No	Tanggal	Keterangan
1	27 Juli 2024	Penulis korespondensi mengirimkan **naskah publikasi** ke redaksi.
2	6 Oktober 2024	Redaksi memberikan hasil review yaitu Diterima dengan Revisi.
3	15 Oktober 2024	Penulis mengirimkan **revisi naskah** sesuai hasil review dan sesuai arahan redaksi.
4	29 Oktober 2024	Naskah memasuki proses editing.
5	6 November 2024	Redaksi menerbitkan **Letter of Acceptance**.
6	6 November 2024	Naskah **terbit** pada **Volume 15 Nomor 1 Tahun 2024**.

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#625 Summary

SUMMARY | REVIEW | EDITING

Submission

Authors	Yosafat Aji Pranata, Anang Kristianto, Novi Novi
Title	Study of the Effect of Grain Angle on the Compressive Strength of Red Meranti Timber (Shorea spp.)
Original file	None
Supp. files	None
Submitter	Dr. Yosafat Aji Pranata
Date submitted	July 27, 2024 - 05:35 AM
Section	Articles
Editor	Dian Anggraini, S.Hut., MM.
Abstract Views	57

ARTICLE SUBMISSION

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Demikian kami sampaikan, atas perhatian dan bantuan yang Bapak berikan, kami ucapkan terima kasih.

Hormat Kami,
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HP. 08128539503

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Home > User > Author > Submissions > #625 > **Review**

#625 Review

SUMMARY | **REVIEW** | EDITING

Submission

Authors	Yosafat Aji Pranata, Anang Kristianto, Novi Novi
Title	Study of the Effect of Grain Angle on the Compressive Strength of Red Meranti Timber (Shorea spp.)
Section	Articles
Editor	Dian Anggraini, S.Hut., MM.

Peer Review

Round 1

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Dengan hormat,
Bersama email ini saya sampaikan revisi naskah dengan judul ""Study of the Effect of Grain Angle on the Compressive Strength of Red Meranti Timber (Shorea spp.)" sesuai hasil review dari Reviewer. Adapun saya juga telah menunggah file revisi melalui sistem OJS WRJ. Terima kasih atas kesempatan yang telah diberikan. Atas perhatiannya saya ucapkan terima kasih.

Salam hormat,
Yosafat Aji Pranata
Penulis korespondensi

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#625 Editing

SUMMARY REVIEW EDITING

Submission

Authors	Yosafat Aji Pranata, Anang Kristianto, Novi Novi
Title	Study of the Effect of Grain Angle on the Compressive Strength of Red Meranti Timber (Shorea spp.)
Section	Articles
Editor	Dian Anggraini, S.Hut., MM.

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Study of the Effect of Grain Angle on the Compressive Strength of Red Meranti Timber (*Shorea spp.*)

Abstract

The compressive strength of timber is the main parameter in design of timber bridges (truss system), building roof (truss system), or column in buildings. In term of design of compression structural components according to the SNI 7973:2013 reference, the corrected compression design value is a calculation of compressive strength parameters and correction factors, for example, wet service factors, temperature factors, column stability factors, and others. Timber as an orthotropic material has three main directions, so the angle of the timber grain has an influence on compressive strength. This research aims to study the effect of timber grain's angle on the compressive strength of Red Meranti wood (*Shorea spp.*) and develop an empirical equation to calculate the compressive strength of timber with the influence of wood grain's angle. The scope of the research were that the timber studied is the Red Meranti species (*Shorea spp.*), the total number of test objects are 45 test objects. The test specimens were made based on the primary method reference for compression test specimens reference method 50mm x 50mm x 200mm (parallel to the grain type), according to ASTM D143-22 regulations for test specimens with variations in fiber direction, namely 0°, 10°, 20° and 30°. Meanwhile, test objects with variations in fiber direction, namely 60°, 70°, 80° and 90°, were made with test object sizes of 50mm x 50mm x 150mm (perpendicular to the grain type). Testings are carried out using a Universal Testing Machine with test speed according to ASTM D143-22. All test objects were made in dry conditions (moisture content ranging from 14% to 16%). The conclusion obtained from this research are an empirical equation for calculating the compressive strength of Red Meranti timber (*Shorea spp.*) with a predictor is the timber grain's angle, which are $F_{CY} = 14.01 – 0.119\theta + 0.000042\theta^2$ (in term of yield of proportional point) and $F_{CU} = 29.82 – 0.417\theta + 0.0018\theta^2$ (in term of peak or ultimate point). This equation provides benefits for academics and practitioners, especially in designing compression structural components, which is the compression design value parameter.

Keywords: Compression Strength, grain angle of timber, Red Meranti, Compressive Design, ASTM D143.

Introduction

The compressive strength of timber is the main parameter in design of timber bridges (truss system), building roof (truss system), or column in buildings. In term of design of compression structural components according to the SNI 7973:2013 reference (BSN, 2013), the corrected compression design value is a calculation of compressive strength parameters and correction factors, for example, wet service factors, temperature factors, column stability factors, and others. Timber as an orthotropic material has three main directions, so the angle of the timber grain has an influence on compressive strength.

This research aims to study the effect of timber grain's angle on the compressive strength of Red Meranti wood (*Shorea spp.*) and develop an empirical equation to calculate the compressive strength of timber with the influence of wood grain's angle.

The scope of the research were that:

1. The timber studied is the Red Meranti species (*Shorea spp.*).
2. The total number of test objects are 45 test objects.
3. The test specimens were made based on the primary method reference for compression test specimens reference method 50mm x 50mm x 200mm (parallel to the grain type), according to ASTM D143-22 regulations for test specimens with variations in fiber direction, namely 0°, 10°, 20° and 30°. Meanwhile, test objects with variations in fiber direction, namely 60°, 70°, 80° and 90°, were made with test object sizes of 50mm x 50mm x 150mm (perpendicular to the grain type).
4. Testings are carried out using a Universal Testing Machine with test speed according to ASTM D143-22.
5. All test objects were made in dry conditions (moisture content ranging from 14% to 16%).
6. The compressive strength referred to in this research is the compressive stress calculated under peak or ultimate load condition (F_{CU}) and proportional load condition (F_{CY}).

Basic Theories and Methods

Previous Research History

Previous research related to timber properties, especially the compressive strength of Meranti species wood, has been carried out several times, namely experimental research on timber compression testing with several variations in grain angles (Pranata and Suryoatmono, 2012) for 3 (three) types of wood, namely Acacia, Meranti, and Keruing, with the results being an alternative von Mises-based equation for calculating the compressive strength of wood, this research is limited to only a few grain's angles and a limited number of test objects. The next research is experimental and numerical research to study the effect of grain's angle on the compressive strength of Red Meranti

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Commented [L6]: How many sample of each degree? How did you make this differenet degree? Need explanation wood (Pranata and Suryoatmono, 2013) with variations in fiber angles of 12°, 60°, and 80°.

Compression Strength

Wood is generally assumed to behave as mutually perpendicular material principal axes, namely and tangential axes. Compressive strength is the compressive force that acts on a unit cross-sectional area of wood that is subjected to that force. Compressive strength of wood defines the limit of wood's ability to accept compressive loads until the wood fails.

Compression Tests

Currently, the parameters for compressive strength of timber are known parallel to the grain (grain's angle of 0°) or longitudinal direction, and compressive strength perpendicular to the grain (grain angle of 90°) or radial direction. These two parameters can be obtained from experimental testing in the laboratory using testing standards including ASTM D143-22 (ASTM, 2022) with primary and secondary test methods.

Testing can be carried out using a Universal Testing Machine (UTM) with output data in the form of a history curve of the relationship between compressive axial load and axial deformation. Figure 1 shows the test equipment used in this research. Figure 2a shows a schematic history of the load vs deformation relationship curve obtained from experimental test results.

Next, the curve then converted into a curve for the relationship between stress and strain, where stress (engineering stress) is the compressive axial force divided by the initial cross-sectional area, while strain is the change in length (in this case shortening) divided by the initial length of the test object. Figure 2b shows a schematic of the stress vs strain relationship curve resulting from the conversion of the load vs deformation relationship curve.

Stress and strain can be calculated using Equation 1 and Equation 2 (Goodno and Gere, 2021).

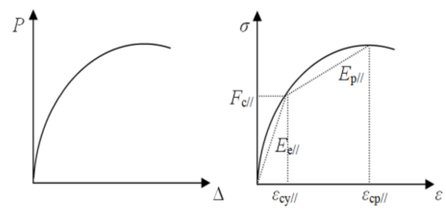
$$\sigma = P / A \quad (1)$$

$$\varepsilon = \Delta / L_o \quad (2)$$

with σ is engineering stress (MPa), P is axial compressive load (N), A is specimen's cross-section (mm^2), ε is strain (mm/mm), Δ is the change in length of shortening (mm), and L_o is initial length of the specimen (mm).

The testing speed (acoodring to the ASTM D143's primary method) for the test object type parallel to the grain is a strain rate of 0.003 mm/mm per minute or a displacement rate of 0.6 mm per minute. While for the test object type perpendicular to the grain, the speed is a displacement rate of 0.305 mm per minute (ASTM, 2022).

Figure 1. Instrumen for testing using Universal Testing Machine (UTM).



(a). Load-Deformation Curve. (b). Stress-Strain Curve.
Figure 2. Idealization of the axial load vs axial deformation curve and normal (axial) stress vs strain (Pranata and Suryoatmono, 2013).

Proportional Load and Ultimate Load

The proportional point indicates when material behavior changes from elastic to plastic. One of the methods to calculate the proportional point is the Yasumura and Kawai Method (Munoz et al., 2010). The calculated initial stiffness was between 10% and 40% of the ultimate or peak load. A straight line between 40% and 90% of the peak load and a straight-line tangent to the load-displacement curve, then parallel to the 40% and 90% second line, were determined.

