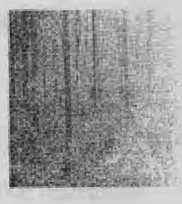
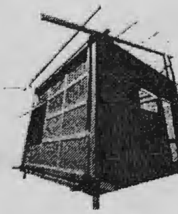
**INTERNATIONAL WORKSHOP ON TIMBER STRUCTURES**

**The Utilization of Low Density Timber As Structural Materials**

# Application of regardless of species conception for mechanical stress grading on tropical timbers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# Application of regardless of species conception for mechanical stress grading on tropical timbers

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**Abstract**. Some reports showed that for single species the relationship between modulus of elasticity (MOE) and modulus of rupture (MOR) in bending was quite high. Tropical timbers consist of hundreds species which were difficult to identify the timber species. This report is dealing with the application of regardless of species conception for mechanical stress grading of tropical timber. Nine timber species or group of species with total number of 1,094 pieces in 60x120x3,000 mm timber were tested in static bending. MOE was measured in flat-wise while MOR was tested in edge-wise. Statistical analysis of linear regression with dummy model and ANCOVA were used to analyze the role of MOE and effect of species on the prediction of MOR. The analysis showed that using MOE as single predictor caused a condition of under/over estimate for one or more species and/or group of species. The percentage of the accuracy of prediction would be increased with species identification. An allowable stress and reference resistance for species and/or group of species were provided to compare with the prediction

of strength through timber grading. The timber strength class for species and/or group of species was also established to support the application of mechanical timber grading.

## Introduction

As a material produced by the nature, wood has a large variation of strength and stiffness properties among species even among pieces in one species. The variations of strength and stiffness are caused by defects or imperfection conditions like knots (numbers, size and location in each piece of timber), slope of grain, and interlocked grain as well. To guarantee the safety of structure, when timber is used for structural purposes, predicting the strength of timber is necessary to be conducted. The strength characteristic of a piece of timber should be evaluated by non-destructive methods. It could be done through visual grading or mechanical grading or combination of such methods. For simplicity and economy, pieces of timber of similar mechanical properties are placed in categories called stress grades[1].

Tropical countries mostly are blessed with the biodiversity of the natural resources which means hundreds or thousands of timber species available for the construction activities. In such cases, the application of visual grading is complicated due to the difficulties of species identification and checking on the imperfection condition. Predicting the strength of wood in full-scale through density is poor in coefficient of determination ($R^2$). A set of study on Norway spruce (*Picea abies*) reported that the $R^2$ value of the relationship between density and bending strength was in the range of 0.16 to 0.40 while the $R^2$ value of the relationship between the density and knots was 0.38. However, the stiffness which is normally expressed as modulus of elasticity (MOE) is by far recognized as the best predictor of strength[2]. The most common method of sorting machine-graded lumber is to measure MOE[1]. The $R^2$ value of the relationship between MOE and bending strength (MOR) of Norway spruce was in the range of 0.51 to 0.72[2,3]. The previous studies on acacia mangium timber showed the $R^2$ value between MOE in flat-wise and MOR was 0.61[4] and for mixed tropical wood of 0.53[5]. Combining MOE with knots and other data gained a quite little improvement of the relationship between MOE and MOR[2].

In the application to the timber grading and strength classes, the strength of a piece of timber regardless of species could be predicted and classified through measuring the MOE. Most species are grouped together and the timber performances from such species are treated similar. With reference to the availability of timber for structural purposes consisting of plenty species in tropical countries, the application of mechanical stress grading needs to be evaluated.

The objective of this study is to figure out the application of mechanical grading to tropical timber which consists of timber from natural forest, timber from plantation forest, hardwood as well as softwood. It is expected that the results could be utilized in timber structure design.

**Materials and methods**

The number of the specimens were 1,094 pieces of tropical wood consisting of the timber from natural forest i.e. Kapur (*Dryobalanops aromatica* Gaertner f.) sp of 60 pieces., a group of meranti or Shorea sp. of 192 pieces, and mixed unknown species namely "borneo" timber of 314 pieces as well as hardwood from plantation forest i.e. Acacia mangium (*Acacia mangium* Willd) of 120 pieces[4)] , falcata (*Paraserianthes falcataria*, L. Nielsen) of 60 pieces, rubber wood (*Hevea brasiliensis*, Willd) of 60 pieces, and maesopsis eminii (*Maesopsis eminii* Engler) of 60 pieces, and softwood from plantation forest, i.e. pinus merkusii (*Pinus merkusii* Junghuhn & de Vriese) of 168 pieces and agathis (*Agathis dammara* Lambert Rich) of 60 pieces. The specimens were in full size of 60 mm x 120 mm x 3,000 (L) mm in air dried. For any piece of lumber, based on the visual grading system of Indonesian Standard for Construction Timber (SNI 03-3527)[6)], the imperfection condition was evaluated. Only timber which classified as timber for building construction was used as specimens.

The MOE in flat-wise with center point loading was measured using a simple operated machine with a deflectometer which can magnify the reading to about 40 times. Before measuring the MOE in flat-wise the machine was calibrated based on a recognized dial gauge. Then the specimens were tested in flexural bending at third point loading in edge wise with a universal testing machine of a capacity of 100 tons following the procedure of ASTM D 198[7]. Based on the moisture content and loading system, adjusting factor had been applied to the MOE and MOR calculation based on the equilibrium moisture content in Indonesia of 15 % and ASTM 2915 procedure[8].

Regression analysis was used for analyzing the relationship between MOE in flat-wise and MOR of the timber. Based on the regression analysis, the allowable stress for the tropical wood and the stress classification were established. The effect of timber species on the MOR of timber will be analyzed using analysis of covariance (ANCOVA) with MOE as the covariate variable and the model as shown in equation (1):

$$Y_{ij} = \mu + \tau_i + \beta(X_{ij} - \bar{X}) + \varepsilon_{ij} \quad \ldots\ldots\ldots\ldots \quad (1)$$

where : $Y_{ij}$, measured MOR of species $i^{th}$ and sample number $j^{th}$ ; $\mu$, average MOR; $\tau_i$ additive effect of species; $\beta$, regression coefficient which expresses the dependency of MOR to MOE; $X_{ij}$, measured MOE; $\bar{X}$, average MOE, $\varepsilon_{ij}$, error of sample number $j^{th}$ of species number $i^{th}$.

