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ORIGINAL ARTICLE

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The critical stress in various stress levels of bending member on fire exposure for mechanical graded lumber

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Abstract This study focused on the relationship between stress level and the fire resistance of structural lumber. The 210 samples were prepared from 15-year-old trees of *Acacia mangium* from the Forest Estate Plantation, Indonesia. Specimens were 20 (R) × 20 (T) × 500 mm (L) and were air-dried. Sixty samples were tested under four-point bending stress to obtain the modulus of elasticity (MOE) and the modulus of rupture (MOR) for classifying the stress grades of the remaining 150 samples. The tests were performed using a four-point load bending position at various stress level while the specimens were exposed to fire along the shear-free region. Time to failure was affected by the stress levels in an exponential trend. Despite changes in stress level, charring rate, and time to failure, the critical stress of a member from the same species was similar. The fire performance under applied load could be predicted by using simplified fire-testing methods. The developed testing apparatus is valid for evaluating the small-scale fire resistant behavior of structural lumber in bending.

Key words Critical stress · Fire resistance · Charring rate · Timber grading · Structural lumber

Introduction

Besides having a high strength-to-weight ratio, as a structural material, wood has some weaknesses such as high variety of mechanical properties, susceptibility to attack by microorganisms and fire, and dimensional instability. Mechanical properties of wood may vary from one piece of lumber to another from the same log, among logs of one species, and among timber species, especially for the tropical woods. Designers require the strength grade of lumber to confirm mechanical properties. In practice, the mechanical properties are estimated by visual or mechanical grading.[1]

Grading of timber stress has been widely applied throughout the world, using the modulus of elasticity (MOE) in bending as a predictor. Because lumber is stress-graded, the lumber will be utilized according to its strength, which means the lumber will be sufficiently loaded. On the other hand, lumber is also known as a combustible material. One well recognized phenomena related to the strength and fire performance of structural lumber is its ability to maintain structural integrity when exposed to fire. The superior fire performance of structural lumber is attributed to the charring effect of wood.

During fire exposure, the height (h) and width (b) of lumber decreases gradually, depending on the charring rate of the species. The remaining uncharred lumber is assumed to contribute to the load-carrying capability. For members stressed in bending during fire exposure, failure occurs when maximum bending capacity is exceeded due to reduction of the section modulus. Such a condition is defined as the critical stress.

Some studies on the structural fire design of wood have been carried out for heavy timber and glulam constructions.[2] To assess safety aspects, we need to take into account the variability in fire endurance by considering variability in the properties of the member (e.g., charring rate, strength, and stiffness), variability in anticipated applied load, and variability in fire severity.[3]

Because the strength of lumber is affected by its density and imperfection condition, various strength grades of lumber can be found even in small specimens. This article examines the performance of various stress grades of structural lumber at various stress levels after fire exposure of small-scale specimens. The effects of stress levels to the fire performance at critical stress of bending members are presented. A small-scale fire testing apparatus has been

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developed to support the testing. This research may be utilized as a validation activity for the developed apparatus and as an initial step toward testing at full-scale.

Materials and methods

Logs were cut from 15-year-old mangium (*Acacia mangium*, Willd) from Sukabumi-in West Java, Indonesia. The specimen dimensions were 20 (T) × 20 (R) × 500 mm (L) and the specimens were prepared to avoid the juvenile wood. Two hundred and ten pieces were randomized and selected for the study. The moisture contents of the specimens ranged between 15.1% and 17.4%. The dimensions and masses of the specimens were measured just before measurement of MOE. The MOE values of the specimens were measured through bending tests with four-point loading with a 390-mm span and 130-mm shear-free area. Sixty samples were randomized and selected from the 210 pieces for testing the modulus of rupture (MOR). The data on the relationship between MOE values and MOR were utilized for analyzing the validity of MOE as a predictor. The MOR values of the remaining 150 pieces were predicted based on the obtained equation. The strength grade of the specimens and their allowable stresses were classified based on the Indonesian Wood Construction Rules.[4]

