which lamina grade designation and its linkage to glulam manufacture are emphasized, and density is not specified in the lamina strength classes. From the perspective of alignment between current Chinese standards and international systems, JAS 1152 [28] and EN 338 [20] therefore represent the two most relevant evaluation pathways for glulam laminas and for structural sawn timber or cross-laminated timber laminas, respectively. It is therefore necessary to clarify how the same Chinese fir laminas are distributed across grades under these two systems, so as to support their more efficient utilization in relevant product applications.

At the same time, specimen size condition must also be considered if differences caused by the standards themselves are to be identified accurately. In practice, laminas do not always occur in a single size, and combinations of different thicknesses, widths, and lengths may alter the statistical relationship between dynamic MOE and static bending performance, thereby affecting grading thresholds and grade yield. Previous research has already provided a preliminary analysis of Chinese fir lamina grading under multi-size conditions within the JAS 1152 [28], showing that the relationship between dynamic MOE and bending performance became weaker and that the grading results tended to concentrate in lower grade ranges [29]. However, it remains unclear to what extent this pattern arises from the additional variability introduced by size mixing.

Based on these considerations, this study hypothesized that the grading outcomes of Chinese fir laminas are influenced not only by the grade-controlling logic of the standard system itself, but also by the effect of specimen size condition on the statistical relationship between dynamic MOE and static bending performance. Beyond this general standard-dependent difference, Chinese fir may exhibit a species-specific grading response if its stiffness, strength, and density do not satisfy the requirements of the two systems in a balanced manner. Thus, determining which GDP becomes limiting is essential for clarifying whether the observed grading outcomes merely reflect the general difference between standards or reveal a distinctive property profile of Chinese fir.

To test these hypotheses, this study used experimental data from Chinese fir laminas and, within a unified analytical framework, considered simultaneously the effects of specimen size condition and standard system. First, grading outcomes under single-size and multi-size conditions were compared within the JAS 1152 [28] to evaluate the effect of specimen size on grade distribution and grading performance. Second, the grade assignments and controlling logic under JAS 1152 [28] and EN 338 [20] were compared. Finally, a statistically meaningful alignment between the two standards was established at the level of the specified bending MOE values. This study aims to provide a basis for the evaluation, comparison, and engineering interpretation of Chinese fir laminas under different standard systems and to support the standardized utilization of structural laminas from domestic plantation species.

## 2. Materials and Methods

### 2.1. Materials and Specimen Datasets

The Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) laminas used in this study were obtained from plantation-grown trees in Nanping, Fujian Province, China, aged 10–13 years. Before testing, specimens with severe defects that would make them unsuitable for structural use were visually removed. Specifically, only visually sound pieces without decay or discoloration were selected; minor surface cracks were permitted if no wider than 0.5 mm and no longer than 15 mm [27–29]. In line with the two main objectives of the study, two specimen datasets were considered.

The first dataset was taken from our previous grading study under JAS 1152 [28] and comprised specimens of multiple sizes [29]. A full-factorial design was adopted with three thicknesses (13, 18, and 35 mm), three widths (45, 60, and 90 mm), and three lengths (750, 1500, and 3000 mm), resulting in 27 size combinations. Six specimens were prepared for each size combination, giving a total of 162 specimens. For this dataset, global density, local density, longitudinal dynamic MOE derived from the resonance frequency method, flatwise three-point bending MOE, and flatwise four-point bending strength were determined with reference to the lamina strength class requirements specified in JAS 1152 [28]. This multi-size dataset was used primarily to evaluate resonance-frequency behavior and grading feasibility under mixed-size conditions [29].

The second dataset consisted of 102 independent single-size specimens prepared from the same source batch of Chinese fir material, with nominal dimensions of 3000 mm × 90 mm × 35 mm. This dataset was not a subset of the 162 multi-size specimens and did not involve re-testing specimens that had already been destructively tested in the previous study [29]. For the 102 single-size specimens, as described in the following sections, global density, local density, longitudinal dynamic MOE derived from the resonance frequency method, and flatwise three-point bending MOE under JAS 1152 [28] were measured. In addition, edgewise bending MOE parallel to grain and bending strength, as required for strength grading under EN 338 [20], were determined for this dataset.

The first dataset was used to examine the effect of specimen size condition on grading outcomes under JAS 1152 [28], whereas the second dataset was used for the single-size evaluation under JAS 1152 [28] and for the direct cross-standard comparison between JAS 1152 [28] and EN 338 [20].

The single-size dataset used for the cross-standard comparison partially overlaps with that intended for related EN 338-oriented analyses. However, the objective of the present work is different, as it focuses on size-condition effects under JAS 1152 [28] and on statistical alignment between the JAS 1152 [28] and EN 338 [20] grading systems.

## 2.2. Physical and Mechanical Property Measurements

Figure 1 summarizes the main experimental workflow adopted in this study. All specimens were first labeled and then measured for dimensions in accordance with EN 1309-1 [30]. Global density was calculated from the measured dimensions and specimen mass. After the static bending tests, a 20 mm long full cross-sectional sample was cut as close as possible to the failure zone for the determination of local density and moisture content. Moisture content was measured using the oven-dry method. Both global and local densities ( $\rho_{\text{global,corr}}$  and  $\rho_{\text{local,corr}}$ ) were adjusted to a reference moisture content of 12% following the procedure adopted in the previous study [29].



**Figure 1.** Main experimental workflow.

Dynamic MOE was determined using the resonance frequency method (Model IET-5; Luoyang Zhuosheng Testing Instrument Co., Ltd., Luoyang, China). During testing, each specimen was simply supported and excited by an impact at one end, while the vibration response was recorded by a microphone at the opposite end. The first longitudinal resonance frequency was extracted from the frequency spectrum and used, together with the specimen mass and dimensions, to calculate dynamic MOE. All dynamic MOE values were further adjusted to a reference moisture content of 12% and denoted as  $E_{\text{dyn,corr}}$ , as calculated by Equation (1):

$$E_{\text{dyn,corr}} = 4 \frac{m}{L \times t \times w} \times f^2 \times L^2 (1 + 0.01(u_s - 12)) \times 10^{-9} \quad (1)$$

where  $f$  is the first longitudinal resonance frequency (Hz),  $m$  is the specimen mass (kg), and  $L$ ,  $t$ , and  $w$  are the specimen length, thickness, and width (m), respectively.  $u_s$  is the mean moisture content of the specimens (%). The moisture content correction factor

$(1 + 0.01(u - 12))$  is taken from the reference [31], and the factor  $10^{-9}$  is included to convert the result from Pa to GPa.

All static bending tests were carried out using a universal testing machine (Model UTM5105, 100 kN capacity; Shenzhen Sansi Zongheng Technology Co., Ltd., Shenzhen, China). For the evaluation parameters required under JAS 1152 [28], the bending MOE of the laminas was determined by flatwise three-point bending tests. The span-to-depth ratio was set to 21:1, and the mid-span deflection was measured using a linear displacement transducer (Model YWC-30; Liyang Chaoyuan Instrument Factory, Liyang, China). Based on the surface defect distribution of each specimen, the most critical section was positioned directly beneath the loading head. The flatwise bending MOE was calculated from the load–deflection relationship within the elastic range and then adjusted to a reference moisture content of 12%, denoted as  $E$ , as calculated by Equation (2):

$$E = \frac{\Delta F l^3}{4bh^3 \Delta \delta} (1 + 0.015(u - 12)) \times 10^{-3} \quad (2)$$

where  $\Delta F$  is the load increment within the elastic range (N),  $\Delta \delta$  is the corresponding increment in mid-span deflection (mm),  $l$  is the span (mm),  $b$  and  $h$  are the cross-sectional breadth and depth, respectively (mm),  $u$  is the moisture content of the specimen (%). The moisture content correction factor  $(1 + 0.015(u - 12))$  is taken from GB/T 26899 [27], and the factor  $10^{-3}$  is included to convert the result from MPa to GPa.