In this research, this method was used to determine the proportional load divided by a cross-section's area, to calculate the compression strength in terms of yield or proportional strength. While the compression strength in terms of ultimate strength was calculated using peak load, divided by cross-section's area..

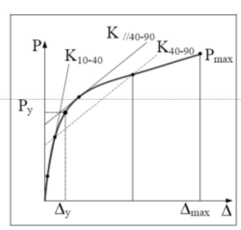


Figure 3. Yasumura and Kawai Method to determine the proportional load of timber (Munoz et.al., 2010).

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Polynomial Regression Analysis

Several parameters for statistical data, which are mean, standard deviation, and coefficient of variation, are needed for analysis. Standard deviation measures how they are distributed around the arithmetic mean (Heumann et.al., 2017). A low standard deviation value indicates that the values are highly concentrated around the mean. Meanwhile, the coefficient of variation (usually expressed as a percentage) is a ratio between the standard deviation and the average value. In this research, polynomial regression analysis was carried out with Minitab software (LLC, 2023).

Results and Discussion

The number of compression test specimens in this study were 45 test specimens with grain angle variations ranging 0°, 10°, 20°, 30°, 60°, 70°, 80°, and 90°. All of the specimens for the compression tests were made from 5 (five) Red Meranti timber different logs (defect-free parts). The specimens were made in accordance with primary method of ASTM D143-22 (ASTM, 2022). The speed of test (deformation speed) was also in accordance with ASTM D143-22 too.

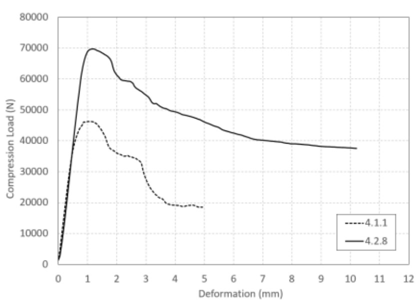

Figure 4. Tests results: Axial load vs deformation curve, obtained from experimental test for specimen 4.1.1 (grain's angle of 30°) and specimen 4.2.8 (grain's angle of 10°).

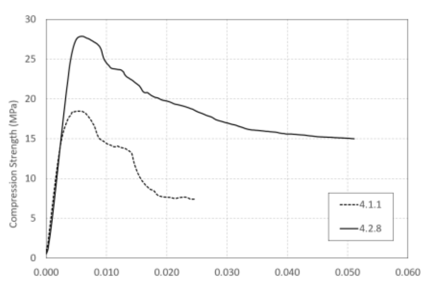

Figure 5. Convertion results: Stress vs strain curves of specimen 4.1.1 (grain's angle of 30°) and specimen 4.2.8 (grain's angle of 10°).

Figure 4 shows an example result obtained from compression test which is axial load vs deformation curve. Figure 5 shows an covertion results, which is calculation of stress and strain curves. The results above show that the test object with a lower grain angle produces a higher peak load than the test object with a larger grain angle.

Figure 6 shows an example of compression test using parallel to the grain method, while Figure 7 shows an example of compression test speciment with grain angle of 70°.

Figure 6. Experimental tests for 50 x 50 x 200mm specimen, using test method of compression parallel to the grain.

Figure 7. Example of 70° specimen of Red Meranti timber.

Figure 8 shows some of test results of the specimens with dimension 50mm x 50mm x 200mm, while Figure 9 shows some of test results of the specimens with dimension 50mm x 50mm x 200mm.

Figure 8. Results of failure mode for some 50 x 50 x 200mm specimens (compression parallel to the grain method of test).

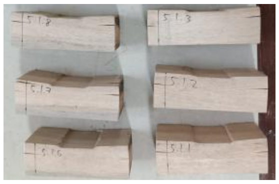

Figure 9. Results of failure mode for some 50 x 50 x 150mm specimens (compression perpendicular to the grain method of test).

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In this research, the compression strength were calculate in term of proportional load, method to determine the yield point were done using Yasumura and Kawai method (Munoz et.al., 2010), and in term of peak of ultimate load. Table 1 shows the results of calculation of the proportional load, peak load, deformation at proportional load, deformation at peak load, and the grain's angle for all 45 specimens. Table 2 shows the results of calculation of the stress and strain in term of proportional stress and peak stress using Equation 1 and Equation 2.

Table 1. Tests results: Load and deformation obtained from experimental tests and calculation using Yasumura and Kawai Method.

Spec-imens	P_y (N)	P_{peak} (N)	D_y (mm)	D_{peak} (mm)	θ (°)
1.1.2	14313.0	26650.6	0.3	5.0	70
1.1.3	7932.0	18839.9	0.7	6.0	80
1.1.4	18834.1	32409.2	0.4	6.2	60
1.1.5	13788.4	25203.8	1.5	6.0	70
1.1.7	15479.0	25547.9	0.5	6.0	70
1.2.3	29603.0	46987.6	0.3	0.8	30
1.2.4	28950.5	46224.6	0.4	1.0	30
1.2.8	24203.2	43516.9	0.3	0.8	30
1.2.9	123246.1	69692.6	1.6	1.2	10
2.1.1	5906.3	14661.3	0.7	6.0	90
2.1.2	17531.7	39520.9	0.8	6.1	30
2.1.4	16969.8	32393.3	0.5	6.0	60
2.1.6	10581.1	21456.7	0.5	6.0	80
2.1.7	6994.9	13948.3	1.5	6.0	90
2.2.10	37925.6	62397.2	0.4	0.8	10
2.2.2	38100.2	53651.3	0.5	0.9	20
2.2.4	32993.8	53975.8	0.3	0.8	20
2.2.6	56268.3	62644.0	0.7	1.1	10
3.1.10	16092.7	33444.2	0.4	6.1	60
3.1.2	6041.2	14045.7	1.3	6.1	90
3.1.3	5608.1	13160.7	1.2	6.1	90
3.1.5	18349.4	27524.6	1.2	6.1	70
3.2.1	36903.4	73806.8	0.3	0.8	0
3.2.4	39992.2	79984.5	0.8	1.7	0
3.2.5	29505.0	77361.8	0.8	1.6	0
3.2.7	26908.8	70598.3	0.4	1.1	10
3.2.8	28731.6	78258.5	0.5	1.3	0
3.2.9	29826.7	80297.5	0.5	1.3	0
4.1.1	21269.1	48193.7	0.4	6.1	30
4.1.6	24211.4	53836.4	0.5	6.1	20
4.2.5	44493.6	74663.0	0.4	0.7	0
4.2.6	32710.6	65421.2	0.5	14.5	10
4.2.7	40336.6	52428.3	0.4	0.9	20
4.2.8	35617.8	71235.7	5.3	1.1	10
5.1.1	12995.6	32007.6	0.5	6.1	60
5.1.10	6229.3	11832.2	1.4	6.1	90
5.1.2	15569.4	27696.7	0.5	6.1	70
5.1.3	13269.9	25523.0	0.4	6.2	70
5.1.4	11873.1	21078.7	0.7	6.1	80
5.1.7	9391.3	17105.2	0.5	6.1	90
5.1.9	11103.5	19313.0	0.4	6.1	80
5.2.1	18469.9	44526.6	0.6	2.2	30
5.2.10	79513.1	46903.8	1.6	1.2	20
5.2.6	15292.9	30585.8	0.3	0.9	60
5.2.8	19199.5	31501.1	0.3	1.0	60

Table 2. Hasil konversi: Tegangan dan Regangan pada kondisi batas proporsional dan batas ultimit.

Spec-imens	F_{CY} MPa)	F_{CU} (MPa)	$ε_y$ mm/mm)	$ε_U$ mm/mm)	θ (°)
1.1.2	5.6	10.4	0.002	0.025	70
1.1.3	3.1	7.4	0.003	0.030	80
1.1.4	7.4	12.7	0.002	0.031	60
1.1.5	5.4	9.9	0.008	0.030	70
1.1.7	6.1	10.1	0.002	0.030	70
1.2.3	11.6	18.4	0.002	0.005	30
1.2.4	11.3	18.0	0.002	0.007	30
1.2.8	9.6	17.2	0.002	0.006	30
1.2.9	13.9	27.8	0.010	0.008	10
2.1.1	2.3	5.8	0.004	0.030	90
2.1.2	7.0	15.7	0.004	0.031	30
2.1.4	6.8	12.9	0.003	0.030	60
2.1.6	4.2	8.4	0.003	0.030	80
2.1.7	2.7	5.5	0.007	0.030	90
2.2.10	14.8	24.4	0.003	0.005	10
2.2.2	15.2	21.4	0.003	0.006	20
2.2.4	13.2	21.7	0.002	0.006	20
2.2.6	12.1	24.6	0.005	0.008	10
3.1.10	6.6	13.7	0.002	0.030	60
3.1.2	2.5	5.7	0.007	0.030	90
3.1.3	2.2	5.2	0.006	0.031	90
3.1.5	7.2	10.8	0.006	0.030	70
3.2.1	15.0	29.9	0.002	0.005	0
3.2.4	15.7	31.4	0.005	0.012	0
3.2.5	11.7	30.6	0.005	0.011	0
3.2.7	10.6	27.9	0.003	0.007	10

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You also nedd to add the abbreviarion of Py, Ppeak, Dy, Dpeak and gama in tne note bellow the tabel. Table should be independent (people can understand table without readyng the text). Also check in other tables.