Ho : $\tau_i = 0$, there is no significant effect of species or group of species to MOR

$H_1$ : $\tau_i \neq 0$, at least there is a species provide a significantly different MOR value than others.

The hypothetical test conducted through an F test.

The prediction of strength characteristic of the timber was analyzed through a model as equation (2):

$$Y_{ij} = z_{ij} a_i + f(X_{ij}) + \varepsilon_{ij} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where: $Y_{ij}$, measured MOR of species number $i^{th}$ and sample number $j^{th}$ ; $z_{ij}$ dummy variable of species number $i^{th}$ , $a_i$ constant of dummy variable; $f(X_{ij})$ function of the relationship between MOR and MOE; $\varepsilon_{ij}$ error of of sample number $j^{th}$ of species number $i^{th}$. Two hypotheses were used as:

1) Ho : $\beta_1 = \beta_2 = \beta_3 \ldots = \beta_k = 0$, species and MOE provide no significant effect to MOR

$H_1$ : $\exists\, \beta_k \neq 0$, at least one species and/or MOE provide significant effect to MOR

2) Ho : species provide no significantly effect on MOR when MOE was included in the analytical model

$H_1$ : at least one species provide significantly effect on MOR when MOE was included in the analytical model.

Strength characteristic based on the allowable stress design (ASD) and load and resistance factor design (LRFD) were established following the ASTM D 2915 and ASTM D 5457[9], respectively.

**Result and discussion**

Modulus of elasticity and bending strength performance of the timber

The MOE and MOR of timber are the two parameters usually used in the evaluation of the bending performance of timber in structural size. The MOE and MOR of timber may vary among the species, trees, logs even among sawn timber of one log[10]. The variations of strength and stiffness are caused by density and imperfection conditions i.e. knots, slope of grain, and interlocked grain as well.

The lowest value of the MOE of the timber was 4.1 GPa of the acaia mangium from the plantation forest and the highest was 28.5 GPa of mixed unknown timber from the natural forest as shown in Table 1. The weakest value of MOR was 10.8 MPa of agathis from plantation forest and the strongest was 134.3 MPa of shorea sp. from natural forest. Generally, the range of MOE and MOR values of timber from natural forest is wider than those of timber from plantation forest. The wider range of such values of timber from natural forest than those of timber from plantation forest may be affected by the cultivation system. Shorea sp. is a group of species as well as the mixed unknown tropical wood which commonly mentioned as "borneo timber". It could be understandable that the range of MOE and MOR of mixed tropical timber is wider than those of timber from plantation forest which the trees were cultivated well and homogenous.

Parametric distributions namely normal, log-normal and Weibull distributions had been applied to evaluate the distribution. Based on the frequency analysis, the apparent distribution was also analyzed to get the good of fitness of the parametric distributions i.e., the normal distribution, the log-normal distribution and the cumulative Weibull distribution[11]. It is not easy to recognize the fit parametric distributions to the actual frequency plots of the timber generalized for all the timber. Some species have a high goodness of fit to the normal distribution, some to the log-normal and others to Weibull distribution as shown in Table 2. The parametric distribution and actual frequency of the MOE and MOR of the tropical timber could be shown in Figs. 1 and 2. Selecting the best fit distribution for the actual frequency values is important especially for the lower tail values in the establishment of allowable MOE and MOR. In ASTM D 5457, the distribution of timber is determined as Weibull distribution while European standard tends to determine in log-normal distribution[12]. With reference to Fig. 1, for the lower tail values, the log-normal and Weibull distributions provide the better fit than the normal distribution, but for the other plots the log-normal distribution seems better than Weibull distribution.

For each species or group of species, the mean and the standard deviation of log-normal distribution, the shape and scale parameter of Weibull distribution as well as the fifth percentile limit have been calculated and presented in Table 3. An observation to the lower tail of the distribution is important in order to reduce error in the establishment of allowable stress. Although from the goodness of fit of the parametric distributions to the actual frequency of MOE and MOR of the timber could not be specified as shown in Table 2 and Figs. 1 and 2, the difference of the fifth percentile limit of both of log-normal and Weibull distributions were relatively small as shown in Table 3. As described above, the fifth percentile limit of the MOE and MOR of timber from natural forest was also higher than planted timber. The MOE of planted softwood was higher than planted hardwood, vise versa, the strength of planted hardwood was higher than that of planted softwood. It might be affected by the difference characteristic of the timbers. Two distinct conditions might be affected the MOE and MOR are the presence of tracheid in softwood and vessels in hardwoods and the different formations of knots in both[12].

The establishment of allowable stress and reference resistance in LRFD of species or group of species

The basic concept of ASD is the working stress in the member of structure should be lower or the same as the product of allowable stress of the member and corresponding duration of loading[9]. The allowable stress is the strength characteristic with the reduction of safety factor. For example, in

Indonesia as well as in USA the safety factor of bending strength is 1/2.1[8,13]. Based on ASTM[8] and European Standards[14], the strength characteristic of the timber is the fifth exclusion limit ($R_{005}$) of the population distribution. The strength characteristic of timber is analyzed using parametric and/or nonparametric procedures[8].

As mentioned above that the distributions of the timber could not easily been distinguished clearly. For parametric procedures, the allowable strength of timber species and group of species could be obtained from Table 3 with the reference to Table 2 for the goodness of fit. There are two statistical ways for non-parametric procedure i.e. non parametric point estimate (NPE) based on interpolated data and non parametric lower tolerance limit (NTL) based on order statistic. The width of the confidence interval is sufficiently small fraction of the mean with the values in the range of 0.016 to 0.067. In such condition, the allowable value of modulus of elasticity is the mean of MOE as shown in Table 1[8].

Through parametric and non parametric procedures with the condition as mentioned above and considering the safety factor of bending in 10 years loading was 2.1[8,13], the strength characteristic and allowable strength is presented in Table 4. With the sufficiently small values of the relative difference between NPE and NTL, the value of NPE as shown in Table 4 is the allowable stress for bending[8]. The allowable stress of any species or group species could also be established through parametric procedures with the small difference value between parametric point estimate (PPE) and NPE or NTL.