For the evaluation parameters required under EN 338 [20], edgewise four-point bending tests were carried out to determine bending MOE and bending strength. The tests were conducted in accordance with EN 408 [32], with the most critical section positioned within the constant-moment region between the two loading points. The global edgewise bending MOE was calculated from the load–deflection relationship within the elastic range and then adjusted to a reference moisture content of 12%, denoted as  $E_{m,g,corr}$ , as calculated by Equation (3):

$$E_{m,g,corr} = \frac{3al^2 - 4a^3}{4bh^3 \left( \frac{\Delta \delta}{\Delta F} - \frac{3a}{5Gb} \right)} (1 + 0.01(u - 12)) \times 10^{-3} \quad (3)$$

where  $a$  is the distance from the loading point to the nearest support (mm), and  $G$  is the shear modulus. According to EN 384 [33],  $G$  was taken as infinite in the calculation, and the effect of shear deformation was neglected. The moisture content correction factor  $(1 + 0.01(u - 12))$  is also taken from EN 384 [33], and the factor  $10^{-3}$  is included to convert the result from MPa to GPa.

The edgewise bending strength was calculated using Equation (4):

$$f_m = \frac{3Fa}{bh^2} \quad (4)$$

where  $F$  is the maximum failure load (N). A depth correction factor,  $k_h$ , was further introduced in accordance with EN 384 [33], and the corrected bending strength,  $f_{m,corr}$ , was calculated using Equations (5) and (6):

$$f_{m,corr} = f_m / k_h \quad (5)$$

$$k_h = \min \left\{ \left( \frac{150}{h} \right)^{0.2}, 1.3 \right\} \quad (6)$$

These property measurements were used to evaluate the same batch of Chinese fir laminas under two grading systems with different required parameters.

### 2.3. Grading Settings Under JAS 1152

Under the JAS 1152 [28], grading settings were established on the basis of the regression relationship between dynamic MOE and static bending properties. In the present study, this procedure served two purposes: first, to examine how specimen size condition influenced the grading settings and grade distribution within JAS 1152 [28]; and second, to provide the MOE-side reference for later comparison with EN 338 [20]. As shown in the previous study, bending MOE is the governing property for grade assignment under JAS 1152 [28]. Accordingly, the derivation of grading settings in the present study was based primarily on the bending MOE requirements specified for its strength classes. In addition, because JAS 1152 [28] does not specify a flatwise bending strength requirement for non-finger-jointed laminas, bending strength was not included in the derivation of the JAS 1152 [28] grading settings. Instead, edgewise bending strength was determined from the same single-size specimens for the separate evaluation under EN 338 [20]. To assess the effect of specimen size, the grading results obtained under the single-size condition were further compared with those previously derived under the multi-size condition within the JAS 1152 [28].

The grading settings were derived using the prediction limit method recommended in EN 14081-2 [34]. Following this approach, the dynamic MOE thresholds corresponding to the mean and lower-limit requirements of bending MOE specified in JAS 1152 [28] were calculated separately, as shown in Equations (7)–(9):

$$S_{E,\text{mean}} = \frac{E_{\text{req,mean}} - b_E}{a_E} \quad (7)$$

$$S_{E,05} = \frac{E_{\text{req},05} - b_E + t_{\alpha,n-2} \times s_{\delta,E}}{a_E} \quad (8)$$

$$S = \text{Max}\{S_{E,\text{mean}}, S_{E,05}\} \quad (9)$$

where  $S_{E,\text{mean}}$  is the dynamic MOE threshold required to satisfy the specified mean bending MOE of a given JAS 1152 [28] grade, and  $S_{E,05}$  is the threshold required to satisfy the corresponding lower-limit bending MOE. The final grading setting  $S$  is taken as the larger of these two thresholds so that both requirements are met simultaneously. Thus,  $S$  represents the minimum dynamic MOE required for assigning a specimen to the corresponding grade. Parameters  $a_E$  and  $b_E$  are the slope and intercept of the regression model, respectively.  $E_{\text{req,mean}}$  and  $E_{\text{req},05}$  are the required mean and lower-limit bending MOE values specified in JAS 1152 [28]. The term  $s_{\delta,E}$  is the standard error of estimate of the regression model for bending MOE.  $t_{(\alpha,n-2)}$  is the critical value from the  $t$ -distribution corresponding to the selected confidence level ( $\alpha$ ) and degrees of freedom ( $n-2$ ). For a 5% prediction level with assumed large samples, as specified in EN 14081-2 [34],  $t_{0.05,\infty} = 1.645$ .

### 2.4. Grading Settings Under EN 338

Under the EN 338 [20], strength class assignment is governed by three grade determining properties (GDPs), namely bending MOE, bending strength, and density. Among them, bending MOE is controlled by its characteristic mean value, whereas bending strength and density are controlled by their characteristic 5th percentile values. Because the class requirements specified in EN 338 [20] cannot be obtained directly from the IPs measured during machine grading, the relevant mechanical properties first needed to be converted and their characteristic values derived in accordance with EN 384 [33] and EN 14358 [35]. The predictive relationships between the IPs and the GDPs were then

established, from which the grading thresholds corresponding to each strength class were derived.

According to EN 384 [33], when bending MOE is determined from the global bending MOE test result,  $E_{m,g,corr}$  must first be converted to the parallel bending MOE,  $E_0$ , as given in Equation (10):

$$E_0 = E_{m,g,corr} \times 10^3 \times 1.3 - 2690 \quad (10)$$

The characteristic value of the parallel bending MOE ( $E_{0,mean}$ ) for each grade is then calculated using Equation (11), where  $\bar{E}_0$  is the arithmetic mean of the sample  $E_0$  values.

$$E_{0,mean} = \bar{E}_0 / 0.95 \quad (11)$$

For bending strength, the characteristic value for each class,  $f_k$ , was derived in accordance with EN 384 [33] from the 5th percentile at the 75% confidence level,  $f_{05}$ , calculated according to EN 14358 [35], as shown in Equation (12). where the factor  $k_v$  is defined by Equation (13) and  $f_{m,k}$  is the target characteristic bending strength specified for the corresponding EN 338 [20] grade.

$$f_k = f_{05} \times k_v \quad (12)$$

$$k_v = \begin{cases} 1.0, & f_{m,k} < 30 \text{ MPa} \\ 1.12, & f_{m,k} \geq 30 \text{ MPa} \end{cases} \quad (13)$$

The density-related GDP was taken as the 5th percentile of local density, calculated in accordance with EN 14358 [35].

On the basis of the predictive relationships between the IPs (dynamic MOE and global density) and the GDPs, the grading thresholds required to satisfy the EN 338 [20] grade requirements can be derived. In the present study, dynamic MOE was used as the indicating property (IP) for both bending MOE and bending strength, whereas global density was used as the IP for density. Therefore, the setting values corresponding to the bending MOE, bending strength, and density requirements were calculated using Equations (14)–(16). Here,  $S_{MOE}$  and  $S_{MOR}$  are both dynamic MOE thresholds, while  $S_{DEN}$  is a global density threshold. The regression coefficients  $a_{E_{m,g,corr}}$  and  $b_{E_{m,g,corr}}$  describe the relationship between dynamic MOE and bending MOE;  $a_{f_{m,corr}}$ ,  $b_{f_{m,corr}}$ , and  $s_{\delta,f_{m,corr}}$  describe the relationship between dynamic MOE and bending strength, where  $s_{\delta,f_{m,corr}}$  is the standard error of estimate used for deriving the lower prediction limit; and  $a_{\rho_{local,corr}}$ ,  $b_{\rho_{local,corr}}$ , and  $s_{\delta,\rho_{local,corr}}$  describe the relationship between global density and local density, where  $s_{\delta,\rho_{local,corr}}$  is the corresponding standard error of estimate. In addition,  $E_{req,0,mean}$ ,  $f_{req,k}$ , and  $\rho_{req,k}$  are the required mean bending MOE, characteristic bending strength, and characteristic density specified in EN 338 [20], respectively.