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Spec-imens	F_{CY} MPa)	F_{CU} (MPa)	ε_y mm/mm)	ε_U mm/mm)	θ (°)
3.2.8	11.5	31.3	0.003	0.009	0
3.2.9	12.0	32.4	0.003	0.009	0
4.1.1	8.8	19.2	0.002	0.030	30
4.1.6	9.4	20.9	0.002	0.030	20
4.2.5	17.4	29.1	0.002	0.005	0
4.2.6	12.8	25.5	0.003	0.096	10
4.2.7	15.4	20.1	0.002	0.006	20
4.2.8	13.6	27.2	0.035	0.008	10
5.1.1	5.3	13.1	0.002	0.030	60
5.1.10	2.6	4.9	0.007	0.030	90
5.1.2	6.4	11.4	0.002	0.031	70
5.1.3	5.4	10.4	0.002	0.031	70
5.1.4	4.9	8.6	0.003	0.030	80
5.1.7	3.9	7.0	0.002	0.030	90
5.1.9	4.5	7.9	0.002	0.031	80
5.2.1	7.6	18.2	0.004	0.015	30
5.2.10	9.6	19.2	0.011	0.008	20
5.2.6	6.3	12.6	0.002	0.006	60
5.2.8	7.8	12.8	0.002	0.007	60

Figure 10 shows the result obtained experimentally (F_{CY}) and the equation-curve obtained from the polynomial regression analysis to predict the value of compression strength of Red Meranti timber in term of proportional or yield point, this empirical equation result shows the relationship between the compression strength (unit in MPa) and the grain angle θ (unit in degrees). The coefficient of R^2 is generally it is relatively near 100%, for timber this is considered normal because timber is a material that comes from nature. The regression equation for the curve in Figure 10 is shown in Equation 3 and Equation 4.

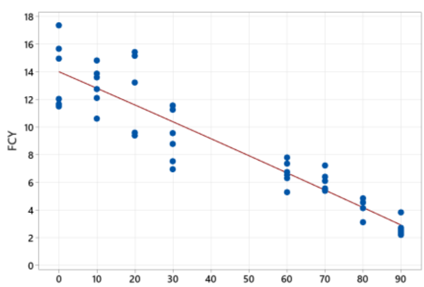

Figure 10. Results obtained from polynomial regression analysis.

$$F_{CY} = 14.01 - 0.119\theta + 0.000042\theta^2 \quad (3)$$
$$R^2 = 85.52\% \quad (4)$$

Figure 11 shows the result obtained experimentally (F_{CU}) and the equation-curve obtained from the polynomial regression analysis to predict the value of compression strength of Red Meranti timber in term of peak or ultimate point, this empirical equation result shows the relationship between the compression strength (unit in MPa) and the grain angle θ (unit in degrees). The coefficient of R^2 is generally it is relatively near 100%, for timber this is considered normal because timber is a material that comes from nature. The regression equation for the curve in Figure 10 is shown in Equation 5 and Equation 6.

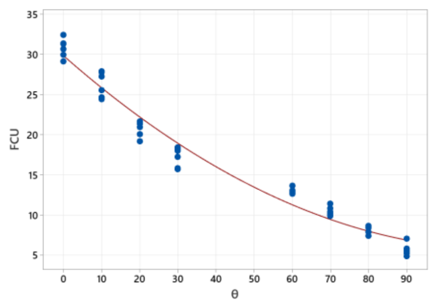

Figure 11. Results obtained from polynomial regression analysis.

$$F_{CU} = 29.82 - 0.417\theta + 0.0018\theta^2 \quad (5)$$
$$R^2 = 96.56\% \quad (6)$$

Conclusions

The conclusion obtained from this research is an empirical equation for calculating the compressive strength of Red Meranti timber (*Shorea spp.*) with a predictor, namely the wood grain's angle, namely F_{CY} = 14.01 – 0.119θ + 0.000042θ² with R^2 = 85.52% in term of yield or proportional point. While in term of peak or ultimate load, an empirial equation is F_{CU} = 29.82 – 0.417θ + 0.0018θ² with R^2 = 96.56%.

F_{CY} or compression design value is an useful parameter for design of column or compression member in timber building, timber bridge truss, or timber roof truss in accordance with SNI 7973:2013. This equation provides benefits for academics and practitioners, especially in designing compression structural components, which is the compression design value parameter.

Acknowledgements

The authors received an internal funding research grant from Universitas Kristen Maranatha in the 2022 fiscal year, which was B-Scheme Research with the title "Experimental Study of the Compressive Mechanical Properties of Timber with Various Angle Direction". For this reason, largely author

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would like to express his deepest gratitude, so that all research activities can be completed in the same year. The authors also would like to thank all parties who have helped with the research process in the laboratory.

References

American Standard Testing and Material. 2022. ASTM D143-22 Standard Test Methods for Small Clear Specimens of Timber, West Conshohocken, Pennsylvania, United States, 2022.

American Standard Testing and Material. 2018. ASTM D5764-97a Standard Test Method for Evaluating Dowel-Bearing Strength of Wood and Wood-Based Products, West Conshohocken, Pennsylvania, United States, 2018.

Bodig, J., Jayne, B.A. 1993. Mechanics of Wood and Wood Composites, Krieger Publishing Company, Malabar, Florida, USA, 1993.

Goodno, B.J., Gere, J.M. 2021. Mechanics of Materials 9th Edition, ISBN-13: 9780357377857, Cengage Learning Asia.

Heumann, Christian, Michael Schomaker, Shalabh. 2017. Introduction to Statistics and Data Analysis: With Exercises, Solutions and Applications in R. Introduction to Statistics and Data Analysis: With Exercises, Solutions and Applications in R. Springer International Publishing, 2017.

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Munoz, W., Mohammad, M., Salenikovich, A. & Quenneville, P. 2010. Determination of Yield Point and Ductility of Timber Assemblies: In Search for a Harmonized Approach, Engineered Wood Products Association, 2010.

Pranata, Y.A., Suryoatmono, B. 2013. Nonlinear Finite Elemen Modeling of Red Meranti Compression at an Angle to the Grain, Journal of Engineering and Technological Science, Volume 45 No. 3, pp. 222-240, 2013.

Pranata, Y.A., Suryoatmono, B. 2012. Distortion Energy Criterion for Timber Uniaxial Compression Mechanical Properties, Jurnal Dinamika Teknik Sipil, Volume 12 No. 02, May 2012 (in Indonesian).

Study of the Effect of Grain Angle on the Compressive Strength of Red Meranti Timber (*Shorea spp.*)

Abstract

The compressive strength of timber is the main parameter in design of timber bridges (truss system), building roof (truss system), or column in buildings. In term of design of compression structural components according to the SNI 7973:2013 reference, the corrected compression design value is a calculation of compressive strength parameters and correction factors, for example, wet service factors, temperature factors, column stability factors, and others. Timber as an orthotropic material has three main directions, therefore the angle of the timber grain has an influence on compressive strength. This research aims to study the effect of timber grain's angle on the compressive strength of Red Meranti wood (*Shorea spp.*) and develop an empirical equation to calculate the compressive strength of timber with the influence of angle of grain. The scope of the research were that the timber studied is the Red Meranti species (*Shorea spp.*), the total number of test objects are 45 test objects. The test specimens were made based on the primary method reference for compression test specimens reference method 50mm x 50mm x 200mm (parallel to the grain type), according to ASTM D143-22 regulations for test specimens with variations in fiber direction, namely 0°, 10°, 20° and 30°. Meanwhile, test objects with variations in fiber direction, namely 60°, 70°, 80° and 90°, were made with test object sizes of 50mm x 50mm x 150mm (perpendicular to the grain type). Testings are carried out using a Universal Testing Machine with test speed according to ASTM D143-22. All test objects were made in dry conditions (moisture content ranging from 14% to 16%). The conclusion obtained from this research are an empirical equation for calculating the compressive strength of Red Meranti timber (*Shorea spp.*) with a predictor is the timber grain's angle, which are F_{CY} = 14.01 – 0.119θ + 0.000042θ^2 (in term of yield of proportional point) and F_{CU} = 29.82 – 0.417θ + 0.0018θ^2 (in term of peak or ultimate point). This equation provides benefits for academics and practitioners, especially in designing compression structural components, which is the compression design value parameter.

Keywords: Compression Strength, grain angle of timber, Red Meranti, empirical equation.

Introduction

The compressive strength of timber is the main parameter in design of timber bridges (truss system), building roof (truss system), or column in buildings. In term of design of compression structural components according to the SNI 7973:2013 reference (BSN, 2013), the corrected compression design value is a calculation of compressive strength parameters and correction factors, for example, wet service factors, temperature factors, column stability factors, and others. Previous research related to timber properties, especially the compressive strength of Meranti species wood, has been carried out several times, before. Timber as an orthotropic material has three main directions, so the angle of the timber grain has an influence on compressive strength.

This research aims to study the effect of timber grain's angle on the compressive strength of Red Meranti wood (*Shorea spp.*) and develop an empirical equation to calculate the compressive strength of timber with the influence of wood grain's angle.

The scope of the research were that:

1. The timber studied is the Red Meranti species (*Shorea spp.*).
2. The total number of test objects are 45 test objects.
3. The test specimens were made based on the primary method reference for compression test specimens reference method 50mm x 50mm x 200mm (parallel to the grain type), according to ASTM D143-22 regulations for test specimens with variations in fiber direction, namely 0°, 10°, 20° and 30°. Meanwhile, test objects with variations in fiber direction, namely 60°, 70°, 80° and 90°, were made with test object sizes of 50mm x 50mm x 150mm (perpendicular to the grain type).
4. Testings are carried out using a Universal Testing Machine with test speed according to ASTM D143-22.
5. All test objects were made in dry conditions (moisture content ranging from 14% to 16%).
6. The compressive strength referred to in this research is the compressive stress calculated under peak or ultimate load condition (F_{CU}) and proportional load condition (F_{CY}).
7. Test objects are made from timber log, with angle dimensions adjusted for testing purposes.

Basic Theories and Methods

Previous Research History

Previous research related to timber properties, especially the compressive strength of Meranti species wood, has been carried out several times, namely experimental research on timber compression testing with several variations in grain angles (Pranata and Suryoatmono, 2012) for 3 (three) types of wood, namely Acacia, Meranti, and Keruing, with the results being an alternative von Mises-based equation for calculating the compressive strength of wood, this research is limited to only a few grain's angles and

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a limited number of test objects. The next research is experimental and numerical research to study the effect of grain's angle on the compressive strength of Red Meranti wood (Pranata and Suryoatmono, 2013) with variations in fiber angles of 12°, 60°, and 80°.