The reference resistance for LRFD of the timber was calculated based on the format conversion and reliability normalization factor as mentioned in ASTM D 5457. Format conversion used the ASD load duration adjustment factor of 1.15, LRFD time effect factor of 0.80 and specified LRFD factor for bending 0.85[8]. The calculation based on reliability normalization factor was conducted using an assumption that the distribution was in Weibull distribution although the goodness of fit of the Weibull distribution for some species or group of species were lower than 100% as shown in Table 2. In reliability normalization factor procedure, sample size and coefficient of variations are the decisive factors.

The reference resistance of a species or group of species which was established through format conversion seemed higher than the one through reliability normalization as shown in Table 5. When the coefficient of variation of the strength of a species is relatively high, the reference resistance based on the reliability normalization would extremely lower than the one of format conversion due the reverse position of the coefficient of variation in reliability normalization equation. Such phenomena indicate that the application of LRFD based on the reliability normalization factor for tropical timbers need more studies.

With reference to Tables 1, 4 and 5, the application of allowable stress and reference resistance for species and/or group of species will be very safe but inefficient use of the timber due to the use of fifth percentile of the distributions and/or statistical non parametric values as the predicted values.

Application grading with regardless of species conception for the tropical timber

Some difficulties appeared when applying the visual grading to the tropical timber due to the variety of timber species with their embedded characteristics. Shorea sp. consists of 194 species of which 163 species were found in Melanesia[15]. It was also reported that from 400 pieces of mixed tropical timber namely "Borneo", 23 species were found with a wide range of density and strength of the timber[5]. Visual grading for predicting the strength through the evaluation of imperfection condition, being expressed as the "strength ratio" of clear straight grain small specimen of a species, is difficult to apply to the tropical species in such conditions.

The MOE is by far the best predictor of MOR[2]. Some studies on single species reported relatively high relationship between MOE and MOR of the timber[2,3,4,5]. Table 6 shows the relationship between MOE in flat-wise and strength of the timber of some species and group of species. The coefficient of determination ($R^2$) of the relationship between MOE and MOR of the known single species was in the range of 0.60 to 0.71, but it was lower for the mixed species. When all of the specimens were taken into account, the $R^2$ value was 0.55 as shown in Fig. 3. The $R^2$ value of softwood which was represented by pinus merkusii and agathis was 0.36. Although the value was quite small, it was better than combining the data of pinus merkusii with falcata of which the mean value of the strength was similar to those of acacia mangium, rubber wood, and maesopsis eminii from the hardwood. The $R^2$ value of the relationship between MOE and MOR of such combination was below 0.30.

Since the $R^2$ value of MOE and MOR of all timber specimens in this experiment was 0.55, MOE is a good predictor of MOR but the application of using MOE as a single variable would become the over/under estimation of MOR, at least for one species as expressed by the high value of F calculated and a very small significant value. The hypothesis that at least there is a species providing a significantly different MOR value than others could be accepted. The fact that there is at least one species providing significantly different MOR endorsed that the identification of the timber species will improve the prediction of MOR through MOE from 74.2 % ($R^2$=0.55) to the range of 77.5%( $R^2$ =0.60) to 84.3% ($R^2$=0.71).

The prediction equation of MOR based on MOE was obtained through the regression dummy analysis with matrices variables for species and/or group of species. It was found that species and group of species and/or MOE gave a significant effect on the MOR with the high F calculated value and very small significant value. The hypothesis that at least one species and/or MOE provide significant effect on the MOR is accepted. The regression line of the species and group of species is shown in Table 7 and Fig. 4. Using the MOE as the strength predictor with a conception of regardless of species will be over estimate for softwood especially pinus merkusii as shown in Fig. 4.

Although the timber from natural forest is still dominant in the timber construction industries in some tropical areas, the promotion of the utilization of planted timber especially fast growing species have been disseminated since some decades ago. As the selection cutting policy has been applied in early 1980s, the availability of some selected species for timber construction has been decreased into less quantity. In many cases, rough visual grading and small clear specimen test results have been applied for predicting the strength of the timber. For the unknown species from natural forest, it is classified as a second class timber although it covers a wide range of strength[5]. The utilization of timber from fast growing trees has not been popular yet due to the opinions on such timber as a low grade for the construction. With such background, the application of mechanical timber stress grading to the tropical planted timber based on MOE with regard and/or regardless of species is very important.

The establishment of timber strength classes

Although the regression line of agathis is close to hardwood as shown in Fig. 4 and Table 7, there is a tendency for the MOE to predict lower MOR than those of hardwood. With a consideration that pinus merkusii and agathis would be over estimated, the timber strength classes regardless of species was established only for hardwood with the regression line and the 5% exclusion limit as shown in Fig. 5. Exclusion of the values of softwood from the equation as shown in Fig. 3 increased the relationship of MOE and MOR to 0.64 as shown in Fig. 5. The strength classes of timber were derived based on 5 % EL ($R_{005}$) of ASD and LRFD as shown in Table 8. The reference resistance was estimated through format conversion with load adjustment factor of 1.15, a LRFD time factor of 0.80 and ratio of live to dead load effects of 3, and specified LRFD resistance factor for bending of 0.85.

The proposed strength classes of the timber provides a wider strength classes than common grades for machine-graded lumber established by American Forest Product Society[1] and Japanese standard for timber structures[16]. The upper parts of the proposed strength classes are occupied by the hardwood from natural forest which usually being cut over 35 years while the planted hardwood mostly between 10 to 25 years depending on the species and the purpose of the plantation. With reference to the Tables 4 and 5, the allowable stiffness and strength properties of planted hardwood timber are almost similar to those of softwood in subtropical area[1,16].

In practical application, timber identification is uneasy to be done especially for mixed tropical wood and shorea sp which consists of hundreds species so that the timber strength classes with regardless of species conception should be applied. When the timber species is not well recognized by the designers, the timber strength classes for regardless of species as shown in Table 8 should be applied due to its more conservative than the strength classes specific for species as shown in Table 9. With the various species in the group, the timber strength classes of group of species namely borneo and shorea sp was not provided. In the design, the timber strength classes for regardless of species as mentioned above and showed in Table 8 should be applied for such group of species.