Because EN 338 [20] requires simultaneous compliance with bending MOE, bending strength, and density, the final assigned grade was expected to reflect a different control logic from that of JAS 1152 [28].

$$S_{MOE} = \frac{(E_{req,0,mean} \times 0.95 + 2690) / (10^3 \times 1.3) - b_{E_{m,g,corr}}}{a_{E_{m,g,corr}}} \quad (14)$$

$$S_{MOR} = \frac{f_{req,k} / k_v + t \times s_{\delta,f_{m,corr}} - b_{f_{m,corr}}}{a_{f_{m,corr}}} \quad (15)$$

$$S_{DEN} = \frac{\rho_{req,k} + t \times s_{\delta,\rho_{local,corr}} - b_{\rho_{local,corr}}}{a_{\rho_{local,corr}}} \quad (16)$$

### 2.5. Cross-Standard Comparison and Grade Alignment

To clarify the differences in the evaluation of the same batch of Chinese fir laminas under the JAS 1152 [28] and EN 338 [20] frameworks, and to examine the correspondence between the two grading systems, the assigned grades under the two standards were first compared directly. Specifically, the grade assigned to each specimen under JAS 1152 [28] was paired with the grade assigned to the same specimen under EN 338 [20], and the number and proportion of specimens in each grade combination were summarized to construct a grade correspondence matrix. This matrix provided a direct comparison of the grade distributions obtained under the two standards and identified the main corresponding grade intervals between them.

Second, bidirectional regression relationships were established between the flatwise three-point bending MOE specified in JAS 1152 [28] and the parallel bending MOE specified in EN 338 [20]. Based on these relationships, the MOE values specified for each grade in one standard were used to predict the corresponding MOE range and potential grade interval in the other standard. Grade prediction was determined using the regression estimate together with the lower bound of its confidence interval.

Finally, the applicability of the cross-standard alignment in each direction was evaluated by comparing the estimated grade intervals with the actually assigned grades and with the measured values of the relevant GDPs. In addition, the symmetry and robustness of the estimated relationships were assessed by examining the concentration and dispersion of the estimated grade distributions. The purpose of this procedure was to establish a statistically meaningful correspondence between the two systems at the MOE level, rather than to claim full equivalence of strength classes across standards. All statistical procedures described in this section, including regression analysis, descriptive statistics, and grade correspondence analysis, were performed using R software (Version 4.4.1; R Foundation for Statistical Computing, Vienna, Austria).

## 3. Results and Discussion

### 3.1. Grading Outcomes of Different Specimen Size Datasets Under JAS 1152

The main physical and mechanical properties of the two specimen groups are presented in Table 1 for reference before the detailed analysis. Table 2 summarizes the regression models and the parameters required for deriving the grading settings under the multi-size and single-size conditions. As shown in Table 2, the regression slopes for predicting bending MOE from dynamic MOE were 0.6202 and 0.6160 under the single-size and multi-size conditions, respectively, indicating only a minor difference. This suggests that the fundamental linear relationship between dynamic MOE and bending MOE remained generally consistent under the two conditions. In contrast, the regression intercept was noticeably higher under the single-size condition, reaching 2.3569 compared with 1.1499 under the multi-size condition. This indicates that, at the same level of dynamic MOE, the predicted bending MOE was generally higher for the single-size specimens than for the multi-size specimens.

A possible explanation is that the short-span flatwise three-point bending test specified in JAS 1152 [28] is more sensitive to local variability within the bending zone. When specimens of different sizes are analyzed together, the inconsistency between the global stiffness represented by dynamic MOE and the local bending response measured in the static test may be further amplified by size effects. As a result, the static bending MOE corresponding to the same dynamic MOE shows a systematic shift, which is reflected in the downward displacement of the regression line for the multi-size dataset. In addition, the model fit under the single-size condition was clearly better than that under the multi-size condition, with the coefficient of determination increasing from 0.35 to 0.60 and the

standard error of estimate decreasing from 1.1009 to 0.809. These results indicate that, when specimen size was controlled, the variability among specimens decreased and the regression relationship between dynamic MOE and bending MOE became more stable.

**Table 1.** Summary of the physical and mechanical properties of the multi-size and single-size specimen datasets.

Sample Type	Sample Size	Moisture Content (%)	Density (kg/m <sup>3</sup> )		Dynamic MOE (GPa)	Bending MOE (GPa)		Bending Strength (MPa)	
			Global	Local		Flatwise 3-Point	Edgewise 4-Point	Flatwise 4-Point	Edgewise 4-Point
Multi-size [29]	162	13.04 ± 2.47	347 ± 44	329 ± 35	7.5 ± 1.3	5.8 ± 1.4		44.50 ± 12.57	
Single-size	102	14.58 ± 1.82	383 ± 52	341 ± 39	8.8 ± 1.6	7.8 ± 1.3	9.7 ± 1.5		37.33 ± 9.65

Note: All values are expressed as mean ± standard deviation.

**Table 2.** Regression models and statistical parameters required grading setting calculations under JAS 1152 [28].

Sample Type	Sample Size	Regression Model	R <sup>2</sup>	<i>a</i>	<i>b</i>	<i>s<sub>δ</sub></i>	<i>t</i>
Multi-size	162	$E = 1.1499 + 0.616E_{\text{dyn,corr}}$	0.35	0.616	1.1499	1.1009	
		$f = -0.89 + 6.05E_{\text{dyn,corr}}$	0.40	6.05	-0.89	9.7308	1.645
Single-size	102	$E = 2.3569 + 0.6202E_{\text{dyn,corr}}$	0.60	0.6202	2.3569	0.809	

Using Equations (7)–(9), the longitudinal dynamic MOE thresholds corresponding to each grade were determined, and the resulting grading settings are summarized in Table 3. Overall, the required threshold values differed markedly between the single-size and multi-size conditions across all grades. For the grades common to both conditions, namely L30–L80, the final threshold values *S* under the single-size condition were 2.4, 3.7, 5.0, 6.4, 8.0, and 9.1 GPa, respectively, all lower than the corresponding values under the multi-size condition, which were 5.4, 6.4, 7.7, 9.2, 10.8, and 11.6 GPa. The differences were approximately 2.5–3.0 GPa, indicating that, for the same grade requirement, the dynamic MOE threshold required under the single-size condition was consistently much lower.

Further examination of the controlling terms showed that, under the multi-size condition, grade L30 was governed by  $S_{f,05}$ , whereas grades L40–L80 were all governed by  $S_{E,05}$ . This indicates that the grading settings under the multi-size condition were mainly constrained by the lower-limit requirements for strength or MOE, with the lower limit of bending MOE being the most dominant. By contrast, under the single-size condition, grades L30–L70 were still mainly governed by  $S_{E,05}$ , but from L80 onward the final threshold value became controlled by  $S_{E,\text{mean}}$ . As a result,  $S_{E,\text{mean}} > S_{E,05}$  was observed for some higher grades. Specifically, for grades L80, L90, L100, and L110, the corresponding  $S_{E,\text{mean}}$  values were 9.1, 10.7, 12.3, and 13.9 GPa, respectively, all higher than the corresponding  $S_{E,05}$  values. As indicated by Equation (17), when the gap between the mean-value requirement and the lower-limit requirement is small, a larger prediction error term  $t s_{\delta,E}$  makes the lower-limit condition more restrictive, resulting in a larger  $S_{E,05}$ . Conversely, when this gap becomes larger, the mean-value requirement becomes more restrictive, and  $S_{E,\text{mean}}$  exceeds  $S_{E,05}$ .

$$S_{E,\text{mean}} - S_{E,05} = \frac{E_{\text{req,mean}} - E_{\text{req,05}} - t \times s_{\delta,E}}{a_E} \quad (17)$$

As shown in Table 3, with increasing target strength grade, the difference between the mean and lower-limit bending MOE specified in JAS 1152 [28] increased from 0.5 to 1.0 GPa at the lower grades to 1.5 GPa at L80 and above, indicating that the mean-value requirement also became progressively more restrictive at the higher grades. Together

with the reduced regression dispersion and improved predictive stability under the single-size condition, the lower-limit requirement no longer remained the principal factor constraining assignment to higher grades. The controlling mechanism in the higher-grade range therefore shifted gradually from lower-limit dominance to mean-value dominance. From the perspective of grading thresholds, this implies that the single-size condition resulted in lower overall threshold values, and allowed the grading range to extend further to L90-L110. By contrast, under the multi-size condition, the stricter lower-limit constraint markedly compressed the range of higher-grade assignments.