The bending test under fire was performed as shown in Fig. 1. To determine the effect of loading on the fire resistance of mangium lumber, the bending test under fire was conducted for specimens of all stress grades. The applied load for each specimen was one third of the design load for each lumber grade. The design load is the short-term allowable stress. Because grades III and IV were the most numerous grades in the specimens prepared in this study, the specimens graded as III and IV were also subjected to one third of the allowable loads of the other grades to compare with the performance of the specimens in different grades with the same applied load. The deflections were measured in the constant moment region or shear-free region of 130 mm on both sides and in the center during the fire exposure. A thermocouple was attached to measure the top of the flame temperature at the specimen center. The energy source was natural gas with an oxygen supply pump to maintain uniform flame along the burner. The gas flow was 2 l/min with the heating energy of 18–19.6 kcal/h or 0.63 kW. The temperature at the top of the flame was maintained at 800°–825°C.

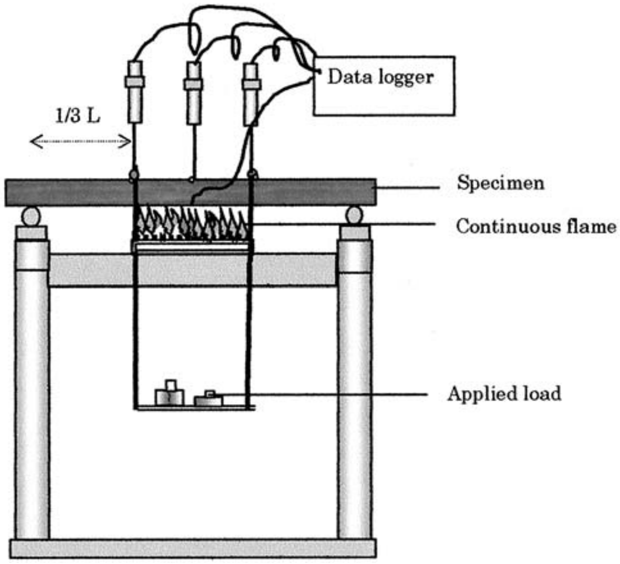

Fig. 1. Testing apparatus for bending under fire exposure

Results and discussion

Strength prediction of the lumber

It was important to ensure that prediction of the strength of the lumber was not biased. The population, and the sample distribution and characteristics should be thoroughly clarified. The density of the population was in the range of 0.51–0.77 g/cm^3 with an average (μ) of 0.63 g/cm^3 and standard deviation (SD) of 0.05 g/cm^3. The density of the samples for MOR testing ranged from 0.54 to 0.77 g/cm^3 with an average ($\bar{X}$) of 0.63 g/cm^3 and SD of 0.05 g/cm^3.

The MOE values of the population were in the range of 8.1–16.4 GPa with an average of 13.5 GPa and SD of 1.7 GPa. The sixty samples ranged from 8.7 to 16.4 GPa, with an average of 13.5 GPa and SD of 1.7 GPa. Statistically, the variation of parameters in populations and samples was not significant due to the high number of specimens. The MOE values for most of the samples were near the average MOE value.

The MOR of samples ranged from 24.6 to 152 MPa with an average of 108 MPa and SD of 26.1 MPa. The goodness-of-fit of MOE values of the samples to normal, log-normal, 2P-Weibull, and 3P-Weibull distributions were 81%, 74%, 100%, and 94%, respectively. For the population, the goodness-of-fit of MOE values was almost the same as the sample. Based on the same procedure, the goodness-of-fit of MOR values to the normal, log-normal, 2P-Weibull, and 3P-Weibull distributions is 78%, 74%, 98%, and 88%, respectively. Such results showed that MOE and MOR values showed better fit to the 2P-Weibull distribution than the normal, log-normal, or 3P-Weibull distributions.