Compression Strength

Wood is generally assumed to behave as mutually perpendicular material principal axes, namely and tangential axes. Compressive strength is the compressive force that acts on a unit cross-sectional area of wood that is subjected to that force. Compressive strength of wood defines the limit of wood's ability to accept compressive loads until the wood fails. Previous study of Red Meranti (shorea spp.) compression strength were done by Nakai (Nakai, 1985), Chik (Chik, 1988), Pranata and Suryoatmono (Pranata and Suryoatmono, 2012; Pranata and Suryoatmono, 2013), Tjondro et al. (Tjondro et al., 2016), Azmi et al. (Azmi et al., 2022), and wood database (Meier, 2024). Table 1 shows the summary of compression strength of Red Meranti (Shorea spp.) timber obtained from previous research histories.

Table 1. Compression strength of Red Meranti (*Shorea spp.*) Timber from previous research histories.

References	θ (°)	F_{CY} (MPa)	F_{CU} (MPa)
Nakai, 1985	0	31.60	36.50
Azmi et.al., 2022	0	31.30	-
Meier, 2024	0	33.90	-
Tjondro et.al.,	0	30.78	41.21
	90	7.51	-
Chik, 1988	0	-	39.60
	90	-	4.14
Pranata and Suryoatmono, 2012; Pranata and Suryoatmono, 2013	0	33.67	-
	5	31.16	-
	10	28.55	-
	12	27.82	33.30
	60	8.52	9.10
	80	7.68	8.10
	90	7.17	-

Compression Tests

Currently, the parameters for compressive strength of timber are known parallel to the grain (grain's angle of 0°) or longitudinal direction, and compressive strength perpendicular to the grain (grain angle of 90°) or radial direction. These two parameters can be obtained from experimental testing in the laboratory using testing standards including ASTM D143-22 (ASTM, 2022) with primary and secondary test methods.

Testing can be carried out using a Universal Testing Machine (UTM) HT-9501 Electro-Hydraulic Servo (maximum load capacity 1000 kN). with output data in the form of a history curve of the relationship between compressive axial load and axial deformation. Figure 1 shows the test equipment used in this research. Figure 2a shows a schematic history of the load vs deformation relationship curve obtained from experimental test results. Next, the curve then converted into a curve for the relationship between stress and strain, where stress (engineering stress) is the compressive axial force divided by the initial cross-sectional area, while strain is the change in length (in this case shortening) divided by the initial length of the test object. Figure 2b shows a schematic of the stress vs strain relationship curve resulting from the conversion of the load vs deformation relationship curve.

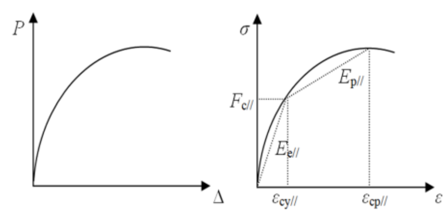
Stress and strain can be calculated using Equation 1 and Equation 2 (Goodno and Gere, 2021).

$$\sigma = P / A \quad (1)$$
$$\varepsilon = \Delta / L_o \quad (2)$$

with σ is engineering stress (MPa), P is axial compressive load (N), A is specimen's cross-section (mm^2), ε is strain (mm/mm), Δ is the change in length of shortening (mm), and L_o is initial length of the specimen (mm).

The testing speed (according to the ASTM D143's primary method) for the test object type parallel to the grain is a strain rate of 0.003 mm/mm per minute or a displacement rate of 0.6 mm per minute. While for the test object type perpendicular to the grain, the speed is a displacement rate of 0.305 mm per minute (ASTM, 2022).

Figure 1. Instrumen for testing using Universal Testing Machine (UTM).



(a). Load-Deformation Curve. (b). Stress-Strain Curve.
Figure 2. Idealization of the axial load vs axial deformation curve and normal (axial) stress vs strain (Pranata and Suryoatmono, 2013).

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Proportional Load and Ultimate Load

The proportional point indicates when material behavior changes from elastic to plastic. One of the methods to calculate the proportional point is the Yasumura and Kawai Method (Munoz et al., 2010). The calculated initial stiffness was between 10% and 40% of the ultimate or peak load. A straight line between 40% and 90% of the peak load and a straight-line tangent to the load-displacement curve, then parallel to the 40% and 90% second line, were determined.

In this research, this method was used to determine the proportional load divided by a cross-section's area, to calculate the compression strength in terms of yield or proportional strength. While the compression strength in terms of ultimate strength was calculated using peak load, divided by cross-section's area..

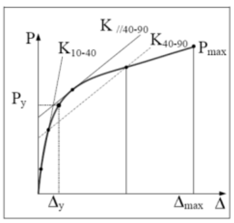

Figure 3. Yasumura and Kawai Method to determine the proportional load of timber (Munoz et.al., 2010).

Polynomial Regression Analysis

Several parameters for statistical data, which are mean, standard deviation, and coefficient of variation, are needed for analysis. Standard deviation measures how they are distributed around the arithmetic mean (Heumann et.al., 2017). A low standard deviation value indicates that the values are highly concentrated around the mean. Meanwhile, the coefficient of variation (usually expressed as a percentage) is a ratio between the standard deviation and the average value. In this research, polynomial regression analysis was carried out with Minitab software (LLC, 2023).

Material and Method

The scope of the research were that the timber studied is the Red Meranti species (*Shorea spp.*), the total number of test objects are 45 test objects. The test specimens with an angle of less than 45° were made and tested based on the primary method reference for compression test specimens reference method 50mm x 50mm x 200mm (parallel to the grain type) according to ASTM D143-22 regulations. This method used for test specimens with variations in fiber direction, namely 0°, 10°, 20° and 30°.

Meanwhile, test objects with an angle of more than 45° with variations in fiber direction, namely 60°, 70°, 80° and 90°, were made and tested with test object sizes of 50mm x 50mm x 150mm (perpendicular to the grain type) in accordance with ASTM D143-22. Testings are carried out using a Universal Testing Machine with test speed according to ASTM D143-22. All test objects were made in dry conditions (moisture content ranging from 14% to 16%). Test objects are made from timber log, with angle dimensions adjusted for testing purposes.

Results and Discussion

The number of compression test specimens in this study were 45 test specimens with grain angle variations ranging 0°, 10°, 20°, 30°, 60°, 70°, 80°, and 90°. All of the specimens for the compression tests were made from 5 (five) Red Meranti timber different logs (defect-free parts). The specimens were made in accordance with primary method of ASTM D143-22 (ASTM, 2022). The speed of test (deformation speed) was also in accordance with ASTM D143-22.

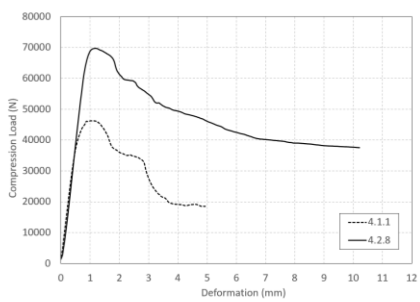

Figure 4. Tests results: Axial load vs deformation curve, obtained from experimental test for specimen 4.1.1 (grain's angle of 30°) and specimen 4.2.8 (grain's angle of 10°).

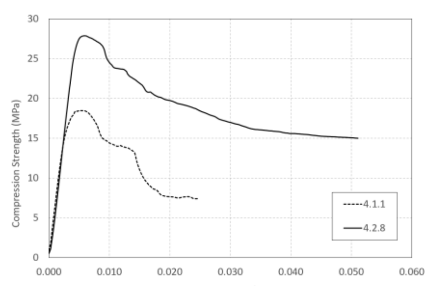

Figure 5. Convertion results: Stress vs strain curves of specimen 4.1.1 (grain's angle of 30°) and specimen 4.2.8 (grain's angle of 10°).

Figure 4 shows an example result obtained from compression test which is axial load vs deformation curve. Figure 5 shows an covertion results, which is calculation of stress and strain curves. The results above show that the test

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Meanwhile, test objects with an angle of more than 45° with variations in fiber direction, namely 60°, 70°, 80° and 90°, were made and tested with perpendicular to the grain type in accordance with ASTM D143-22. All test objects were made in dry conditions (moisture content ranging from 14% to 16%). Test objects are made from timber log, with angle dimensions adjusted for testing purposes.

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Test objects are made from timber log, with angle dimensions adjusted for testing purposes

object with a lower grain angle produces a higher peak load than the test object with a lar`ger grain angle.

Figure 6 shows an example of compression test using parallel to the grain method, while Figure 7 shows an example of compression test speciment with grain angle of 70°.

Figure 6. Experimental tests for 50 x 50 x 200mm specimen, using test method of compression parallel to the grain.

Figure 7. Example of 70° specimen of Red Meranti timber.

Figure 8 shows some of test results of the specimens with dimension 50mm x 50mm x 200mm, while Figure 9 shows some of test results of the specimens with dimension 50mm x 50mm x 200mm.

In this research, the compression strength were calculate in term of proportional load, method to determine the yield point were done using Yasumura and Kawai method (Munoz et.al., 2010), and in term of peak of ultimate load. Table 2 shows the results of calculation of the proportional load, peak load, deformation at proportional load, deformation at peak load, and the grain's angle for all 45 specimens. Table 3 shows the results of calculation of the stress and strain in term of proportional stress and peak stress using Equation 1 and Equation 2.

Table 2. Tests results: Load and deformation obtained from experimental tests and calculation using Yasumura and Kawai Method.