**Table 3.** Calculated dynamic MOE setting values for JAS 1152 [28] grades.

Grade	Setting of Dynamic MOE (GPa)							
	Multi-Size [29]					Single-Size		
	$S_{E,mean}$	$S_{E,05}$	$S_{f,mean}$	$S_{f,05}$	S	$S_{E,mean}$	$S_{E,05}$	S
Reject								
L30	3.0	5.1	3.6	5.4	5.4	1.0	2.4	2.4
L40	4.6	6.4	4.1	5.8	6.4	2.6	3.7	3.7
L50	6.2	7.7	4.6	6.2	7.7	4.3	5.0	5.0
L60	7.9	9.2	5.1	6.5	9.2	5.9	6.4	6.4
L70	9.5	10.8	5.6	6.9	10.8	7.5	8.0	8.0
L80	11.1	11.6	6.1	7.3	11.6	9.1	8.8	9.1
L90	12.7	13.2	6.6	7.7	13.2	10.7	10.4	10.7
L100	14.4	14.9	7.1	8.0	14.9	12.3	12.1	12.3
L110	16.0	16.5	7.6	8.4	16.5	13.9	13.7	13.9

As shown in Table 4, the final grade assignments differed markedly between the two size conditions. Under the multi-size condition, the specimens were concentrated mainly in grades L30–L60, with L40 being the most frequent grade, accounting for 77 specimens (47.5%). Grades L30, L50, and L60 contained 26, 37, and 14 specimens, representing 16.0%, 22.8%, and 8.6%, respectively. Only four specimens (2.5%) reached L70, and no specimens were assigned to L80 or above; an additional four specimens (2.5%) were classified as Reject. Overall, 154 specimens (95.1%) fell within grades L30–L60, indicating that the grading outcomes under the multi-size condition were strongly concentrated in the low- to mid-grade range.

By contrast, under the single-size condition, the grade distribution shifted upward overall. No specimens were assigned to Reject, L30, or L40. Grades L50, L60, L70, and L80 contained 6, 22, 43, and 20 specimens, accounting for 5.9%, 21.6%, 42.2%, and 19.6%, respectively. In addition, specimens could be further assigned to grades L90, L100, and L110, with 7, 3, and 1 specimens, respectively, corresponding to 6.9%, 2.9%, and 1.0%. Altogether, 31 specimens, or 30.4%, were classified as L80 or above, indicating that the single-size condition was more favorable for producing higher grades.

Further examination of Table 2 shows that, under the single-size condition, the regression intercept was 1.21 GPa higher than that under the multi-size condition. At the same time, the standard error of estimate under the multi-size condition was 0.2919 higher. When the lower prediction limit is used to derive grading settings, this larger standard error results in a greater safety-margin deduction. Using  $t = 1.645$ , the deduction amounts to approximately 1.82 GPa under the multi-size condition ( $1.645 \times 1.1009$ ) and 1.33 GPa under the single-size condition ( $1.645 \times 0.809$ ). Thus, the additional lower-limit penalty caused by the greater dispersion under the multi-size condition was about 0.48 GPa. In other words, the combination of a lower regression intercept and a larger lower-limit penalty under the multi-size condition created a disadvantage of approximately 1.7 GPa in the threshold required for higher-grade assignment. This was also a major reason

why the yield of grades L80 and above was markedly lower under the multi-size condition.

**Table 4.** JAS 1152 [28] grade requirements and statistics of specimens assigned to grades for the multi-size and single-size datasets.

Grade	Requirements in JAS 1152 [28]				Multi-Size [29]					Single-Size				
	$E$ (GPa)		$f$ (MPa)		$E_a$ (GPa)		$f_a$ (MPa)		$N$	Ratio (%)	$E_a$ (GPa)		$N$	Ratio (%)
	Mean	Lower Limit	Mean	Lower Limit	Mean	$P_{5,75}$	Mean	$P_{5,75}$			Mean	$P_{5,75}$		
Reject					4.4	2.4	42.0	21.1	4	2.5			0	0.0
L30	3.0	2.5	21.0	16.0	4.9	3.5	36.3	18.8	26	16.0			0	0.0
L40	4.0	3.3	24.0	18.0	5.5	3.8	40.4	24.4	77	47.5			0	0.0
L50	5.0	4.1	27.0	20.5	6.3	4.1	50.3	32.9	37	22.8	6.5	4.8	6	5.9
L60	6.0	5.0	30.0	22.5	7.1	4.2	61.9	47.8	14	8.6	6.7	5.4	22	21.6
L70	7.0	6.0	33.0	25.0	8.3	6.1	65.1	39.3	4	2.5	7.7	6.2	43	42.2
L80	8.0	6.5	36.0	27.0					0	0.0	8.6	7.2	20	19.6
L90	9.0	7.5	39.0	29.5					0	0.0	9.3	6.9	7	6.9
L100	10.0	8.5	42.0	31.5					0	0.0	10.3	7.9	3	2.9
L110	11.0	9.5	45.0	34.0					0	0.0	10.8		1	1.0

Note:  $E$  and  $f$  denote the required bending MOE and bending strength specified in JAS 1152 [28], respectively;  $E_a$  and  $f_a$  denote the measured bending MOE and bending strength, respectively, of the specimens assigned to each grade under the multi-size and single-size conditions.  $N$  denotes the number of specimens assigned to each grade, and  $P_{5,75}$  denotes the 5th percentile estimated at the 75% confidence level.

On the other hand, the single-size dataset itself showed higher mean MOE and density than the multi-size dataset, with the mean bending MOE being approximately 2 GPa higher and local density about 12 kg/m<sup>3</sup> higher (Table 1). This suggests that the greater yield of higher grades under the single-size condition was not attributable solely to improved statistical stability resulting from size consistency, but was also influenced, to some extent, by differences in the initial property distributions of the two datasets.

From the within-grade property statistics, both bending MOE and bending strength generally increased with increasing grade under the multi-size condition, indicating that the grading results still exhibited reasonable grade discrimination. However, the accessible high-grade range remained limited, and the lower-limit bending MOE of grade L60 fell below the standard requirement, suggesting that the stability of higher-grade assignments under the multi-size condition was still restricted. Under the single-size condition, the mean and lower-limit values of bending MOE for grades L50–L80 generally corresponded well to the values specified in JAS 1152 [28], indicating that the assignments in the mid- to high-grade range were reasonably valid. Although the mean bending MOE values for grades L90 and L100 satisfied the corresponding grade requirements, the calculated lower-limit values did not fully meet the specified lower-limit criteria because of the limited sample sizes, reflecting the conservative nature of characteristic-value estimation under small-sample conditions. When the specimens assigned to grades L90, L100, and L110 were combined into a single group, both the mean and lower-limit values satisfied the requirement for grade L90. This result suggests that the higher-grade range identified under the single-size condition was meaningful, although the statistical stability of the highest grades was still constrained by sample size.