## Conclusion

Timber is a building material produced by the nature with the embedded properties from the tree and during production process. The MOE and MOR of timber were in wide range and the distributions of the performances were not clearly recognized fit to one parametric distribution i.e. normal, log-normal or Weibull distribution. The allowable stress for timber produced inefficient of prediction. To utilize timber for structural material effectively, timber grading could be applied visually and/or mechanically. With various timber species available and technical difficulties for applying visual grading, the mechanical grading with MOE as the predictor has been studied with regard and regardless of species.

The ANCOVA statistical analysis showed that using MOE as a single variable for predicting MOR caused a condition of under/over estimate for one or more species and/or group of species. The percentage of the accuracy of prediction would be increased with species identification. The analysis model with regression dummy found that at least one or more species gave a significant effect on MOR. It was also found that pinus merkusii as tropical softwood produced a significant different MOR in the same MOE to other timber.

The hardwood timber strength classes had been proposed to support the application of mechanical timber stress grading. To anticipate the application of LRFD concept in global development, a reference resistance based on the stress graded timber has also been established through more research studies in strength characteristic of tropical timber.

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**List of literatures**

1. Kretschmann DE, Green DW (1999) Lumber stress grades and design properties. Wood handbook: wood as an engineering materials, chapter 6, pp 6-1 – 6-14.

2. Johanson CJ (2002) Grading of timber with respect to mechanical properties. Timber engineering, chapter 3, p 23-43, Wiley.

3. Steffen A, Johansson CJ, Wormuth EW (1997) Study in the relationship between flat-wise and edge-wise moduli of elasticity of sawn timber as a means to improve mechanical strength grading technology, Holz als Roh-und Werksoff 55:245-253

4. Firmanti A, Surjokusumo S, Komatsu K, Kawai S (2004) The establishment of strength characteristic of fast growing acacia mangium timber for structural materials, submitted paper.

5. Firmanti, Anita . 1996. Basic concept of timber grading in Indonesia. Journal Masalah Bangunan. Vol. 346. RIHS. Bandung. Indonesia.

6. Indonesian Standardization Board (1994) Standard quality of timber for building structure, SNI 03-3527-2, Jakarta, in Indonesian.

7. ASTM Standard D 198-1999 (2000) Standard test methods of static tests of lumber in structural sizes, Vol. 04.10. Wood, Philadelphia

8. ASTM Standard D 2915-1997 (2000); Evaluating allowable properties for grades of structural timber. Vol.

04.10. Wood, Philadelphia

9. ASTM Standard D-5457. 1997; Standard specification for computing reference resistance of wood based materials and structural connections for load and resistance factor design. Vol. 04:10, Wood, Philadelphia

10. Gloss P (1993) Strength grading. STEP EUROFORTECH lecture, 6 A6:1-8

11. Horie K (1997) The statistical and probability method of timber strength data, Timber Engineering Institute Co. Ltd. Sunagawa-Hokaido Japan. In Japanese.

12. Brown HP, Panshin AJ, Forsaith CC (1949) Text book of wood technology, Structure, identification, defects, and uses of the commercial woods of the United States, Vol. I, p 111 – 285. McGraw-Hill Book Company, Inc. New York, Toronto, London.

13. Indonesian Standard Board (2002) Code of practice for timber construction, SNI 03-3974, Jakarta, in Indonesian

14. European Committee for Standardization. 1995. EN 384: Structural timber - determination of characteristic value of mechanical properties and density. Brussels, Belgium, 13p

15. Soerianegara I, Lemmens RHMJ (1993) Timber trees : major commercial timbers, p 391 – 434, Pudoc Scientific Publishers, Wageningen.

16. Japan Institute of Architecture (2002) Standard for structural design of timber structures, p 335-337.

17. Lawless JF (1982) Statistical models and methods for lifetime data. Wiley series in probability and

mathematical statistic. John Wiley and Sons Ltd.

18. Gomez KA, Gomez AA (1984) Statistical procedure for agricultural research, John Wiley and Sons Ltd

Table 1. MOE and MOR performance of the tested timber

| Species or group of species name | MOE (GPa) | | | | MOR (MPa) | | | |
|---|---|---|---|---|---|---|---|---|
| | Min. | Max. | Mean. | SD | Min. | Max. | Mean | SD |
| Hardwood from natural forest | 5.3 | 28.5 | 15.1 | 4.1 | 13.8 | 134.3 | 59.8 | 20.3 |
| - Borneo timber | 8.3 | 28.5 | 15.3 | 4.1 | 30.0 | 108.0 | 62.8 | 15.4 |
| - Shorea sp | 5.3 | 25.9 | 14.9 | 3.9 | 13.8 | 134.3 | 55.1 | 26.1 |
| - Kapur | 8.4 | 28.3 | 14.2 | 4.7 | 23.0 | 107.6 | 56.1 | 22.2 |
| Planted fast growing hardwood | 4.1 | 22.1 | 9.8 | 2.9 | 11.6 | 92.0 | 41.6 | 13.1 |
| - Acacia mangium | 4.1 | 15.8 | 8.9 | 2.6 | 11.6 | 92.0 | 42.2 | 15.8 |
| - Falcata | 6.2 | 13.0 | 8.7 | 1.4 | 15.3 | 48.0 | 32.7 | 8.1 |
| - Rubber wood | 6.3 | 17.6 | 10.6 | 3.0 | 29.4 | 56.7 | 43.9 | 7.9 |
| - Maesopsis eminii | 5.5 | 22.1 | 12.0 | 3.4 | 28.5 | 70.8 | 45.8 | 10.2 |
| Total hardwood | 4.1 | 28.5 | 13.6 | 4.5 | 11.6 | 134.3 | 54.7 | 20.1 |
| Planted fast growing softwood | 5.6 | 21.7 | 12.6 | 3.3 | 10.8 | 67.2 | 37.1 | 11.8 |
| - Pinus merkusii | 5.6 | 21.7 | 12.9 | 3.6 | 15.4 | 55.9 | 34.2 | 8.6 |
| - Agathis | 7.6 | 16.6 | 12.0 | 2.3 | 10.8 | 67.2 | 44.6 | 12.3 |
| Tropical timber (total) | 4.1 | 28.5 | 13.3 | 4.3 | 10.8 | 134.3 | 50.6 | 20.0 |

