Study on Mechanical Properties of Tropical Timber Hardwood Species: Promoting Javanese Inferior Timbers for Traditional Wooden Houses

Yulianto P Prihatmaji, Akihisa Kitamori, Satoru Murakami and Kohei Komatsu

Abstract

Recent earthquake hitting Java Island in Indonesia has caused many damaged to Javanese wooden houses, including Joglo-type building. The Traditional wooden houses use Teak wood or locally known as Jati (*Tectona grandis*) and Nangka wood (*Artocarpus heterophyllus*) as the primary construction material for both building structure and ornaments. Repair or reconstruction of the damaged house needs the same wood material (Teak wood) in order to get the same strength, durability, and prestige. Unfortunately, obtaining Teak wood in sufficient size is difficult because of limited quantity and very expensive price. Therefore, promoting substitute wood material having similar mechanical properties to Teak wood is needed. To understand the mechanical properties of timber for Javanese timber house, compression test, three point bending test, four point bending test and four point shear test were carried out in radial and tangential direction.

In this paper, authors showed substitute wood materials for Javanese timber houses from tropical timber. A total of 840 specimens made from 9 tropical timber species were tested. All tropical timber specimens showed that the MOE (Modulus of elasticity) had strong relationship with density. There was a clear trend that smaller density indicated smaller MOE. Yield stress described strong relationship with densities. From all specimens tested, shear modulus, shear strength and MOR showed quite strong relationship with densities. In terms of shear modulus, Acacia, Jati and Nangka had quite similar mechanical properties. For shear strength, Nangka closely resembled Jati while glued-Acacia had equal mechanical properties to Jati in terms of MOR.

Keywords: tropical timber, mechanical properties, traditional joint system, Javanese timber structure.

Introduction

Recent earthquake hitting Java Island in Indonesia has caused damage to many buildings, including Javanese wooden houses. Javanese timber structures of Joglo-type house have the most complicated and sophisticated roof type in terms of the construction and techniques of Javanese wooden houses. The Joglo use Teak wood (*Tectona grandis*) or Jati wood (local name) as the primary construction material for both the building structure and ornaments. The houses use a knock down construction method using mortise and tenon.

The repair or reconstruction of damaged house requires the same material (Teak wood) in relation with strength, durability and prestige. Reconstruction must be carried out using the same material that comply the local wisdom and the minimum standards of structural strength. Prihatmaji (2010b) summarized the work carried out to characterize physical properties, mechanical properties and chemical properties in order to identify the original material of Manggarai traditional building in Flores, Indonesia. If the original materials are not usable due to damage, they should be substituted with suitable equal material (Jogja Heritage Society 2007). Nowadays, obtaining Jati wood in sufficient size is difficult because of limited quantity and very expensive price (Yahmo 2007). Searching of substitute material is needed in consideration with mechanical properties of Teak wood. In this paper, comparison of substitute material for Javanese wooden house was carried out associated with mechanical properties of tropical timber.

Study on tropical hardwood timber species in relation with MOE and MOR have been carried out. Prihatmaji *et al*. (2011) did compression test on 288 specimens made from 6 tropical timber species. All of tropical timber specimens showed strong correlation between MOE (Modulus of elasticity) and density. There was a clear trend that smaller density indicated smaller MOE. Jati, Nangka, Sonokeling, Ketepeng and Acacia had similar increasing mechanical properties as the density increased while in the case of Falcata specimen, its mechanical properties were stagnant. Bigger density indicated bigger MOE. Acacia and Ketepeng have MOE and density closely resembled Jati. Both specimens also demonstrated similar trend to that of mechanical properties of Jati.

Traditional joint construction use mortise and tenon system of which embedment in joints occurred. Compression and partial compression properties, bending and shear properties are quite important for traditional joint construction. Relationship between mechanical properties and density of tropical timber were especially studied. Therefore, re-evaluation of shear strength, shear modulus and young modulus perpendicular to the grain of tropical timber is needed. In this paper, authors showed alternative materials for traditional wooden houses from tropical hardwood timber species including those that have been regarded as inferior timbers, associated with their mechanical properties. Comparison of mechanical properties (Young's modulus and Yield stress) among each material in each test on compression, bending and shear will be shown. A total of 840 specimens made from 9 tropical timber species were tested.

Materials and Methods

In this study, 9 kinds of tropical timbers tested were selected by purposive random sampling method. The 9 hardwood species chosen were Jati (*Tectona grandis* L.f.), Nangka (*Artocarpus heterophyllus*), Sonokeling (*Dalbergia latifolia* Roxb), Ketepeng (*Terminalia catappa*), Acacia (*Acacia mangium*), Falcata (*Paraserianthes falcataria*), Mindi (*Melia azedarach* L), Wadang (*Pterospermum javanicum*) and Ulin (*Eusideroxylon zwagerii* T et B).

According to tropical timber grading issued by Pendidikan Industri Kayu Atas (1981), there are 5 grades of timber in terms of strength. In this study, 5 timbers represented second grade (Acacia, Jati, Ketepeng, Nangka and Sonokeling), 3 timbers represented third grade (Mindi, Wadang and Falcata) and 1 timber represented first grade (Ulin). Jati (as an original building material), Ulin (first grade) and glued-Acacia will be used as control specimens for mechanical property testing. All specimens were sent from several small timber shops in Yogyakarta, Indonesia which were chosen from available materials, except Acacia came from Bandung, Indonesia, Ulin from Pontianak, Kalimantan, Falcata was taken from Okinawa, Japan and glued-Acacia was manufactured at Osaka, Japan.