Overall, under the JAS 1152 [28], the single-size condition produced a more dispersed and hierarchical grade distribution and yielded a higher proportion of higher-grade laminas, whereas the multi-size condition led to a stronger concentration in lower grades. It

should be noted, however, that this difference should not be attributed solely to specimen size condition itself, but more likely reflects the combined effects of size condition and differences in the initial property distributions of the two datasets. Therefore, when evaluating the grading potential of Chinese fir laminas, both specimen size condition and the intrinsic property level of the dataset should be considered, and the grading results obtained under multi-size conditions should not be directly extrapolated to single-size grading scenarios.

### 3.2. EN 338 Grading Outcomes and Comparison with JAS 1152

As shown in Table 5, under the EN 338 [20], the regression models established from the single-size specimens indicated that dynamic MOE was more strongly correlated with bending MOE ( $R^2 = 0.60$ ) than with bending strength ( $R^2 = 0.44$ ). At the same time, local density showed a clear relationship with global density ( $R^2 = 0.67$ ). The standard errors of estimate ( $s_\delta$ ) for the three models were 0.9488, 7.265, and 22.2896, respectively. These results indicate that dynamic MOE is more effective in characterizing stiffness-related properties than strength-related properties, while global density can provide a reasonably good prediction of local density.

**Table 5.** Regression models and statistical parameters required for grading setting calculations under EN 338 [20].

Sample Type	Sample Size	Regression Model	$R^2$	$a$	$b$	$s_\delta$	$t$
Single-size	102	$E_{m,g,corr} = 3.2966 + 0.7289E_{dyn,corr}$	0.60	0.7289	3.2966	0.9488	
		$f_{m,corr} = 1.7835 + 4.0599E_{dyn,corr}$	0.44	4.0599	1.7835	7.265	1.645
		$\rho_{local,corr} = 109.138 + 0.6403\rho_{global,corr}$	0.67	0.6403	109.138	22.2896	

Table 6 presents the specified values for each EN 338 [20] grade, the corresponding threshold settings for dynamic MOE and global density, as well as the measured property values, specimen counts, and proportions within each final assigned grade. Compared with the broader and generally higher-grade distribution obtained under JAS 1152 [28] for the same single-size dataset, the EN 338 [20] results already suggest a more downward-concentrated grading outcome.

Considering the results for the individual assigned grades, the specimens were distributed across several grades from C14 to C30, although the number of specimens in the higher grades was generally small. In addition, 36 specimens were classified as Reject, representing 35.3%. Under the individual-grade assignment approach, specimens in the higher grades were sparsely distributed, and the sample size for some grades was clearly insufficient, leading to density characteristic values that did not satisfy the standard requirements for any individual grade. According to EN 14081-2 [34], if an assigned grade or grade group is to be initially validated, each grade should contain at least 20 specimens. After grade grouping, the results were statistically more stable and were better able to satisfy the requirements of the corresponding strength classes.

Moreover, compared with bending strength and bending MOE, the density values were consistently closer to the lower grade limits. Further analysis also showed that final grade assignment under EN 338 [20] was governed predominantly by density. Among the 102 specimens, density controlled the final grades of 91 specimens, either alone or in combination with other GDPs. These results indicate that, for the Chinese fir laminas examined in this study, density was the dominant property controlling final grade assignment under the EN 338 [20] grading system. This density-dominated grading behavior also indicates a species-specific feature of Chinese fir under the EN 338 framework, differing from patterns reported for some other species, where the three GDPs may be relatively balanced or where grade assignment may be limited mainly by stiffness or strength [18,19].

**Table 6.** EN 338 [20] grade requirements, derived setting values, and resulting assigned grades for Chinese fir laminas.

Grade	Requirements in EN 338 [20]			Settings of Dynamic MOE and Global Density			Assigned Grade				
	$E_{0,mean}$ (GPa)	$f_{m,k}$ (MPa)	$\rho_k$ (kg/m <sup>3</sup> )	$S_{MOE}$ (GPa)	$S_{MOR}$ (GPa)	$S_{DEN}$ (kg/m <sup>3</sup> )	$E_{0,mean,d}$ (GPa)	$f_{m,k,d}$ (MPa)	$\rho_{k,d}$ (kg/m <sup>3</sup> )	$N$	Ratio (%)
Reject										36	35.3
C14	7.0	14	290	5.334	5.583	359.967	10.550	24.030	308.246	30	29.4
C16	8.0	16	310	6.337	6.023	393.063	11.316	16.923	294.404	9	8.8
C18	9.0	18	320	7.339	6.463	409.611	10.509	20.934	272.121	7	6.9
C14–C18							10.694	23.083	297.501	46	45.1
C20	9.5	20	330	7.841	6.903	426.159	11.631	27.579	321.414	6	5.9
C22	10.0	22	340	8.342	7.343	442.707	12.706	23.629	309.002	7	6.9
C24	11.0	24	350	9.344	7.782	459.255	12.300	14.247	292.608	2	2.0
C27	11.5	27	360	9.846	8.442	475.803	12.375	29.076	350.666	4	3.9
C30	12.0	30	380	10.347	9.102	508.899	12.166			1	1.0
C20–C30							12.250	28.955	330.065	20	19.6

Note: According to EN 14081-2 [34], initial setting validation requires that each assigned grade or grade combination should contain at least 20 specimens. Therefore, the individual EN 338 [20] grades were combined into C20–C30 and C14–C18 to satisfy this requirement, while preserving the highest possible grade yield. In addition, values under “Assigned grade” are the GDP values calculated for the specimens assigned to each final grade according to the procedures described in Section 2.4.