The relationship between the MOE and MOR of samples was analyzed with linear regression analysis as shown in Fig. 2. The coefficient of correlation (R) between the MOE and MOR of the samples was 0.80 and the coefficient of determination (R^2) was 0.64. Such a coefficient of correlation is reasonable, considering that a study on commercial lumbers showed the relationship between MOE and MOR to have an R of 0.7–0.8.[5] Table 1 shows the results of analysis of variance (ANOVA) for a test on MOE as a predictor. Through the higher value of Fcal than $F_{0.01}$ took from ANOVA of such relationship, it is affirmed that MOE values can be used as a predictor of MOR. The stress grade of the lumber was in the range of grade I to grade VIII

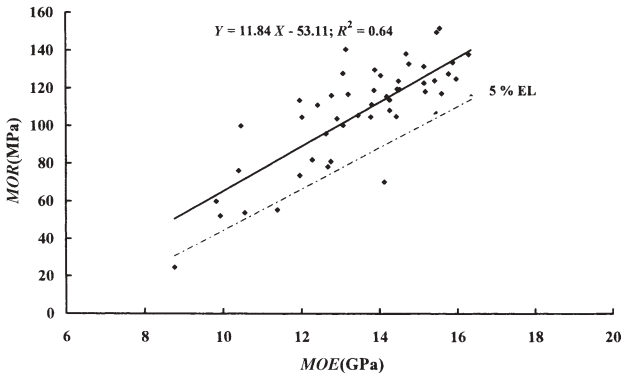

Fig. 2. Relationship between modulus of elasticity (*MOE*) and modulus of rupture (*MOR*), and the predicted equation. *EL*, exclusion limit

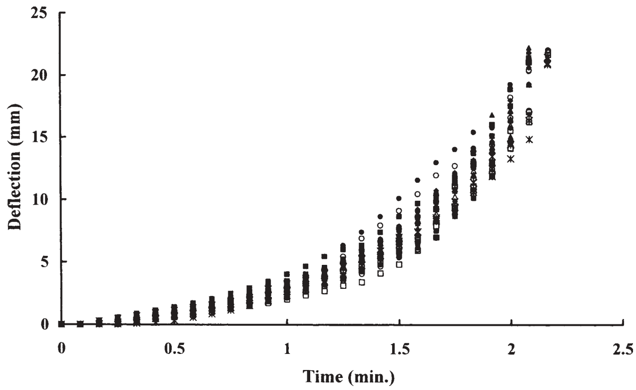

Fig. 3. The deflection of specimens in various grades with one third of their design loads applied. *Diamonds*, grade I; *filled squares*, grade II; *filled triangles*, grade III; *filled circles*, grade IV; *crosses*, Grade V; *open circles*, grade VI; *open squares*, grade VII; *open triangles*, grade VIII

Table 1. Analysis of variance (ANOVA) for regression of E-values and modulus of rupture (MOR)

Parameter	*DF*	*SS*	*MS*	*F* cal	$F_{.05}$	$F_{.01}$
Regression	1	98780.4	98780.4	70.95**	4.01	7.10
Error	58	80748.1	1392.2			
Total	59	179528.5				

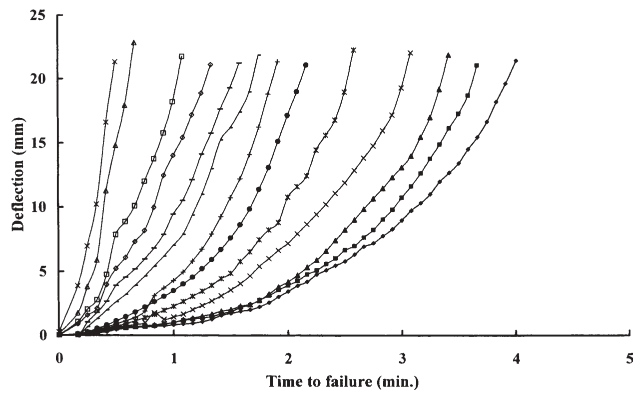

Fig. 4. Deflection of specimens when subjected to various stress levels in bending moment and fire exposure

based on the strength classification of the Indonesian Wood Construction Rules.[4] The variation of strength grades of the lumbers is affected by the wide range of density of the samples and the imperfection conditions such as knots and slope of grain.