Remarks: MOE, modulus of elasticity in bending: MOR, modulus of rupture in bending

Table 2. Goodness of fit of parametric distribution to the plots of tropical timber

| Species or group of species name | MOE (GPa) | | | MOR (MPa) | | |
|---|---|---|---|---|---|---|
| | Normal | Log-normal | Weibull | Normal | Log-normal | Weibull |
| Timber from natural forest | 67 | 100 | 47 | 84 | 68 | 100 |
| - Borneo timber | 69 | 100 | 56 | 100 | 51 | 56 |
| - Shorea sp | 100 | 79 | 92 | 55 | 100 | 73 |
| - Kapur | 60 | 100 | 50 | 71 | 100 | 72 |
| Planted fast growing hardwood | 85 | 85 | 100 | 97 | 100 | 98 |
| - Acacia mangium | 100 | 100 | 71 | 65 | 100 | 69 |
| - Falcata | 85 | 80 | 100 | 100 | 86 | 100 |
| - Rubber wood | 65 | 100 | 56 | 95 | 100 | 86 |
| - Maesopsis eminii | 69 | 100 | 55 | 88 | 100 | 82 |
| Hardwood | 84 | 99 | 100 | 90 | 100 | 100 |
| Planted fast growing softwood | 100 | 87 | 75 | 66 | 100 | 60 |
| - Pinus merkusii | 100 | 91 | 87 | 91 | 100 | 73 |
| - Agathis | 94 | 83 | 100 | 100 | 82 | 90 |
| Tropical timber (total) | 91 | 96 | 86 | 73 | 100 | 86 |

Remarks: MOE. modulus of elasticity in bending: MOR. modulus of rupture in bending

Table 3. The parameters of parametric distribution and their fifth percentile limit

| Species or group of species name | Modulus of elasticity (GPa) | | | | | | Modulus of rupture (MPa) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Log-normal dist. | | | Weibull dist. | | | Log-normal dist. | | | Weibull dist. | | |
| | $\lambda$ | $\xi$ | $R_{0.05}$ | $\eta$ | $\alpha$ | $R_{0.05}$ | $\lambda$ | $\xi$ | $R_{0.05}$ | $\eta$ | $\alpha$ | $R_{0.05}$ |
| Timber from natural forest | 2.68 | 0.26 | 9.1 | 16.5 | 4.5 | 9.3 | 4.04 | 0.33 | 29.8 | 66.6 | 3.4 | 26.5 |
| -Borneo timber | 2.69 | 0.26 | 9.4 | 16.8 | 4.6 | 9.6 | 4.11 | 0.24 | 39.4 | 68.5 | 4.9 | 38.7 |
| -Shorea sp | 2.67 | 0.26 | 8.8 | 16.3 | 4.4 | 8.5 | 3.91 | 0.45 | 20.7 | 62.2 | 2.5 | 20.6 |
| -Kapur sp | 2.60 | 0.32 | 7.8 | 15.7 | 3.8 | 8.5 | 3.95 | 0.38 | 26.6 | 62.7 | 3.0 | 28.8 |
| Planted fast growing hardwood | 2.24 | 0.30 | 5.7 | 10.8 | 4.1 | 5.3 | 3.68 | 0.31 | 22.4 | 46.2 | 3.6 | 21.3 |
| -Acacia mangium | 2.15 | 0.28 | 5.1 | 9.8 | 4.2 | 4.9 | 3.68 | 0.36 | 19.6 | 47.2 | 3.1 | 16.3 |
| -Falcata | 2.16 | 0.16 | 6.5 | 9.4 | 6.8 | 6.6 | 3.46 | 0.24 | 19.5 | 36.0 | 4.2 | 17.9 |
| -Rubber wood | 2.32 | 0.27 | 6.2 | 11.6 | 4.3 | 6.0 | 3.77 | 0.18 | 30.9 | 47.1 | 6.4 | 31.2 |
| -Maesopsis eminii | 2.45 | 0.37 | 7.2 | 13.2 | 4.4 | 7.7 | 3.80 | 0.22 | 30.0 | 49.5 | 5.3 | 30.5 |
| Hardwood | 2.56 | 0.33 | 7.2 | 15.1 | 3.6 | 7.0 | 3.94 | 0.36 | 26.3 | 61.1 | 3.2 | 24.2 |
| Planted fast growing softwood | 2.51 | 0.25 | 7.8 | 13.8 | 4.7 | 7.6 | 3.56 | 0.31 | 19.8 | 41.1 | 3.7 | 19.6 |
| -Pinus merkusii | 2.52 | 0.27 | 7.6 | 14.2 | 4.3 | 7.3 | 3.50 | 0.25 | 21.2 | 37.4 | 4.7 | 21.3 |
| -Agathis | 2.47 | 0.19 | 8.4 | 12.9 | 6.2 | 8.4 | 3.74 | 0.33 | 18.7 | 50.1 | 2.7 | 14.2 |
| Tropical timber (total) | 2.54 | 0.32 | 7.2 | 14.7 | 3.8 | 7.1 | 3.85 | 0.38 | 23.5 | 56.6 | 3.1 | 22.8 |

Remark : MOE, modulus of elasticity; MOR, modulus of rupture; $\mu$, mean of normal distribution; $\sigma$, standard deviation; $\lambda$, mean of log-normal distribution; $\xi$, standard deviation of log-normal distribution; $\eta$, scale parameter of Weibull distribution; m, shape parameter of Weibull distribution

Table 4. The allowable bending stress (in MPa) for ASD

| Species or group of species | Parametric (distribution) | | Nonparametric | | |
|---|---|---|---|---|---|
| | 5%PE Weibull | 5%PE Log-Normal | 5%PE | 5%TL | δ |
| Timber from natural forest | 12.62 | 14.19 | 13.09 | 12.62 | 0.036 |
| - Borneo timber | 18.43 | 18.76 | 19.48 | 18.10 | 0.071 |
| -Shorea | 9.81 | 9.86 | 9.90 | 9.48 | 0.042 |
| -Kapur | 13.71 | 12.67 | 14.75 | 14.52 | 0.015 |
| Planted hardwood | 10.14 | 10.67 | 10.71 | 10.38 | 0.032 |
| -Acacia mangium | 7.76 | 9.33 | 8.57 | 7.86 | 0.083 |
| -Falcata | 8.52 | 9.29 | 8.43 | 8.19 | 0.030 |
| -Rubber wood | 14.86 | 14.71 | 15.26 | 15.10 | 0.010 |
| -Maesopsis eminii | 14.52 | 14.29 | 14.86 | 14.43 | 0.028 |
| Hardwood | 11.52 | 12.52 | 11.62 | 11.48 | 0.011 |
| Softwood | 9.33 | 9.43 | 9.29 | 8.95 | 0.028 |
| -Pinus merkusii | 10.14 | 10.10 | 10.38 | 10.14 | 0.022 |
| -Agathis | 6.76 | 8.90 | 7.04 | 6.62 | 0.061 |
| Topical timber (total) | 10.86 | 11.19 | 10.91 | 10.76 | 0.014 |