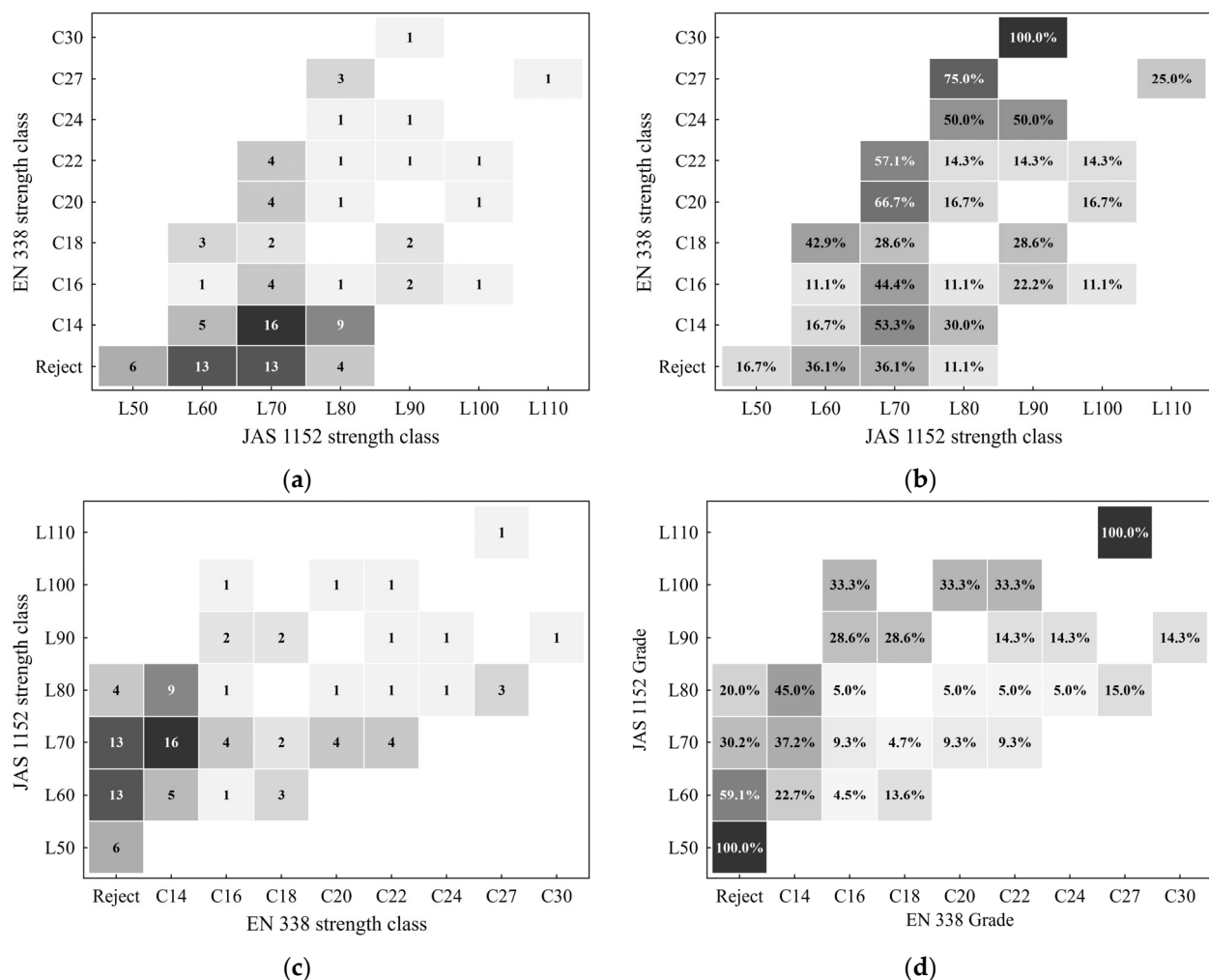
Combined with the single-size grading results under JAS 1152 [28], Figure 2 presents the correspondence between the final assigned grades under JAS 1152 [28] and EN 338 [20] in terms of both counts and proportions. In Figure 2a,b, the EN 338 [20] grades are shown on the vertical axis and the JAS 1152 [28] grades on the horizontal axis, illustrating the count and proportion distributions of each EN 338 [20] grade across the JAS 1152 system. In Figure 2c,d, the axes are reversed to show the corresponding count and proportion distributions of each JAS 1152 [28] grade across the EN 338 [20] system. Overall, the assigned grades under the two standards did not exhibit strict one-to-one correspondence; instead, a given grade under one system was often distributed across several grade intervals under the other.

From the perspective of EN 338-to-JAS 1152 correspondence, low grades and even Reject under EN 338 [20] were still distributed across several JAS 1152 [28] grades. In particular, specimens classified as Reject under EN 338 [20] were not confined to a single low JAS 1152 [28] grade, but were distributed from L50 to L80, mainly concentrated in L60 and L70. This indicates that rejection under EN 338 [20] does not necessarily imply extremely low stiffness performance under JAS 1152 [28]. At the same time, specimens assigned to C14 were mainly distributed in L70 and L80, whereas those assigned to C20 and above were more frequently found in grades above L70. Thus, although the corresponding JAS 1152 [28] grade interval tended to shift upward with increasing EN 338 [20] grade, the distribution remained clearly dispersed rather than converging to a fixed grade mapping.

From the perspective of JAS 1152-to-EN 338 correspondence, an increase in JAS 1152 [28] grade did not necessarily result in a corresponding increase in EN 338 [20] grade. All L50 specimens were classified as Reject under EN 338 [20], while L60 specimens were mainly distributed between Reject and C14. Even within L70 and L80, specimens were still spread across Reject, C14, C16, C18, and higher grades. In other words, even when relatively high grades were achieved under JAS 1152 [28], some specimens could still be assigned to lower grades or even Reject under EN 338 [20]. This shows that higher grades

under JAS 1152 [28] cannot be directly interpreted as equivalent high strength classes under EN 338 [20] and must still be re-evaluated according to the grading criteria of the latter.

The dispersion of grade correspondence across standards fundamentally reflects the different control logic of the two systems. JAS 1152 [28] is primarily governed by bending MOE, whereas EN 338 [20] is determined jointly by bending MOE, bending strength, and density, with density playing a particularly important role. As a result, although the grading outcomes under the two standards were broadly related, their correspondence was distributed over a range of grades rather than concentrated within a single matching interval. This indicates that the two grading systems are comparable at an overall level, but cannot be interpreted through a simple one-to-one grade mapping.

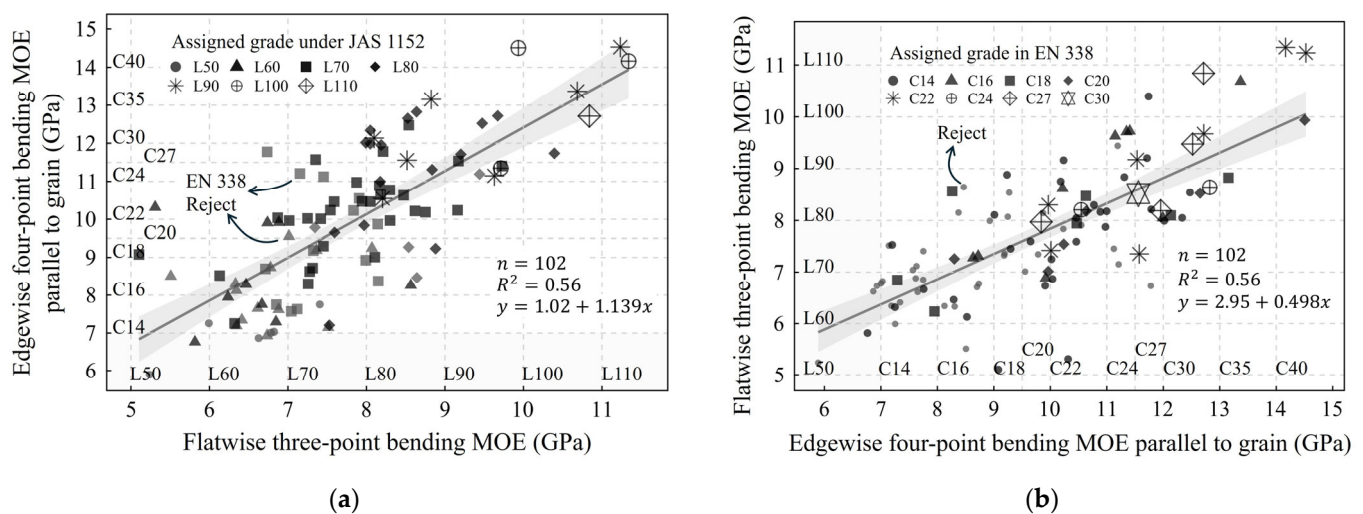


**Figure 2.** Relationship between assigned grades under JAS 1152 [28] and EN 338 [20] for Chinese fir laminas: (a,c) counts; (b,d) proportions.

### 3.3. Grade Alignment Between JAS 1152 and EN 338

The grade count and proportion matrices presented above show that the final assigned grades under JAS 1152 [28] and EN 338 [20] did not exhibit a strict one-to-one correspondence. However, because both standards use bending MOE as an important basis for grade classification, it remains possible to establish a statistically meaningful grade alignment at the MOE level, despite differences in test configuration. On this basis, Figure 3 further presents the regression equations describing grade alignment between the two standards, thereby providing a statistical basis for the subsequent validation of the alignment results.