Spec-imens	P_y (N)	P_{peak} (N)	D_y (mm)	D_{peak} (mm)	θ (°)
1	14313.0	26650.6	0.3	5.0	70
2	7932.0	18839.9	0.7	6.0	80
3	18834.1	32409.2	0.4	6.2	60
4	13788.4	25203.8	1.5	6.0	70
5	15479.0	25547.9	0.5	6.0	70
6	29603.0	46987.6	0.3	0.8	30
7	28950.5	46224.6	0.4	1.0	30
8	24203.2	43516.9	0.3	0.8	30
9	123246.1	69692.6	1.6	1.2	10
10	5906.3	14661.3	0.7	6.0	90
11	17531.7	39520.9	0.8	6.1	30
12	16969.8	32393.3	0.5	6.0	60
13	10581.1	21456.7	0.5	6.0	80
14	6994.9	13948.3	1.5	6.0	90
15	37925.6	62397.2	0.4	0.8	10
16	38100.2	53651.3	0.5	0.9	20
17	32993.8	53975.8	0.3	0.8	20
18	56268.3	62644.0	0.7	1.1	10
19	16092.7	33444.2	0.4	6.1	60
20	6041.2	14045.7	1.3	6.1	90
21	5608.1	13160.7	1.2	6.1	90
22	18349.4	27524.6	1.2	6.1	70
23	36903.4	73806.8	0.3	0.8	0
24	39992.2	79984.5	0.8	1.7	0
25	29505.0	77361.8	0.8	1.6	0
26	26908.8	70598.3	0.4	1.1	10
27	28731.6	78258.5	0.5	1.3	0
28	29826.7	80297.5	0.5	1.3	0
29	21269.1	48193.7	0.4	6.1	30
30	24211.4	53836.4	0.5	6.1	20
31	44493.6	74663.0	0.4	0.7	0
32	32710.6	65421.2	0.5	14.5	10
33	40336.6	52428.3	0.4	0.9	20
34	35617.8	71235.7	5.3	1.1	10
35	12995.6	32007.6	0.5	6.1	60
36	6229.3	11832.2	1.4	6.1	90
37	15569.4	27696.7	0.5	6.1	70
38	13269.9	25523.0	0.4	6.2	70
39	11873.1	21078.7	0.7	6.1	80
40	9391.3	17105.2	0.5	6.1	90
41	11103.5	19313.0	0.4	6.1	80
42	18469.9	44526.6	0.6	2.2	30
43	79513.1	46903.8	1.6	1.2	20
44	15292.9	30585.8	0.3	0.9	60
45	19199.5	31501.1	0.3	1.0	60

Table 3. Conversion results: Stress and Strain at proportional and ultimate limit conditions.

Spec-imens	F_{CY} MPa)	F_{CU} (MPa)	ε_y mm/mm)	ε_U mm/mm)	θ (°)
1	5.6	10.4	0.002	0.025	70
2	3.1	7.4	0.003	0.030	80

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Spec-imens	F_{CY} MPa)	F_{CU} (MPa)	ε_y mm/mm)	ε_U mm/mm)	θ (°)
3	7.4	12.7	0.002	0.031	60
4	5.4	9.9	0.008	0.030	70
5	6.1	10.1	0.002	0.030	70
6	11.6	18.4	0.002	0.005	30
7	11.3	18.0	0.002	0.007	30
8	9.6	17.2	0.002	0.006	30
9	13.9	27.8	0.010	0.008	10
10	2.3	5.8	0.004	0.030	90
11	7.0	15.7	0.004	0.031	30
12	6.8	12.9	0.003	0.030	60
13	4.2	8.4	0.003	0.030	80
14	2.7	5.5	0.007	0.030	90
15	14.8	24.4	0.003	0.005	10
16	15.2	21.4	0.003	0.006	20
17	13.2	21.7	0.002	0.006	20
18	12.1	24.6	0.005	0.008	10
19	6.6	13.7	0.002	0.030	60
20	2.5	5.7	0.007	0.030	90
21	2.2	5.2	0.006	0.031	90
22	7.2	10.8	0.006	0.030	70
23	15.0	29.9	0.002	0.005	0
24	15.7	31.4	0.005	0.012	0
25	11.7	30.6	0.005	0.011	0
26	10.6	27.9	0.003	0.007	10
27	11.5	31.3	0.003	0.009	0
28	12.0	32.4	0.003	0.009	0
29	8.8	19.2	0.002	0.030	30
30	9.4	20.9	0.002	0.030	20
31	17.4	29.1	0.002	0.005	0
32	12.8	25.5	0.003	0.096	10
33	15.4	20.1	0.002	0.006	20
34	13.6	27.2	0.035	0.008	10
35	5.3	13.1	0.002	0.030	60
36	2.6	4.9	0.007	0.030	90
37	6.4	11.4	0.002	0.031	70
38	5.4	10.4	0.002	0.031	70
39	4.9	8.6	0.003	0.030	80
40	3.9	7.0	0.002	0.030	90
41	4.5	7.9	0.002	0.031	80
42	7.6	18.2	0.004	0.015	30
43	9.6	19.2	0.011	0.008	20
44	6.3	12.6	0.002	0.006	60
45	7.8	12.8	0.002	0.007	60

P_Y is propotional load (yield point), P_U is ultimate load (peak load), D_Y is axial deformation at proportional or yield point, D_U is axial deformation at peak load, and θ is angle of grain. F_{CY} is compression strength in term of yield point or proportional load, F_{CU} is compression strength in term of ultimate or peak load, ε_Y is strain in term of yield point or proportional load, and ε_U is peak strain.

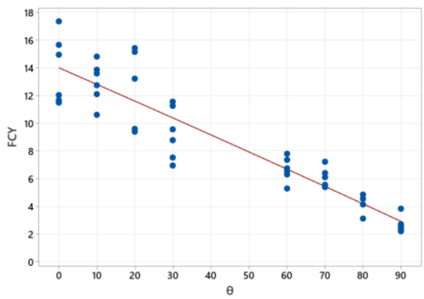

Figure 8. Results obtained from polynomial regression analysis.

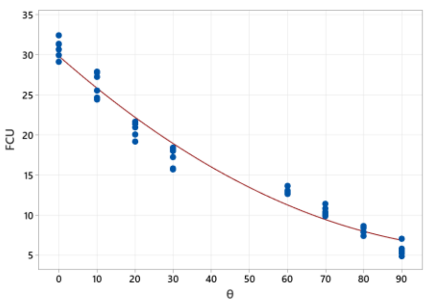

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Figure 8 shows the result obtained experimentally (F_{CY}) and the equation-curve obtained from the polynomial regression analysis to predict the value of compression strength of Red Meranti timber in term of proportional or yield point, this empirical equation result shows the relationship between the compression strength (unit in MPa) and the grain angle θ (unit in degrees). The coefficient of R^2 is generally it is relatively near 100%, for timber this is considered normal because timber is a material that comes from nature. The regression equation for the curve in Figure 10 is shown in Equation 3 and Equation 4.

$$F_{CY} = 14.01 - 0.119\theta + 0.000042\theta^2 \quad (3)$$

$$R^2 = 85.52\% \quad (4)$$

Figure 9 shows the result obtained experimentally (F_{CU}) and the equation-curve obtained from the polynomial regression analysis to predict the value of compression strength of Red Meranti timber in term of peak or ultimate point, this empirical equation result shows the relationship between the compression strength (unit in MPa) and the grain angle θ (unit in degrees). The coefficient of R^2 is generally it is relatively near 100%, for timber this is considered normal because timber is a material that comes from nature. The regression equation for the curve in Figure 10 is shown in Equation 5 and Equation 6.

$$F_{CU} = 29.82 - 0.417\theta + 0.0018\theta^2 \quad (5)$$
$$R^2 = 96.56\% \quad (6)$$

Conclusions

The conclusion obtained from this research is an empirical equation for calculating the compressive strength of Red Meranti timber (*Shorea spp.*) with a predictor, namely the wood grain's angle, namely $F_{CY} = 14.01 – 0.119\theta + 0.000042\theta^2$ with $R^2 = 85.52\%$ in term of yield or proportional point. While in term of peak or ultimate load, an empirial equation is $F_{CU} = 29.82 – 0.417\theta + 0.0018\theta^2$ with $R^2 = 96.56\%$.

F_{CY} or compression strength in term of proportional load is an useful parameter for design of column or compression member in timber building, timber bridge truss, or timber roof truss in accordance with SNI 7973:2013. This equation provides benefits for academics and practitioners, especially in designing compression structural components, which is the compression design value parameter.

Acknowledgements

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References

American Standard Testing and Material. 2022. ASTM D143-22 Standard Test Methods for Small Clear Specimens of Timber, West Conshohocken, Pennsylvania, United States, 2022.

American Standard Testing and Material. 2018. ASTM D5764-97a Standard Test Method for Evaluating Dowel-Bearing Strength of Wood and Wood-Based Products, West Conshohocken, Pennsylvania, United States, 2018.

Azmi, A., Ahmad, Z., Lum, W.C., Baharin, A., Za'ba N.I.L., Bhkari, N.M., Lee, S.H. 2022. Compressive Strength Characteristic Values of Nie Structural Sized Malaysian Tropical Hardwoods, Forests 2022, 13(8), 1172; https://doi.org/10.3390/f13081172.

Bodig, J., Jayne, B.A. 1993. Mechanics of Wood and Wood Composites, Krieger Publishing Company, Malabar, Florida, USA, 1993.

Chik, E.A.R. 1988. Basic And Grade Stresses For Some Malaysian Timbers. Malayan Forest Service Trade Leaflet No.38. The Malaysian Timber Industry Board And Forest Research Institute Malaysia, Kuala Lumpur 13 pp.

Goodno, B.J., Gere, J.M. 2021. Mechanics of Materials 9th Edition, ISBN-13: 9780357377857, Cengage Learning Asia.