Load applied and fire resistance of structural lumber

The time to failure and deflection for all grades of lumber to which one third of the design load was applied were similar, as shown in Fig. 3. The statistical analysis by ANOVA in Table 2 shows that there is no significant difference for the means of time to failure for any grade of timber as long as the samples were properly loaded as a certain fraction of the allowable stress. The deflection characteristics of the various grades of timber under the allowable stress were not extremely different from each other, as shown in Fig. 3.

Without loading, the fire resistance of lumber is affected by the thermal diffusivity of the materials. Thermal diffusivity is the ratio of thermal conductivity to the product of density and heat capacity.[6] Because the heat capacity depends on the temperature and moisture content which were maintained during testing and the variation of density was not high [coefficient of variance (CV) of 7%], loading was the main factor affecting the fire resistance of the member. With reference to Fig. 3 and Table 2, it is shown that when structural lumbers are under a load, the fire resistance performance will be similar.

To obtain further results on the effect of loading on the fire performance of structural lumber, specimens of various grades were loaded with the same load: one third of the design load for grade III. With the normal distribution of MOE of the population, the number of specimens in lower and upper grades was fewer than those of mid grades, e.g., grades III and IV. Therefore, one third of the design loads of various stress grades were applied to lumbers of the stress grade III and grade IV. The deflections of specimens of grade III at various stress levels are shown in Fig. 4. Similar characteristics of deflection and insignificant differences in times to failure for graded lumber may be caused by the constant energy supplied during the fire exposure.

Table 2. ANOVA for effect of grades on time to failure of stress-graded timber

Parameter	*DF*	*SS*	*MS*	*F* cal	$F_{.05}$	$F_{.01}$
Grades	7	384.5	54.93	0.65^{ns}	2.44	3.55
Error	16	2027.8	84.49			
Total	23	2411.3				

^{ns}not significance

With reference to Fig. 5, the stress level was in the range of 11.1% to 88.9% with the dense on the 33.3% of the

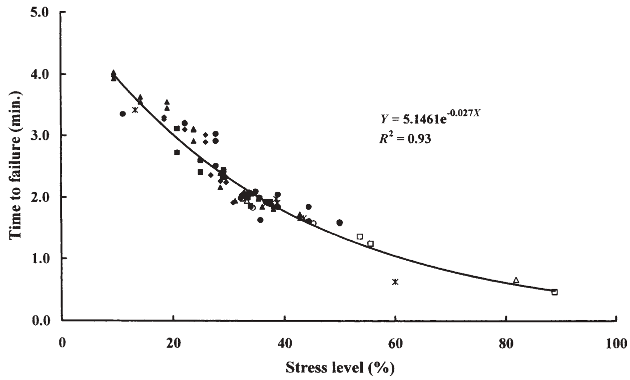

Fig. 5. Relationship between stress level and time to failure of bending test under fire exposure

allowable stress. When the stress level increases, the time to failure decreases. An exponential master curve can be drawn in the relationship between stress level applied to the various graded lumber and the time to failure as:

$$Y = 309e^{-0.0265X}$$

where Y is stress level and X is time to failure. The coefficient of determination of the equation (R^2) was 0.92. The exponential trend could be explained through a phenomenon that there is a reduction of strength and stiffness of a zone progressing ahead of the char front degraded by heat. Specimens subjected to high stress levels produced a narrower area of such a zone than those specimens subjected to stress levels.