As shown in Figure 3, regression equations were established from the relationship between the flatwise three-point bending MOE specified in JAS 1152 [28] and the edge-wise bending MOE parallel to grain specified in EN 338 [20]. Figure 3a shows the conversion from JAS 1152 [28] to EN 338 [20], whereas Figure 3b shows the reverse alignment from EN 338 [20] to JAS 1152 [28]. The vertical and horizontal threshold lines indicate the MOE values specified for the strength classes in the corresponding standards. Both conversion directions showed positive correlations, with  $R^2 = 0.56$ . The regression equation from JAS 1152 [28] to EN 338 [20] was  $y = 1.02 + 1.139x$ , whereas that from EN 338 [20] to JAS 1152 [28] was  $y = 2.95 + 0.498x$ . These results indicate that the two standards can be linked through a moderate statistical relationship based on MOE.



**Figure 3.** Grade alignment between JAS 1152 [28] and EN 338 [20] for Chinese fir laminas based on bending MOE regression: (a) from JAS 1152 [28] to EN 338 [20]; (b) from EN 338 [20] to JAS 1152 [28]. Note: The vertical and horizontal threshold lines in the figure represent the characteristic bending MOE values specified for the strength classes under the corresponding standards, respectively. The light-colored data points represent the specimens assigned to the Reject grade under EN 338 [20]. The grey shaded area represents the 95% confidence interval of the fitted regression line.

Accordingly, when the bending MOE value specified for a given grade in one standard is known, it can be substituted into the corresponding regression equation to predict the MOE range and potential strength grade in the other standard. To reduce the risk of overestimation arising from regression scatter, the subsequent grade prediction was based on the lower bound of the predicted confidence interval. In addition, for the conversion from JAS 1152 [28] to EN 338 [20], the final predicted grade was further restricted by the characteristic density requirement. Thus, the regression equations shown in Figure 3 were primarily used to establish the overall grade alignment between the two standards, whereas their practical reliability still required further verification using the results presented in the subsequent tables.

At the same time, the alignment relationships shown in Figure 3 should be understood as describing the overall correspondence trend between the two grading systems. Their practical predictive performance remains influenced by sample variability and by the different control logic underlying the two standards. Therefore, these equations are more suitable for estimating the overall grade correspondence between JAS 1152 [28] and EN 338 [20] than for direct one-to-one grade substitution, and the specific conversion results should be interpreted together with the validation results presented in Tables 7 and 8.

As shown in Table 7, a statistically meaningful grade alignment between JAS 1152 [28] and EN 338 [20] can be established on the basis of bending MOE. Using the flatwise three-point bending MOE specified for each JAS 1152 [28] grade together with the regression equation in Figure 3, the corresponding mean value and confidence interval of the edgewise bending MOE parallel to grain under EN 338 [20] were predicted. From L50 to L110, the predicted EN 338 [20] grades, determined from the lower bound of the predicted confidence interval, were Reject, C14, C16, C20, C22, C27, and C30, respectively. Validation against the measured bending MOE and the lower-limit characteristic values of bending strength showed that these predicted grades satisfied the corresponding requirements. These results indicate that, although the final assigned grades under the two standards were not in strict one-to-one correspondence, the two systems remained statistically linked at the level of bending-related properties.

**Table 7.** Prediction and validation of EN 338 [20] grades for Chinese fir laminas from JAS 1152 [28] grades based on the regression relationship for bending MOE.

JAS 1152 [28]		EN 338 [20]					
Grade	$E_{req,mean}$ (GPa)	Predicted Mean (GPa)	Confidence Interval (GPa)	Predicted Grade	Validation		
					$E_{0,mean,d}$ (GPa)	$f_{m,k,d}$ (MPa)	$\rho_{k,d}$ (kg/m <sup>3</sup> )
L50	5.0	6.7	[6.1, 7.3]	Reject	7.332	12.269	246.066
L60	6.0	7.9	[7.4, 8.3]	C14	8.707 (✓)	19.435 (✓)	239.158 (X)
L70	7.0	9.0	[8.7, 9.3]	C16	10.444 (✓)	23.862 (✓)	285.549 (X)
L80	8.0	10.1	[9.9, 10.4]	C20	11.548 (✓)	31.299 (✓)	289.142 (X)
L90	9.0	11.3	[10.9, 11.6]	C22	12.997 (✓)	26.268 (✓)	311.480 (X)
L100	10.0	12.4	[11.9, 12.9]	C27	14.042 (✓)	31.649 (✓)	304.988 (X)
L110	11.0	13.6	[12.9, 14.2]	C30	13.382 (✓)		

Note: The prediction equation used in this table was  $y = 1.02 + 1.139x$ , where  $y$  is the predicted mean edgewise four-point bending MOE parallel to grain under EN 338 [20] and  $x$  is the requirement for mean flatwise three-point bending MOE under JAS 1152 [28]. “✓” indicates that the derived value satisfied the requirement of the predicted EN 338 [20] grade, whereas “X” indicates that the requirement was not satisfied. Blank cells indicate that validation was not applicable because the corresponding characteristic value could not be derived reliably. For the Reject grade, no validation was performed because no corresponding strength class values are specified for this category.

When the predicted grades were further checked against the density requirements of EN 338 [20], the admissible grades decreased markedly. As shown in Table 7, the characteristic density values of the individual EN 338 [20] grades did not satisfy the requirements of their respective target classes. After progressively merging the higher grades and recalculating the characteristic values for the grouped grades, L50–L70 corresponded only to Reject, whereas L80–L110 could be stably aligned only with C14. These results show that the MOE-based alignment between JAS 1152 [28] and EN 338 [20] reflects the overall correspondence of stiffness levels but does not directly translate into full class equivalence under the complete EN 338 [20] GDP framework.

As shown in Table 8, the mean edgewise bending MOE specified for each EN 338 [20] grade was converted, using the regression equation, into the corresponding flatwise three-point bending MOE under JAS 1152 [28], from which the corresponding JAS 1152 [28] grades were predicted. The results revealed a clear interval-based correspondence between the two systems: C14 and C16 corresponded to L60, C18, C20, and C22 corresponded to L70, and C24, C27, and C30 corresponded to L80.

**Table 8.** Prediction and validation of JAS 1152 [28] grades for Chinese fir laminas from EN 338 [20] grades based on the regression relationship for bending MOE.

EN 338 [20]		JAS 1152 [28]				
Grade	$E_{0,\text{mean}}$ (GPa)	Predicted Mean (GPa)	Confidence Interval (GPa)	Predicted Grade	Validation	
					$E_{\text{mean,d}}$ (GPa)	$E_{05,\text{d}}$ (GPa)
Reject					7.1	5.6
C14	7.0	6.4	[6.1, 6.7]	L60	7.7 (✓)	5.4 (✓)
C16	8.0	6.9	[6.6, 7.1]	L60	8.7 (✓)	5.8 (✓)
C14–C16				L60	7.9 (✓)	5.5 (✓)
C18	9.0	7.4	[7.2, 7.5]	L70	7.9 (✓)	5.7 (X)
C20	9.5	7.6	[7.4, 7.8]	L70	8.1 (✓)	5.6 (X)
C22	10.0	7.8	[7.7, 8.0]	L70	9.2 (✓)	5.5 (X)
C18–C22				L70	8.4 (✓)	5.8 (X)
C24	11.0	8.3	[8.1, 8.5]	L80	8.4 (✓)	6.6 (✓)
C27	11.5	8.6	[8.4, 8.8]	L80	9.1 (✓)	5.5 (X)
C30	12.0	8.8	[8.6, 9.1]	L80	8.5 (✓)	
C24–C30				L80	8.8 (✓)	6.6 (✓)

Note: The prediction equation used in this table was  $y = 2.95 + 0.498x$ , where  $y$  is the predicted mean flatwise three-point bending MOE under JAS 1152 [28] and  $x$  is the requirement for characteristic mean edgewise bending MOE parallel to grain under EN 338 [20].  $E_{\text{mean,d}}$  and  $E_{05,\text{d}}$  denote the mean and 5th percentile, respectively, of the measured flatwise three-point bending MOE of the specimens assigned to each predicted JAS 1152 [28] grade. The symbols “✓” and “X” indicate that the corresponding measured mean or 5th percentile value satisfies and does not satisfy the relevant JAS 1152 [28] requirement for the predicted grade, respectively.