Heumann, Christian, Michael Schomaker, Shalabh. 2017. Introduction to Statistics and Data Analysis: With Exercises, Solutions and Applications in R. Introduction to Statistics and Data Analysis: With Exercises, Solutions and Applications in R. Springer International Publishing, 2017.

Tjondro, A., Suryoatmono, B., Imran, I. 2016, Non-linier Compression Stress-Strain Curve Model for Hardwood, Jurnal Teknik Sipil Mekanika, Volume 1 No. 1, pp. 49-52, June 2016.

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Meier, E. The Wood database, URL: https://www.wood-database.com/worlds-strongest-woods, accessed on 15 October 2024.

Munoz, W., Mohammad, M., Salenikovich, A. & Quenneville, P. 2010. Determination of Yield Point and Ductility of Timber Assemblies: In Search for a Harmonized Approach, Engineered Wood Products Association, 2010.

Nakai, T. 1985. Mechanical Properties of Tropical Woods, JARQ Volume 18 No. 4, pp. 315-323, 1985.

Pranata, Y.A., Suryoatmono, B. 2013. Nonlinear Finite Elemen Modeling of Red Meranti Compression at an Angle to the Grain, Journal of Engineering and Technological Science, Volume 45 No. 3, pp. 222-240, 2013.

Pranata, Y.A., Suryoatmono, B. 2012. Distortion Energy Criterion for Timber Uniaxial Compression Mechanical Properties, Jurnal Dinamika Teknik Sipil, Volume 12 No. 02, May 2012 (in Indonesian).

Commented [L21]: Is this the suit term?

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November 6th, 2024

Yosafat Aji Pranata
Universitas Kristen Maranatha
Jl. Suria Sumantri 65, Bandung, 40164, Jawa Barat

Dear **Yosafat Aji Pranata**,

We would like to inform you that your paper entitled:

" Study of the Effect of Grain Angle on the Compressive Strength of Red Meranti Timber (*Shorea spp.*)"

Yosafat Aji Pranata, Anang Kristianto, Novi

has been accepted to be published at Wood Research Journal Vol. 15 No. 1, 2024.

Wood Research Journal is the official journal of the Indonesian Wood Research Society. This journal is an international medium in exchanging, sharing and discussing the science and technology of wood. The journal publishes original manuscripts of basic and applied research of wood science and technology related to Anatomy, Properties, Quality Enhancement, Machining, Engineering and Constructions, Panel and Composites, Entomology and Preservation, Chemistry, Non Wood Forest Products, Pulp and Papers, Biomass Energy, and Biotechnology. Besides that, this journal also publishes review manuscripts which topics are decided by the Editors. Published articles and other information are available at the journal's website, http://ejournalmapeki.org/.

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Editor in Chief

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Wood Research Journal: Indonesian Wood Research Society accredited "PERINGKAT 3"

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Posted: 2022-09-26

Study of the Effect of Grain Angle on the Compressive Strength of Red Meranti Timber (*Shorea spp.*)

Abstract

The compressive strength of timber is the main parameter in design of timber bridges (truss system), building roof (truss system), or column in buildings. In term of design of compression structural components according to the SNI 7973:2013 reference, the corrected compression design value is a calculation of compressive strength parameters and correction factors, for example, wet service factors, temperature factors, column stability factors, and others. Timber as an orthotropic material has three main directions, therefore the angle of the timber grain has an influence on compressive strength. This research aims to study the effect of timber grain's angle on the compressive strength of Red Meranti wood (*Shorea spp*.) and develop an empirical equation to calculate the compressive strength of timber with the influence of angle of grain. The scope of the research were that the timber studied is the Red Meranti species (*Shorea spp*.), the total number of test objects are 45 test objects. The test specimens were made based on the primary method reference for compression test specimens reference method 50mm x 50mm x 200mm (parallel to the grain type), according to ASTM D143-22 regulations for test specimens with variations in fiber direction, namely 0°, 10°, 20° and 30°. Meanwhile, test objects with variations in fiber direction, namely 60°, 70°, 80° and 90°, were made with test object sizes of 50mm x 50mm x 150mm (perpendicular to the grain type). Testings are carried out using a Universal Testing Machine with test speed according to ASTM D143-22. All test objects were made in dry conditions (moisture content ranging from 14% to 16%). The conclusion obtained from this research are an empirical equation for calculating the compressive strength of Red Meranti timber (*Shorea spp*.) with a predictor is the timber grain's angle, which are $F_{CY} = 14.01 - 0.119\theta + 0.000042\theta^2$ (in term of yield of proportional point) and $F_{CU} = 29.82 - 0.417\theta + 0.0018\theta^2$ (in term of peak or ultimate point). This equation provides benefits for academics and practitioners, especially in designing compression structural components, which is the compression design value parameter.

Keywords: Compression Strength, grain angle of timber, Red Meranti, empirical equation.

Introduction

The compressive strength of timber is the main parameter in design of timber bridges (truss system), building roof (truss system), or column in buildings. In term of design of compression structural components according to the SNI 7973:2013 reference (BSN, 2013), the corrected compression design value is a calculation of compressive strength parameters and correction factors, for example, wet service factors, temperature factors, column stability factors, and others. Previous research related to timber properties, especially the compressive strength of Meranti species wood, has been carried out several times, before. Timber as an orthotropic material has three main directions, so the angle of the timber grain has an influence on compressive strength.

This research aims to study the effect of timber grain's angle on the compressive strength of Red Meranti wood (*Shorea spp*.) and develop an empirical equation to calculate the compressive strength of timber with the influence of wood grain's angle.

The scope of the research were that:

1. The timber studied is the Red Meranti species (*Shorea spp*.).
2. The total number of test objects are 45 test objects.
3. The test specimens were made based on the primary method reference for compression test specimens reference method 50mm x 50mm x 200mm (parallel to the grain type), according to ASTM D143-22 regulations for test specimens with variations in fiber direction, namely 0°, 10°, 20° and 30°. Meanwhile, test objects with variations in fiber direction, namely 60°, 70°, 80° and 90°, were made with test object sizes of 50mm x 50mm x 150mm (perpendicular to the grain type).
4. Testings are carried out using a Universal Testing Machine with test speed according to ASTM D143-22.
5. All test objects were made in dry conditions (moisture content ranging from 14% to 16%).
6. The compressive strength referred to in this research is the compressive stress calculated under peak or ultimate load condition (F_{CU}) and proportional load condition (F_{CY}).
7. Test objects are made from timber log, with angle dimensions adjusted for testing purposes.

Basic Theories and Methods

Previous Research History

Previous research related to timber properties, especially the compressive strength of Meranti species wood, has been carried out several times, namely experimental research on timber compression testing with several variations in grain angles (Pranata and Suryoatmono, 2012) for 3 (three) types of wood, namely Acacia, Meranti, and Keruing, with the results being an alternative von Mises-based equation for calculating the compressive strength of wood, this research is limited to only a few grain's angles and a limited number of test objects. The next research is experimental and numerical research to study the effect of grain's angle on the compressive strength of Red Meranti wood (Pranata and Suryoatmono, 2013) with variations in fiber angles of 12°, 60°, and 80°.

Compression Strength

Wood is generally assumed to behave as mutually perpendicular material principal axes, namely and tangential axes. Compressive strength is the compressive force that acts on a unit cross-sectional area of wood that is subjected to that force. Compressive strength of wood defines the limit of wood's ability to accept compressive loads until the wood fails. Previous study of Red Meranti (shorea spp.) compression strength were done by Nakai (Nakai, 1985), Chik (Chik, 1988), Pranata and Suryoatmono (Pranata and Suryoatmono, 2012; Pranata and Suryoatmono, 2013), Tjondro et al. (Tjondro et al., 2016), Azmi et al. (Azmi et al., 2022), and wood database (Meier, 2024). Table 1 shows the summary of compression strength of Red Meranti (Shorea spp.) timber obtained from previous research histories.

Table 1. Compression strength of Red Meranti (*Shorea spp.*) Timber from previous research histories.

References	θ (°)	F_{CY} (MPa)	F_{CU} (MPa)
Nakai, 1985	0	31.60	36.50
Azmi et.al., 2022	0	31.30	-
Meier, 2024	0	33.90	-
Tjondro et.al.,	0	30.78	41.21
	90	7.51	-
Chik, 1988	0	-	39.60
	90	-	4.14
Pranata and Suryoatmono, 2012; Pranata and Suryoatmono, 2013	0	33.67	-
	5	31.16	-
	10	28.55	-
	12	27.82	33.30
	60	8.52	9.10
	80	7.68	8.10
	90	7.17	-

Compression Tests

Currently, the parameters for compressive strength of timber are known parallel to the grain (grain's angle of 0°) or longitudinal direction, and compressive strength perpendicular to the grain (grain angle of 90°) or radial direction. These two parameters can be obtained from experimental testing in the laboratory using testing standards including ASTM D143-22 (ASTM, 2022) with primary and secondary test methods.

Testing can be carried out using a Universal Testing Machine (UTM) HT-9501 Electro-Hydraulic Servo (maximum load capacity 1000 kN). with output data in the form of a history curve of the relationship between compressive axial load and axial deformation. Figure 1 shows the test equipment used in this research. Figure 2a shows a schematic history of the load vs deformation relationship curve obtained from experimental test results. Next, the curve then converted into a curve for the relationship between stress and strain, where stress (engineering stress) is the compressive axial force divided by the initial cross-sectional area, while strain is the change in length (in this case shortening) divided by the initial length of the test object. Figure 2b shows a schematic of the stress vs strain relationship curve resulting from the conversion of the load vs deformation relationship curve.

Stress and strain can be calculated using Equation 1 and Equation 2 (Goodno and Gere, 2021).

$$\sigma = P / A \quad (1)$$

$$\varepsilon = \Delta / L_o \quad (2)$$

with σ is engineering stress (MPa), P is axial compressive load (N), A is specimen's cross-section (mm^2), ε is strain (mm/mm), Δ is the change in length of shortening (mm), and L_o is initial length of the specimen (mm).