One well known analysis of the time to failure of heavy structural timber members exposed to fire, introduced by Lie[7] in the 1970s, is the calculation method. The calculation method was widely applied with a certain assumed charring rate. It was evaluated by American Forest and Paper Association in 1997 for the load ratio below 50% and the result showed that for such a ratio the equation underestimated the time to failure. Another study on timber frames which used density as the predictor of MOR ($R^2 = 0.42$) showed that in compression and tension parts, the relationship between the relative load and the time to failure also showed an exponential trend.[8]

Charring rate of lumber

Generally, the charring rate is defined as the rate of penetration of char, and it serves as a measure of strength loss. Charring begins after the surface layer has been heated up; it proceeds relatively quickly until charcoal begins to retard the penetration of heat.[5,9] In this research, charring area in cross section of specimens of various stress grades subjected to one third of design load showed similar behavior. At the lower stress level, the longer time to failure gives a larger charring area in cross section than those of higher stress levels. The time to failure significantly affected the charring depth in horizontal and vertical directions as shown in Fig. 6. The charring depth in the horizontal direction was determined as the width of the specimen before fire exposure

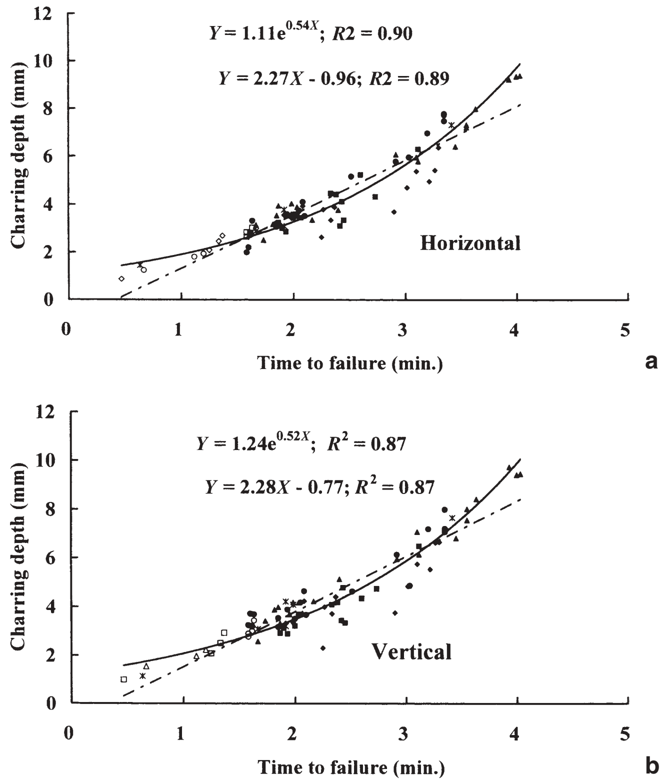

Fig. 6. Relationship between time to failure and charring depth in horizontal (**a**) and vertical (**b**) directions

minus the width of the specimen after exposure. The relationship between time to failure and charring depth could be expressed as linear or exponential relationships. The exponential phenomenon could be explained partly by the thermal conduction in lumber which was expressed as partial differential equations on time and space in the second order. In early fire exposure, the flow of moisture and gaseous materials in wood is slow due to low temperature and the long barrier from the wood tissues. When the temperature increases, the flow will be slightly accelerated. Such a phenomenon is also endorsed by the weight loss characteristic as shown in Fig. 7.

The charring rate of timber can be assumed to be constant as shown by the linear relationship between time to failure and charring depth in Fig. 6. The residual cross section is considered to be rectangular in simple methods of structural fire design.[10] The charring rates in horizontal and vertical directions of the lumber were not affected by the stress levels or time to failure. The charring rate in the vertical direction, the SD, and CV were evaluated as 1.86 mm/min, 0.19 mm/s, and 7.7%, respectively, and in the horizontal direction were 1.80 mm/min, 0.12 mm/min, and 7.0%, respectively.