At the individual-grade level, the measured mean flatwise bending MOE of all EN 338 [20] grades satisfied the requirements of their predicted JAS 1152 [28] grades, indicating good agreement at the mean level. By contrast, incomplete validation was mainly associated with the lower-limit values and was concentrated in the middle-grade interval. For example, although C18, C20, and C22 were all predicted as L70, and their measured mean values of 7.9, 8.1, and 9.2 GPa all exceeded the specified value for L70, their lower-limit values were 5.7, 5.6, and 5.5 GPa, respectively, all only slightly below the required 6.0 GPa. This suggests that these grades were already close to the corresponding JAS 1152 [28] requirement, although validation based on the lower-limit values remained slightly conservative.

When sample size was further taken into account, the lower-grade interval C14–C16 included 39 specimens and, after grouping, corresponded to L60, with both the measured mean and lower-limit values satisfying the required grade. The middle-grade interval C18–C22 included 20 specimens and, after grouping, corresponded to L70; the measured mean satisfied the requirement, whereas the lower-limit value was 5.8 GPa, only slightly below the specified 6.0 GPa. The higher-grade interval C24–C30 included 7 specimens and, after grouping, corresponded to L80, with both the measured mean and lower-limit values satisfying the required grade. These results indicate that the reverse prediction from EN 338 [20] to JAS 1152 [28] became more stable after adjacent grades were grouped, with full validation achieved in the lower- and higher-grade intervals and the middle-grade interval remaining close to the required lower limit.

Overall, the reverse prediction from EN 338 [20] to JAS 1152 [28] showed some variation at the individual-grade level but formed a clear correspondence at the grade-interval level, with C14–C16 corresponding to L60, C18–C22 to L70, and C24–C30 to L80. This indicates that the reverse alignment is well suited to describing the correspondence of

stiffness levels between the two standards and, after grade grouping, shows good interpretability and stability. By comparison, the conversion from JAS 1152 [28] to EN 338 [20] is more directly constrained by the density requirement and therefore reflects the fundamental difference in grading logic between the two systems. Notably, the dispersed grade correspondence and the density-governed behaviour of Chinese fir under EN 338 are empirical findings that go beyond the known differences in standard principles, quantifying the practical limits of cross-standard alignment.

### 3.4. Practical Implications and Future Research

The results showed that Chinese fir laminas followed distinctly different grading control logics under JAS 1152 [28] and EN 338 [20]. Under JAS 1152 [28], grade assignment was governed primarily by bending MOE, whereas under EN 338 [20] it was controlled mainly by density, with bending MOE playing a secondary role and bending strength contributing relatively little. The different grading outcomes obtained under the two standards are therefore manifested more clearly in the inconsistent proportions of high- and low-grade assignments than in a simple mismatch between individual grades.

These differences also define the limits of cross-standard interpretation. The MOE-based grade alignment established between JAS 1152 [28] and EN 338 [20] provides a useful statistical basis for describing the correspondence between the two systems at the stiffness level, but it does not imply full equivalence of strength classes. In particular, conversion from JAS 1152 [28] to EN 338 [20] cannot be determined from MOE correspondence alone and must be further constrained by density. The alignment should therefore be regarded as a stiffness-based statistical framework rather than a direct conversion rule. At the same time, specimens classified as Reject under EN 338 [20] may still correspond to usable grades under JAS 1152 [28], indicating that rejection in one system does not necessarily imply the absence of utilization potential in the other, although such use should be interpreted conservatively.

From a practical perspective, under the current standards, Chinese fir laminas are more likely to show their utilization advantage within a JAS 1152-type, stiffness-dominated grading framework, whereas under EN 338 [20] they are more readily limited by density. This difference should not be interpreted merely as a confirmation of the general distinction between the two standards. Rather, it also reflects the grading response of the investigated Chinese fir laminas under the two grading frameworks. In the present dataset, stiffness-related properties showed relatively favorable grading potential, whereas density more frequently became the limiting criterion under EN 338 [20]. This does not mean JAS 1152 is a looser or superior standard; rather, it reflects a better match between Japanese standard logic and the material properties of Chinese fir. As a well-proven standard, JAS 1152 allows Chinese fir to realize its utilization advantage in glulam production.

Based on our findings, we recommend that for Chinese fir laminas intended for EN 338-based applications, density should be checked as a critical property, as it is the main reason for rejection. For cases where a lamina is accepted by JAS 1152 [28] but would be rejected by EN 338 [20], direct substitution is not advised; such material may still be suitable for JAS-based glued laminated timber production, but should not be used in EN-governed structural elements without additional density verification. The influence of specimen size should also be emphasized. The single-size condition produced higher regression accuracy, finer grade differentiation, and a markedly higher proportion of high-grade specimens than the multi-size condition. When higher grading accuracy, finer grade separation, or greater high-grade yield is required, grading should therefore preferably be carried out under fixed nominal dimensions.

More broadly, these findings suggest that future revisions of standards for domestic plantation species should place greater emphasis on their own property distributions

rather than simply adopting grade boundaries developed for imported timber species. As discussed by Steiger and Arnold [21], the three GDPs in EN 338 [20] within each strength class should match as closely as possible; if a population that fulfills the criteria for bending strength and MOE must be downgraded solely because its density values fall short, then the appropriateness of the density limits should be questioned.

Further research should expand the dataset, particularly by including more high-grade specimens and materials from a wider range of Chinese fir sources, in order to further verify the robustness of the present grading results, the identified control logic, and the grade alignment relationships under broader sampling conditions.

#### 4. Conclusions

This study compared the grading outcomes of Chinese fir laminas under JAS 1152 [28] and EN 338 [20] and examined the linkage between the two systems. The main conclusions are as follows.

First, under the present datasets, the grading outcomes under JAS 1152 [28] differed markedly between the single-size and multi-size conditions. Under the single-size condition, the specimens were classified into seven grades, from L50 to L110, and high grades (L80 and above) accounted for 30.4%; under the multi-size condition, the material was concentrated mainly in L30–L60, with a much lower yield of higher grades. Under the single-size condition, grades L30–L70 were governed mainly by the lower-limit MOE requirement, whereas grades L80–L110 were governed mainly by the mean MOE requirement. These results indicate that fixed nominal dimensions are preferable when finer grade separation and higher grading accuracy are required.

Second, the two standards followed different grading control logics for the same material. Under JAS 1152 [28], grade assignment was governed primarily by bending MOE, whereas under EN 338 [20] density was the principal GDP and bending MOE played a secondary role. Thus, the difference between the two systems was reflected more clearly in the inconsistent proportions of high- and low-grade assignments than in a simple mismatch between individual grades.

Third, the two systems could be linked statistically through bending MOE, but this linkage should be interpreted as stiffness-level grade correspondence rather than full class equivalence. From JAS 1152 [28] to EN 338 [20], L50, L60, L70, L80, L90, L100, and L110 corresponded to Reject, C14, C16, C20, C22, C27, and C30, respectively, and this direction was generally more robust, although density constraints remained essential. In the reverse direction, C14–C16 mainly corresponded to L60, C18–C22 to L70, and C24–C30 to L80; this interval-based alignment was clear, but less stable under lower-limit requirements.

Overall, these results clarify the dominant controlling properties of the two systems and define the practical boundary of grade alignment for Chinese fir laminas, while also providing a useful reference for the standard-linked evaluation of other fast-grown plantation species.

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## Abbreviations

The following abbreviations are used in this manuscript:

EN	European Norm
GDP	Grade determining property (plural: GDPs)
IP	Indicating property (plural: IPs)
JAS	Japanese Agricultural Standard
MOE	Modulus of elasticity

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