The testing speed (according to the ASTM D143's primary method) for the test object type parallel to the grain is a strain rate of 0.003 mm/mm per minute or a displacement rate of 0.6 mm per minute. While for the test object type perpendicular to the grain, the speed is a displacement rate of 0.305 mm per minute (ASTM, 2022).

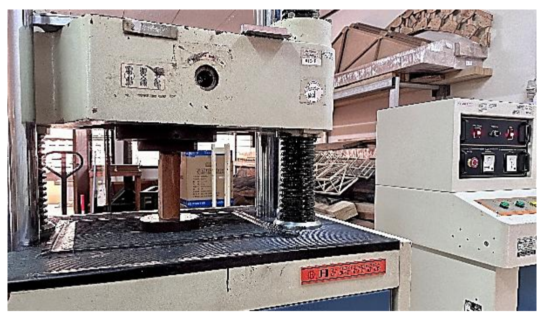
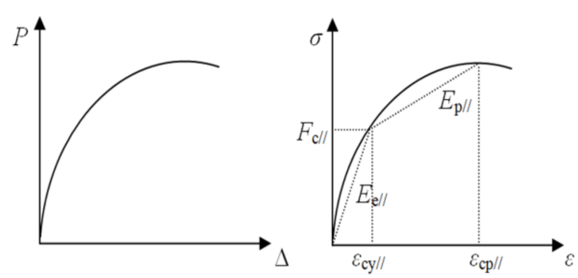


Figure 1. Instrumen for testing using Universal Testing Machine (UTM).



(a). Load-Deformation Curve. (b). Stress-Strain Curve.
Figure 2. Idealization of the axial load vs axial deformation curve and normal (axial) stress vs strain (Pranata and Suryoatmono, 2013).

Proportional Load and Ultimate Load

The proportional point indicates when material behavior changes from elastic to plastic. One of the methods to calculate the proportional point is the Yasumura and Kawai Method (Munoz et al., 2010). The calculated initial stiffness was between 10% and 40% of the ultimate or peak load. A straight line between 40% and 90% of the peak load and a straight-line tangent to the load-displacement curve, then parallel to the 40% and 90% second line, were determined.

In this research, this method was used to determine the proportional load divided by a cross-section's area, to calculate the compression strength in terms of yield or proportional strength. While the compression strength in terms of ultimate strength was calculated using peak load, divided by cross-section's area..

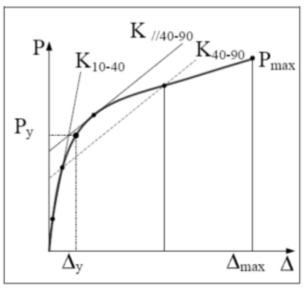


Figure 3. Yasumura and Kawai Method to determine the proportional load of timber (Munoz et.al., 2010).

Polynomial Regression Analysis

Several parameters for statistical data, which are mean, standard deviation, and coefficient of variation, are needed for analysis. Standard deviation measures how they are distributed around the arithmetic mean (Heumann et.al., 2017). A low standard deviation value indicates that the values are highly concentrated around the mean. Meanwhile, the coefficient of variation (usually expressed as a percentage) is a ratio between the standard deviation and the average value. In this research, polynomial regression analysis was carried out with Minitab software (LLC, 2023).

Material and Method

The scope of the research were that the timber studied is the Red Meranti species (*Shorea spp.*), the total number of test objects are 45 test objects. The test specimens with an angle of less than 45° were made and tested based on the primary method reference for compression test specimens reference method 50mm x 50mm x 200mm (parallel to the grain type) according to ASTM D143-22 regulations. This method used for test specimens with variations in fiber direction, namely 0°, 10°, 20° and 30°.

Meanwhile, test objects with an angle of more than 45° with variations in fiber direction, namely 60°, 70°, 80° and 90°, were made and tested with test object sizes of 50mm x 50mm x 150mm (perpendicular to the grain type) in accordance with ASTM D143-22. Testings are carried out using a Universal Testing Machine with test speed according to ASTM D143-22. All test objects were made in dry conditions (moisture content ranging from 14% to 16%). Test objects are made from timber log, with angle dimensions adjusted for testing purposes.

Results and Discussion

The number of compression test specimens in this study were 45 test specimens with grain angle variations ranging 0°, 10°, 20°, 30°, 60°, 70°, 80°, and 90°. All of the specimens for the compression tests were made from 5 (five) Red Meranti timber different logs (defect-free parts). The specimens were made in accordance with primary method of ASTM D143-22 (ASTM, 2022). The speed of test (deformation speed) was also in accordance with ASTM D143-22.

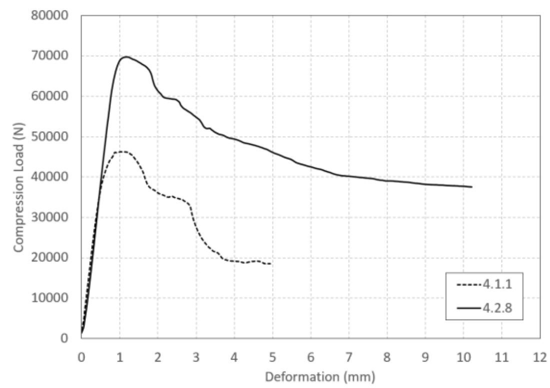


Figure 4. Tests results: Axial load vs deformation curve, obtained from experimental test for specimen 4.1.1 (grain's angle of 30°) and specimen 4.2.8 (grain's angle of 10°).

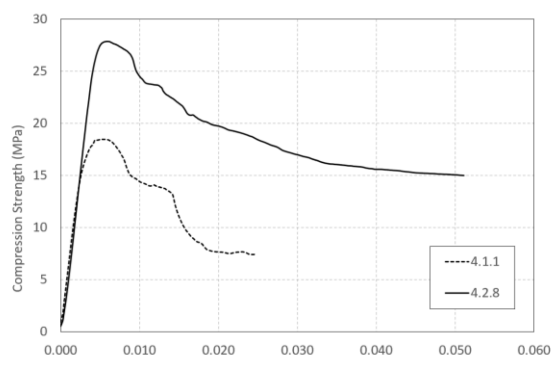


Figure 5. Convertion results: Stress vs strain curves of specimen 4.1.1 (grain's angle of 30°) and specimen 4.2.8 (grain's angle of 10°).

Figure 4 shows an example result obtained from compression test which is axial load vs deformation curve. Figure 5 shows an covertion results, which is calculation of stress and strain curves. The results above show that the test object with a lower grain angle produces a higher peak load than the test object with a lar`ger grain angle.

Figure 6 shows an example of compression test using parallel to the grain method, while Figure 7 shows an example of compression test speciment with grain angle of 70°.

Figure 6. Experimental tests for 50 x 50 x 200mm specimen, using test method of compression parallel to the grain.

Figure 7. Example of 70° specimen of Red Meranti timber.

Figure 8 shows some of test results of the specimens with dimension 50mm x 50mm x 200mm, while Figure 9 shows some of test results of the specimens with dimension 50mm x 50mm x 200mm.

In this research, the compression strength were calculate in term of proportional load, method to determine the yield point were done using Yasumura and Kawai method (Munoz et.al., 2010), and in term of peak of ultimate load. Table 2 shows the results of calculation of the proportional load, peak load, deformation at proportional load, deformation at peak load, and the grain's angle for all 45 specimens. Table 3 shows the results of calculation of the stress and strain in term of proportional stress and peak stress using Equation 1 and Equation 2.

Table 2. Tests results: Load and deformation obtained from experimental tests and calculation using Yasumura and Kawai Method.

Spec-imens	P_y (N)	P_{peak} (N)	D_y (mm)	D_{peak} (mm)	θ (°)
1	14313.0	26650.6	0.3	5.0	70
2	7932.0	18839.9	0.7	6.0	80
3	18834.1	32409.2	0.4	6.2	60
4	13788.4	25203.8	1.5	6.0	70
5	15479.0	25547.9	0.5	6.0	70
6	29603.0	46987.6	0.3	0.8	30
7	28950.5	46224.6	0.4	1.0	30
8	24203.2	43516.9	0.3	0.8	30
9	123246.1	69692.6	1.6	1.2	10
10	5906.3	14661.3	0.7	6.0	90
11	17531.7	39520.9	0.8	6.1	30
12	16969.8	32393.3	0.5	6.0	60
13	10581.1	21456.7	0.5	6.0	80
14	6994.9	13948.3	1.5	6.0	90
15	37925.6	62397.2	0.4	0.8	10
16	38100.2	53651.3	0.5	0.9	20
17	32993.8	53975.8	0.3	0.8	20
18	56268.3	62644.0	0.7	1.1	10
19	16092.7	33444.2	0.4	6.1	60
20	6041.2	14045.7	1.3	6.1	90
21	5608.1	13160.7	1.2	6.1	90
22	18349.4	27524.6	1.2	6.1	70
23	36903.4	73806.8	0.3	0.8	0
24	39992.2	79984.5	0.8	1.7	0
25	29505.0	77361.8	0.8	1.6	0
26	26908.8	70598.3	0.4	1.1	10
27	28731.6	78258.5	0.5	1.3	0
28	29826.7	80297.5	0.5	1.3	0
29	21269.1	48193.7	0.4	6.1	30
30	24211.4	53836.4	0.5	6.1	20
31	44493.6	74663.0	0.4	0.7	0
32	32710.6	65421.2	0.5	14.5	10
33	40336.6	52428.3	0.4	0.9	20
34	35617.8	71235.7	5.3	1.1	10
35	12995.6	32007.6	0.5	6.1	60
36	6229.3	11832.2	1.4	6.1	90
37	15569.4	27696.7	0.5	6.1	70
38	13269.9	25523.0	0.4	6.2	70
39	11873.1	21078.7	0.7	6.1	80
40	9391.3	17105.2	0.5	6.1	90
41	11103.5	19313.0	0.4	6.1	80
42	18469.9	44526.6	0.6	2.2	30
43	79513.1	46903.8	1.6	1.2	20
44	15292.9	30585.8	0.3	0.9	60
45	19199.5	31501.1	0.3	1.0	60

Table 3. Conversion results: Stress and Strain at proportional and ultimate limit conditions.