Remarks: ASD. Allowable stress design; PE. point estimate; TL. tolerance limit; δ. relative difference between NPE and NTL which was express as (NPE-NTL)/NPE; the bold numbers should be the allowable stress values.

Table 5. Reference resistance of the bending strength (in MPa) of timber for LRFD based on ASTM D 5457

| Species or group of species | Format conversion | | | | Reliability normalization |
|---|---|---|---|---|---|
| | Parametric | | Nonparametric | | |
| | 5%PE Weibull | 5%PE Log-Normal | 5%PE | 5%TL | |
| Timber from natural forest | 32.05 | 36.04 | 33.25 | 32.05 | 26.71 |
| - Borneo timber | 46.81 | 47.65 | 49.48 | 45.97 | 41.95 |
| -Shorea | 24.92 | 25.04 | 25.15 | 24.08 | 16.83 |
| -Kapur | 34.82 | 32.18 | 37.47 | 36.88 | 20.70 |
| Planted hardwood | 25.76 | 27.10 | 27.20 | 26.37 | 18.98 |
| -Acacia mangium | 19.71 | 23.70 | 21.77 | 19.96 | 16.60 |
| -Faicata | 21.64 | 23.60 | 21.41 | 20.80 | 17.19 |
| -Rubber wood | 37.74 | 37.36 | 38.76 | 38.35 | 33.51 |
| -Maesopsis eminii | 36.88 | 36.30 | 37.74 | 36.65 | 29.99 |
| Hardwood | 29.26 | 31.80 | 29.51 | 29.16 | 23.41 |
| Softwood | 23.70 | 23.95 | 23.60 | 22.73 | 17.36 |
| -Pinus merkusii | 25.76 | 25.65 | 26.37 | 25.76 | 22.18 |
| -Agathis | 17.17 | 22.61 | 17.80 | 16.81 | 14.27 |
| Tropical timber (total) | 27.58 | 28.42 | 27.71 | 27.33 | 20.93 |

able 6. The coefficient of determination of the relationship between MOE and MOR

| pecies or group of species name | Number of samples | Coefficient of determination ($R^2$) |
|---|---|---|
| mber from natural forest | 566 | 0.56 |
| Borneo timber | 314 | 0.53 |
| Shorea | 192 | 0.64 |
| Kapur | 60 | 0.71 |
| anted hardwood | 300 | 0.57 |
| Acacia mangium | 120 | 0.71 |
| Falcata | 60 | 0.63 |
| Rubber wood | 60 | 0.61 |
| Maesopsis eminii | 60 | 0.64 |
| nted softwood | 228 | 0.36 |
| Pinus merkusii | 168 | 0.60 |
| Agathis | 60 | 0.68 |

narks: MOE, modulus of elasticity in bending; MOR, modulus of rupture in bending

Table 7. The equation of predicted MOR based on MOE of the timber species

| Species of group of group of species | Regression line |
|---|---|
| Borneo | MOR = 10.67 + 3.11 MOE |
| Shorea | MOR = 4.41 + 3.11 MOE |
| Kapur | MOR = 7.64 + 3.11 MOE |
| Acacia mangium | MOR = 11.86 + 3.11 MOE |
| Falcata | MOR = 2.86 + 3.11 MOE |
| Rubber wood | MOR = 7.54 + 3.11 MOE |
| Maesopsis eminii | MOR = 4.76 + 3.11 MOE |
| Pinus merkusii | MOR = - 9.69 + 3.11 MOE |
| Agathis | MOR = 3. 87 + 3.11 MOE |

Remarks: MOE. modulus of elasticity in bending in GPa: MOR. modulus of rupture in bending in MPa e 8. The timber strength classes for ASD and LRFD based on the mechanical stress grading

ropical hardwood timber regardless of species.

| Grade | MOE (GPa) | Allowable stress (MPa) | Reference resistance (MPa) |
|---|---|---|---|
| E 255 | 25.5 | 37.3 | 94.8 |
| E 240 | 24.0 | 34.1 | 86.7 |
| E 225 | 22.5 | 32.2 | 81.8 |
| E 210 | 21.0 | 30.0 | 76.2 |
| E 195 | 19.5 | 27.4 | 69.6 |
| E 180 | 18.0 | 25.2 | 64.1 |
| E 165 | 16.5 | 22.8 | 57.9 |
| E 150 | 15.0 | 20.3 | 51.7 |
| E 135 | 13.5 | 17.9 | 45.5 |
| E 120 | 12.0 | 15.5 | 39.3 |
| E 105 | 10.5 | 13.0 | 33.1 |
| 0 | 9.0 | 10.6 | 26.9 |
| 5 | 7.5 | 8.2 | 20.7 |
| 0 | 6.0 | 5.7 | 14.5 |

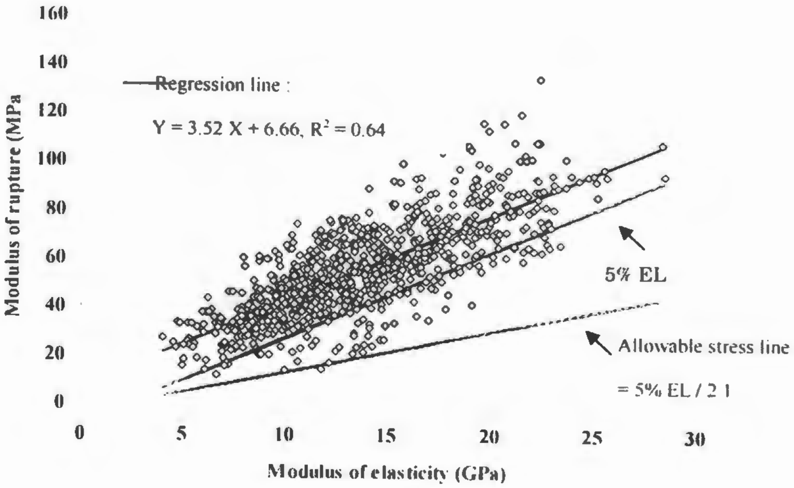
rks: ASD. allowable stress design; LRFD. load and resistance factor design; MOE. modulus of elasticity.