There was no significant difference between the charring rates in the horizontal and vertical directions. In three sides of specimens, the exposed area was calculated as 0.0078 m^2 and the supplied heat was 0.63 kW. This gives a heat flux of 80.5 kW/m^2. With the high heat flux and small specimens, the charring rates of mangium in this experiment were

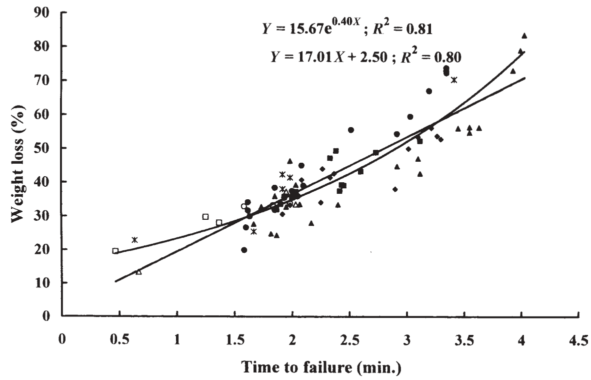

Fig. 7. Relationship between time to failure and weight loss in bending test under fire exposure

higher than those of subtropical lumber exposed to constant heat fluxes of 15, 25, 35, and 50 kW/m^2.[11] Charring rates of pine, redwood, oak, and basswood under constant heat flux of 25 kW/m^2 are 0.66, 0.74, 0.52, and 0.80 mm/min, and with a heat flux of 50 kW/m^2 are 0.85, 1.02, 0.73, 1.31 mm/min, respectively. Another study with lower heat fluxes also reported that the charring rates of subtropical lumber are lower than the charring rate of tested specimens.[3,10,11]

Critical stress

The critical stress, σ_c or $\sigma(t_c)$, is defined as the stress at the failure time, t_c, of the member due to the reduction of the section. When lumber is exposed to fire, the outer part of the lumber will be degraded and the volume of the lumber will be reduced. The longer the time exposed to fire, the larger is the section loss, thus, σ_c is a function of time. The critical stress can be obtained through the strength prediction based on lumber grade, stress level, time to failure, and observed charring rate. The stress, $\sigma(t)$, of the bending member exposed to fire for a certain time t can be calculated as:

$$\sigma(t) = \frac{M}{Z(t)} \tag{1}$$

where M is a load-dependent factor related to grade and stress level and Z is a fire-dependent factor related to time to failure and charring rate. The $Z(t)$ is calculated as:

$$Z(t) = 1/6(b - v_1 t)(h - v_2 t)^2 \tag{2}$$

where v_1 and v_2 are the charring rates in the vertical and horizontal directions, respectively. At the time to failure, the critical stress, $\sigma(t_c)$, can be calculated as:

$$\sigma_c = \sigma(t_c) = \frac{M}{Z(t_c)} \geq \frac{M\max}{Z(t_0)} = MOR \tag{3}$$

where t_0 is the critical time or time to failure, and M max is the load when a member ruptures. Failure occurs when $\sigma(t_c)$ is over the MOR value.

The critical stresses of specimens were calculated based on the test result and analysis as in Eqs. 1 and 2. Because the critical stress is a function of applied load and time to failure, the result shows that there is no significant difference of the critical stress among grades, among applied loads (stress level), and time to failure as shown in Fig. 8. It gives an assertion that the newly developed small-scale testing apparatus is valid for testing the bending member under fire exposure.

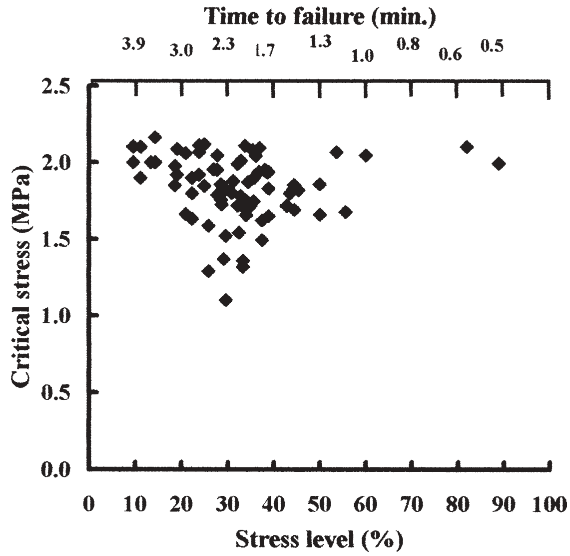

Fig. 8. Relationship between stress level and critical stress of bending test under fire exposure

The average critical stress of mangium is 21.8 MPa with a SD of 2.4 MPa and CV of 11.3%. As shown in Fig. 8, even with high variation in stress levels, similar critical stress values were obtained over a range of times to failure, that is, the critical stress can be applied in allowable stress design (ASD) and load and resistance factor design (LRFD). The minimum cross section of the member can be calculated based on the critical stress, charring rates, and standardized fire endurance time.