Spec-imens	F_{CY} MPa)	F_{CU} (MPa)	ε_y mm/mm)	ε_U mm/mm)	θ (°)
1	5.6	10.4	0.002	0.025	70
2	3.1	7.4	0.003	0.030	80

Spec-imens	F_{CY} MPa)	F_{CU} (MPa)	ε_y mm/mm)	ε_U mm/mm)	θ (°)
3	7.4	12.7	0.002	0.031	60
4	5.4	9.9	0.008	0.030	70
5	6.1	10.1	0.002	0.030	70
6	11.6	18.4	0.002	0.005	30
7	11.3	18.0	0.002	0.007	30
8	9.6	17.2	0.002	0.006	30
9	13.9	27.8	0.010	0.008	10
10	2.3	5.8	0.004	0.030	90
11	7.0	15.7	0.004	0.031	30
12	6.8	12.9	0.003	0.030	60
13	4.2	8.4	0.003	0.030	80
14	2.7	5.5	0.007	0.030	90
15	14.8	24.4	0.003	0.005	10
16	15.2	21.4	0.003	0.006	20
17	13.2	21.7	0.002	0.006	20
18	12.1	24.6	0.005	0.008	10
19	6.6	13.7	0.002	0.030	60
20	2.5	5.7	0.007	0.030	90
21	2.2	5.2	0.006	0.031	90
22	7.2	10.8	0.006	0.030	70
23	15.0	29.9	0.002	0.005	0
24	15.7	31.4	0.005	0.012	0
25	11.7	30.6	0.005	0.011	0
26	10.6	27.9	0.003	0.007	10
27	11.5	31.3	0.003	0.009	0
28	12.0	32.4	0.003	0.009	0
29	8.8	19.2	0.002	0.030	30
30	9.4	20.9	0.002	0.030	20
31	17.4	29.1	0.002	0.005	0
32	12.8	25.5	0.003	0.096	10
33	15.4	20.1	0.002	0.006	20
34	13.6	27.2	0.035	0.008	10
35	5.3	13.1	0.002	0.030	60
36	2.6	4.9	0.007	0.030	90
37	6.4	11.4	0.002	0.031	70
38	5.4	10.4	0.002	0.031	70
39	4.9	8.6	0.003	0.030	80
40	3.9	7.0	0.002	0.030	90
41	4.5	7.9	0.002	0.031	80
42	7.6	18.2	0.004	0.015	30
43	9.6	19.2	0.011	0.008	20
44	6.3	12.6	0.002	0.006	60
45	7.8	12.8	0.002	0.007	60

P_Y is propotional load (yield point), P_U is ultimate load (peak load), D_Y is axial deformation at proportional or yield point, D_U is axial deformation at peak load, and θ is angle of grain. F_{CY} is compression strength in term of yield point or proportional load, F_{CU} is compression strength in term of ultimate or peak load, ε_Y is strain in term of yield point or proportional load, and ε_U is peak strain.

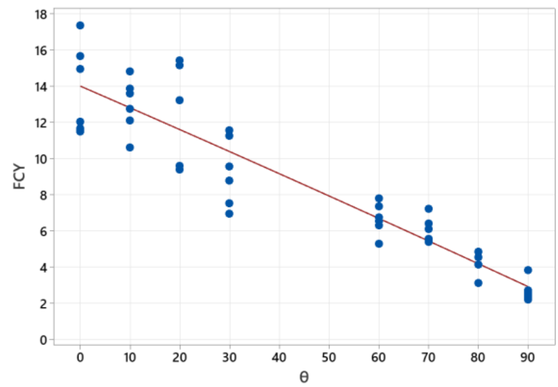


Figure 8. Results obtained from polynomial regression analysis.

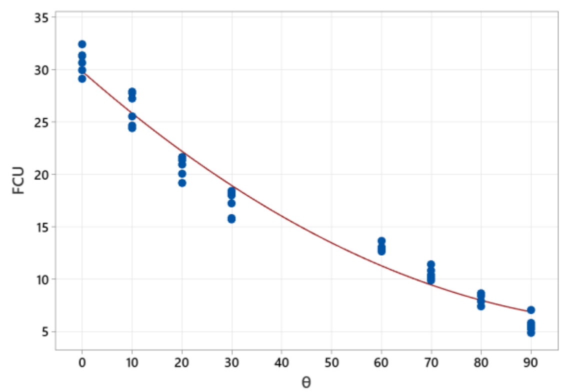


Figure 9. Results obtained from polynomial regression analysis.

Figure 8 shows the result obtained experimentally (F_{CY}) and the equation-curve obtained from the polynomial regression analysis to predict the value of compression strength of Red Meranti timber in term of proportional or yield point, this empirical equation result shows the relationship between the compression strength (unit in MPa) and the grain angle θ (unit in degrees). The coefficient of R^2 is generally it is relatively near 100%, for timber this is considered normal because timber is a material that comes from nature. The regression equation for the curve in Figure 10 is shown in Equation 3 and Equation 4.

$$F_{CY} = 14.01 - 0.119\theta + 0.000042\theta^2 \quad (3)$$

$$R^2 = 85.52\% \quad (4)$$

Figure 9 shows the result obtained experimentally (F_{CU}) and the equation-curve obtained from the polynomial regression analysis to predict the value of compression strength of Red Meranti timber in term of peak or ultimate point, this empirical equation result shows the relationship between the compression strength (unit in MPa) and the grain angle θ (unit in degrees). The coefficient of R^2 is generally it is relatively near 100%, for timber this is considered normal because timber is a material that comes from nature. The regression equation for the curve in Figure 10 is shown in Equation 5 and Equation 6.

$$F_{CU} = 29.82 - 0.417\theta + 0.0018\theta^2 \quad (5)$$
$$R^2 = 96.56\% \quad (6)$$

Conclusions

The conclusion obtained from this research is an empirical equation for calculating the compressive strength of Red Meranti timber (*Shorea spp*.) with a predictor, namely the wood grain's angle, namely $F_{CY} = 14.01 – 0.119\theta + 0.000042\theta^2$ with $R^2 = 85.52\%$ in term of yield or proportional point. While in term of peak or ultimate load, an empirial equation is $F_{CU} = 29.82 – 0.417\theta + 0.0018\theta^2$ with $R^2 = 96.56\%$.

F_{CY} or compression strength in term of proportional load is an useful parameter for design of column or compression member in timber building, timber bridge truss, or timber roof truss in accordance with SNI 7973:2013. This equation provides benefits for academics and practitioners, especially in designing compression structural components, which is the compression design value parameter.

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References

American Standard Testing and Material. 2022. ASTM D143-22 Standard Test Methods for Small Clear Specimens of Timber, West Conshohocken, Pennsylvania, United States, 2022.

American Standard Testing and Material. 2018. ASTM D5764-97a Standard Test Method for Evaluating Dowel-Bearing Strength of Wood and Wood-Based Products, West Conshohocken, Pennsylvania, United States, 2018.

Azmi, A., Ahmad, Z., Lum, W.C., Baharin, A., Za'ba N.I.L., Bhkari, N.M., Lee, S.H. 2022. Compressive Strength Characteristic Values of Nie Structural Sized Malaysian Tropical Hardwoods, Forests 2022, 13(8), 1172; https://doi.org/10.3390/f13081172.

Bodig, J., Jayne, B.A. 1993. Mechanics of Wood and Wood Composites, Krieger Publishing Company, Malabar, Florida, USA, 1993.

Chik, E.A.R. 1988. Basic And Grade Stresses For Some Malaysian Timbers. Malayan Forest Service Trade Leaflet No.38. The Malaysian Timber Industry Board And Forest Research Institute Malaysia, Kuala Lumpur 13 pp.

Goodno, B.J., Gere, J.M. 2021. Mechanics of Materials 9th Edition, ISBN-13: 9780357377857, Cengage Learning Asia.

Heumann, Christian, Michael Schomaker, Shalabh. 2017. Introduction to Statistics and Data Analysis: With Exercises, Solutions and Applications in R. Introduction to Statistics and Data Analysis: With Exercises, Solutions and Applications in R. Springer International Publishing, 2017.

Tjondro, A., Suryoatmono, B., Imran, I. 2016, Non-linier Compression Stress-Strain Curve Model for Hardwood, Jurnal Teknik Sipil Mekanika, Volume 1 No. 1, pp. 49-52, June 2016.

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Meier, E. The Wood database, URL: https://www.wood-database.com/worlds-strongest-woods, accessed on 15 October 2024.

Munoz, W., Mohammad, M., Salenikovich, A. & Quenneville, P. 2010. Determination of Yield Point and Ductility of Timber Assemblies: In Search for a Harmonized Approach, Engineered Wood Products Association, 2010.

Nakai, T. 1985. Mechanical Properties of Tropical Woods, JARQ Volume 18 No. 4, pp. 315-323, 1985.

Pranata, Y.A., Suryoatmono, B. 2013. Nonlinear Finite Elemen Modeling of Red Meranti Compression at an Angle to the Grain, Journal of Engineering and Technological Science, Volume 45 No. 3, pp. 222-240, 2013.

Pranata, Y.A., Suryoatmono, B. 2012. Distortion Energy Criterion for Timber Uniaxial Compression Mechanical Properties, Jurnal Dinamika Teknik Sipil, Volume 12 No. 02, May 2012 (in Indonesian).