e 9. The timber strength classes for ASD and LFRD based on mechanical stress grading of

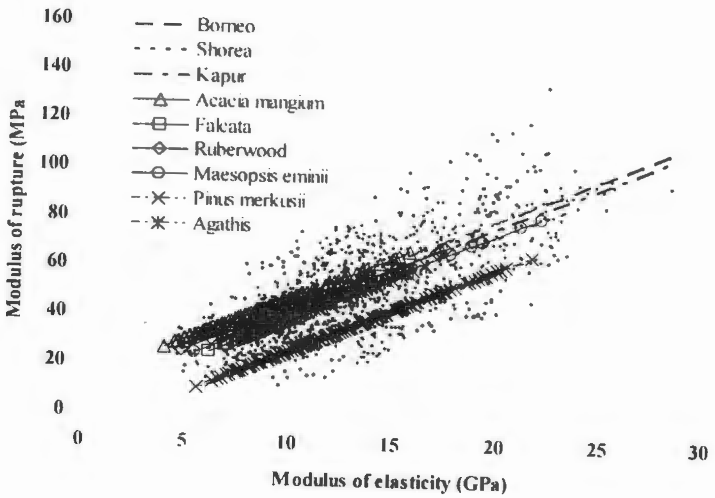
e tropical timber species

| Species name | Grade | MOE (GPa) | Allowable stress (MPa) | Reference resistance (MPa) |
|---|---|---|---|---|
| ır | E 225 | 22.5 | 32.2 | 81.7 |
| | E 210 | 21.0 | 29.7 | 75.5 |
| | E 195 | 19.5 | 27.3 | 69.4 |
| | E 180 | 18.0 | 24.9 | 63.2 |
| | E 165 | 16.5 | 22.4 | 57.0 |
| | E150 | 15.0 | 20.0 | 50.8 |
| | E 135 | 13.5 | 17.5 | 44.6 |
| | E120 | 12.0 | 15.2 | 38.4 |
| cia mangium | E 150 | 15.0 | 25.2 | 63.9 |
| | E 135 | 13.5 | 22.7 | 57.7 |
| | E 120 | 12.0 | 20.3 | 51.5 |
| | E 115 | 10.5 | 17.8 | 45.4 |
| | E 90 | 9.0 | 15.4 | 39.2 |
| | E 75 | 7.5 | 13.0 | 33.0 |
| | E 60 | 6.0 | 10.5 | 26.8 |
| ata | E 150 | 15.0 | 22.2 | 56.3 |
| | E 135 | 13.5 | 19.7 | 50.2 |
| | E 120 | 12.0 | 17.3 | 43.9 |
| | E 105 | 10.5 | 14.9 | 37.8 |
| | E 90 | 9.0 | 12.4 | 31.6 |
| ber wood | E 165 | 16.5 | 26.6 | 67.7 |
| | E 150 | 15.0 | 24.2 | 61.5 |
| | E135 | 13.5 | 21.8 | 55.3 |
| | E120 | 12.0 | 19.3 | 49.1 |
| | E105 | 10.5 | 16.9 | 43.0 |
| | E 90 | 9.0 | 14.5 | 36.8 |
| sopsis eminii | E 210 | 21.0 | 31.8 | 80.7 |
| | E 195 | 19.5 | 29.3 | 74.5 |
| | E 180 | 18.0 | 26.9 | 68.3 |
| | E 165 | 16.5 | 24.5 | 62.2 |
| | E 150 | 15.0 | 22.0 | 56.0 |
| | E 135 | 13.5 | 19.6 | 49.8 |
| | E 120 | 12.0 | 17.2 | 43.6 |
| | E 105 | 10.5 | 14.7 | 37.4 |

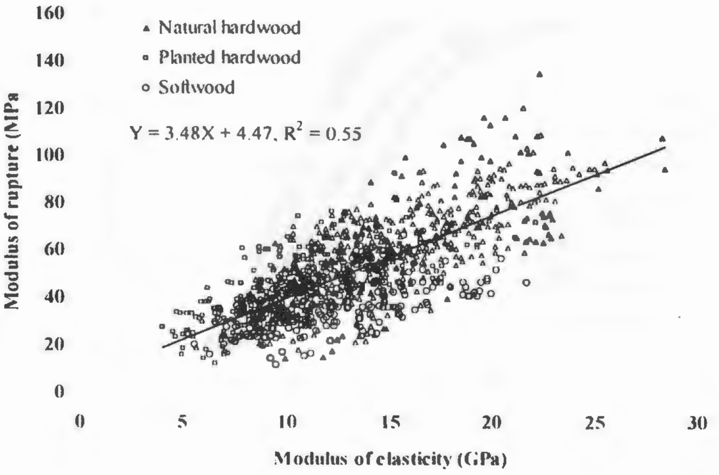
rks: ASD, allowable stress design; LRFD, load and resistance factor design; MOE, modulus of elasticity.