The critical parameter for fire endurance is defined as the ratio of critical stress, $\sigma(t_c)$, to the ultimate stress, $\sigma(t_0)$ at 5% exclusion limit (EL). In this study, the average MOR was 105 MPa with SD of 22.2 MPa, so the 5% EL of ultimate stress is 68.2 MPa in mangium. The critical parameter for fire endurance of mangium is calculated to be 0.31. For full-scale softwood beams, the critical parameters in Finland, Sweden, New Zealand, and Britain were proposed to be 0.75, 0.8, 0.5, and 0.68, respectively.[3] With respect to the ultimate strength of the lumber, the lower critical parameter for fire endurance obtained in this study might be due to the higher charring rate of the lumber.

Conclusions

Samples for predicting strength of the lumber represented the characteristic of the population and MOE is a good predictor for MOR. Applying mechanical grading in structural lumber will be useful in determining mechanical and fire performance. When structural lumbers are graded and properly loaded in application, the fire resistance performance will be in accordance with the planning design.

The time to failure, charring depth, and weight loss are significantly affected by the ratio of stress level. With the high heat flux and small specimens used in this experiment, the charring rate of mangium in the vertical direction was 1.86 mm/min while in the horizontal direction was 1.80 mm/min.

The critical stress value was roughly constant with various applied loads which evoked a wide range of times to failure. The critical stress is a function of the stress level and the charring rate. For bending under fire exposure, the critical stress of mangium is 21.8 MPa. This value can be applied in ASD or LRFD concepts.

The newly developed testing apparatus is appropriate to evaluate the fire performance behavior of structural lumber in bending on a small scale. It may be utilized for evaluating various species and heat fluxes to provide data on critical parameters of fire endurance for building structures. The fire performance under applied load can be predicted by using the simplified fire testing method.

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References

1. Forest Product Laboratory (1999) Wood Handbook. Wood as engineering materials: lumber stress grade and design properties. Forest Prod Soc USA, 6:1–14
2. American Forest and Paper Association (1999) Calculating the fire resistance of exposed wood member. Technical report 10. American Wood Council, pp 1–23
3. Scaffer EL (1984) Structural fire design: wood. Forest Product Laboratory, pp 1–16
4. Indonesian Forestry and Forest Product Standard (1987) Indonesian wood construction rules (in Indonesian). pp 3–5
5. Glos P (1995) Strength grading, timber engineering STEP 1. Lecture A6. Centrum Hout, The Netherlands, pp A6/1–A6/8
6. Wilcox WW, Botsai EE, Kubler H (1991) Wood as a building material: thermal properties and performance of structural wood. Wiley, Toronto, pp 101–113
7. Lie TT (2003) Calculating resistance to fire. Canadian Building Digest, CBD-204, Institute for Research in Construction, Ottawa, pp 1–6
8. Konig J, Noren J (1991) Fire tests on timber frame members under pure bending. Proceeding of 1991 International Timber Engineering Conference, London, 4:4.75–4.82
9. White RH, Nordheim EV (1992) Charring rate of wood for ASTM E 119 exposure. J Fire Tech 28:6–30
10. Hartl H (1995) Behavior of timber and wood based materials in fire, timber engineering STEP 1. Lecture A13. Centrum Hout, The Netherlands, pp A13/1–A13/7
11. White RH, Tran HC (1996) Charring rate of wood exposed to a constant heat flux, Proceedings of Wood and Fire Safety Conference, Zvolen, Slovak Republic, Technical University Zvolen, pp 175–183