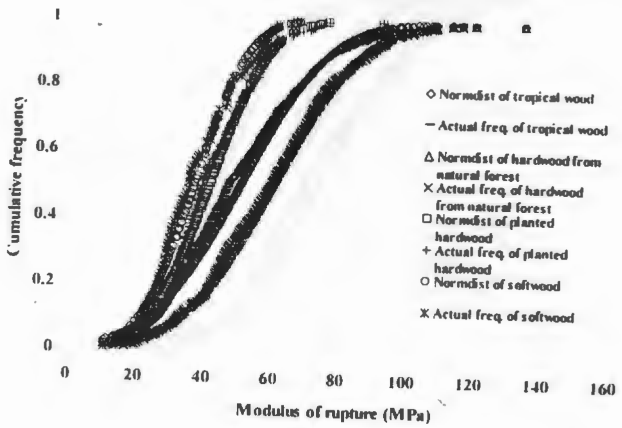


160
140
120
100
80
60
40
20
0
Modulus of rupture (MPa
Regression line :
Y = 3.52 X + 6.66, R² = 0.64
5% EL
Allowable stress line
= 5% EL / 2.1
0
5
10
15
20
25
30
Modulus of elasticity (GPa)

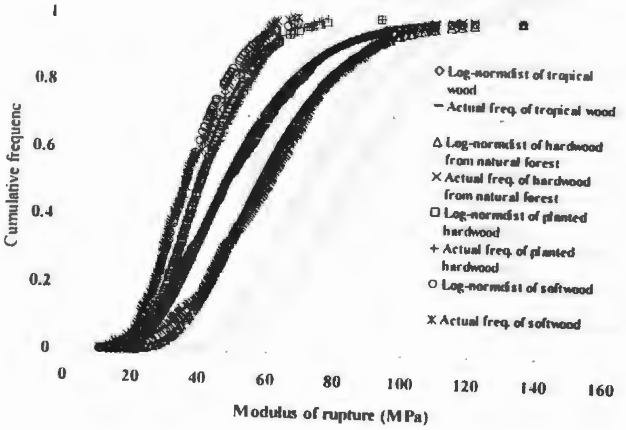


160
140
120
100
80
60
40
20
0
Modulus of rupture (MPa
0
5
10
15
20
25
30
Modulus of elasticity (GPa)
Borneo
Shorea
Kapur
Acacia mangium
Falcata
Ruberwood
Maesopsis eminii
Pinus merkusii
Agathis

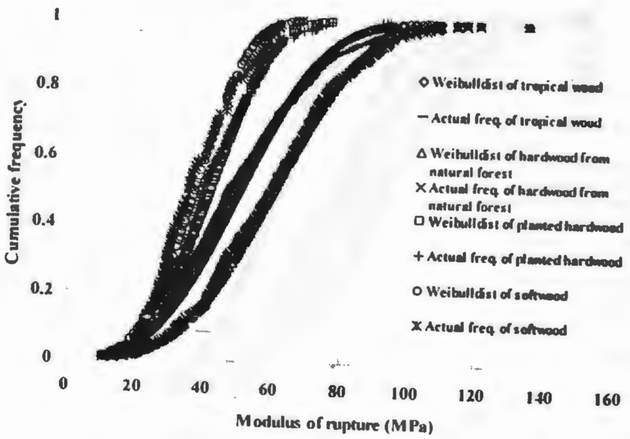

Natural hardwood
Planted hardwood
Softwood
Y = 3.48X + 4.47, R² = 0.55
Modulus of rupture (MPa
160
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
Modulus of elasticity (GPa)



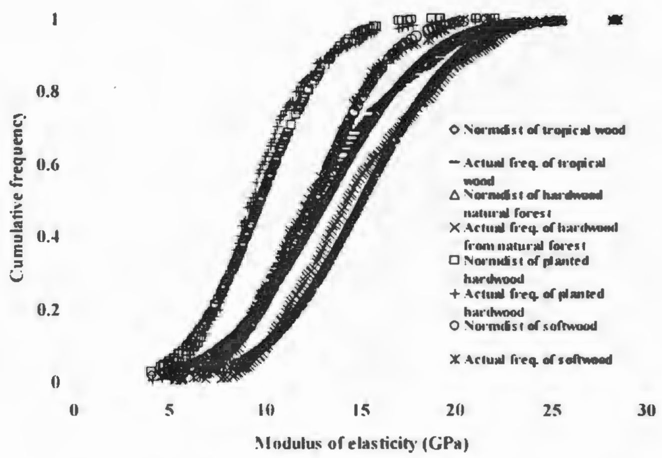

Normal distribution and actual frequency of tested timber



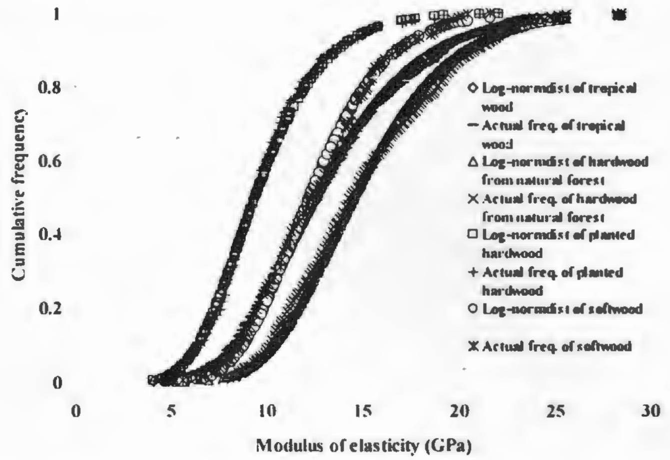

Log-normal distribution and actual frequency of tested timber



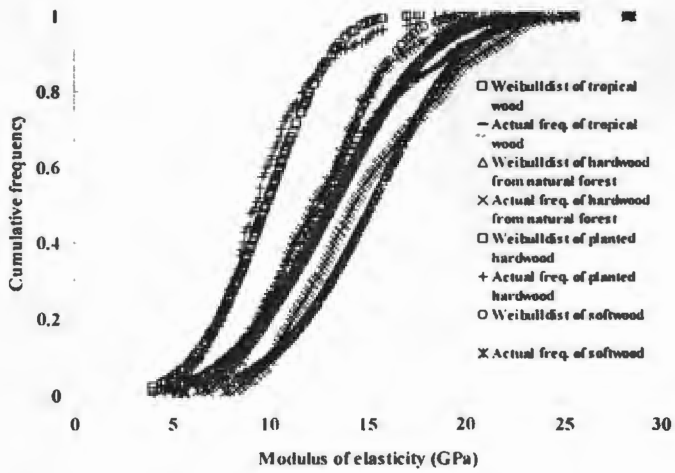

Weibull distribution and actual frequency of tested timber




Normal distribution and actual frequency of tested timber




Log-normal distribution and actual frequency of tested timber




Weibull distribution and actual frequency of tested timber