All of the 840 structural size timber specimens were tested using compression test (full compression and partial compression), three point and four points bending test, and four points shear test in radial and tangential direction using Instron 100kN to measure their mechanical properties. Prior to testing, all of the specimens were put in a chamber with temperature of 22°C and humidity of 60% for 2 months. Acacia wood has been stored for 2 years outdoor covered. Following the test, all specimens were oven dried at temperature of 105°C for a week. Moisture content of specimens was obtained from the difference between weights after and before drying. Density was measured by dividing the oven-dried weight by the volume.

Compression test

Altogether, 480 structural size timber specimens were compression tested (40 x 40 x 40 mm, 40 x 40 x 80 mm, 40 x 40 x 120 mm, 40 x 40 x 160 mm), full and partial test in radial and tangential direction. Both of test type represented configuration of traditional joint construction as shown in Figure 1. Figure 2a shows the scheme of compression test that was executed using compression test set-up as shown in Figure 2b.

Type A indicates full compression test and type B indicates partial compression with end distance of 0.5, 1 and 1.5 times of the height. End distance indicates type of traditional joint construction. Larger end distance causes higher rotation property due to stress distribution to the extended part of tenon as shown in Figure 1.

The compression load was applied on the specimen in full contact test and partial contact test. For partial contact test, steel plate of 40 mm in width was put on the center of specimen. The compression loading protocol was static loading with speed of 0.5 mm/min. It was applied until deformation of 3 mm.

Three points bending test, four points bending test and four points shear test

A total of 360 specimens made from 10 tropical hardwood timber species (20 x 20 x 380 mm) were tested using three point bending test, four point bending test and four point shear test. Figure 3a, 3b, and 3c show the set-up of three points bending test, four points bending test and four points shear test, respectively. The Instron 100kN was used to apply the static load at the center of the 2 supports (span 360 mm) with speed of 0.5 mm/min. The load for four points bending test and four points shear test was applied until failure and the load return to zero. For three points bending test, the load was applied until 532.5 N.

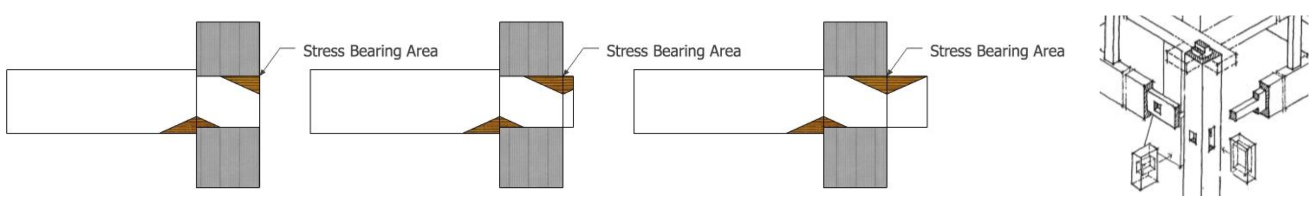


Figure 1. Basic type of joint construction and stress distribution against rotation (left) and detail of joint construction in Javanese wooden house (right) (Leerdam 1995)

a b

Figure 2. Compression test set-up of tropical timber specimens.

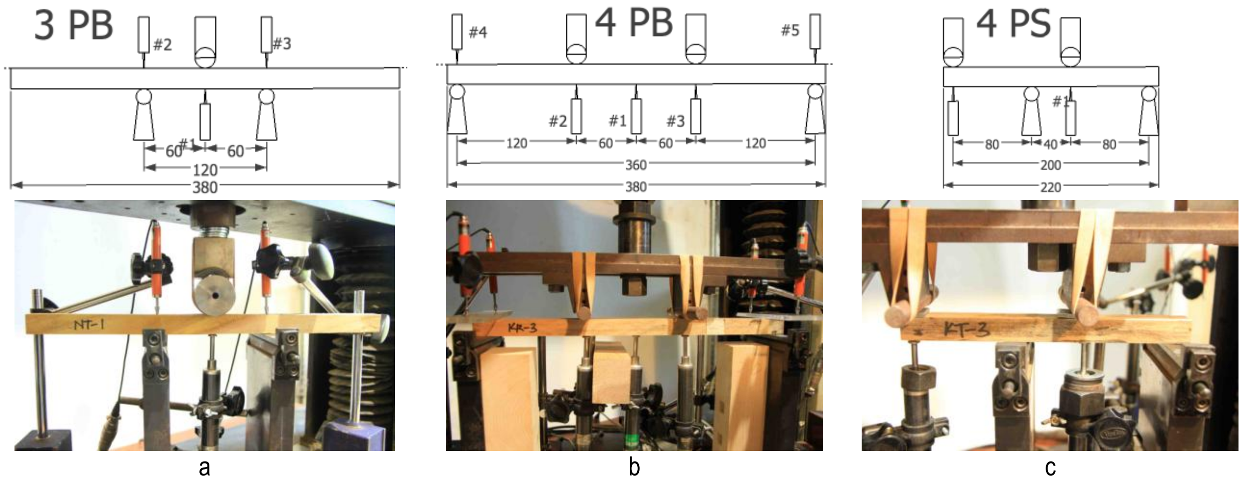


Figure 3. Set-up for three points bending test (a), four points bending test (b), and four points shear test.

Results and Discussions

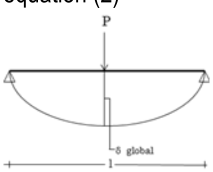
Mechanical Properties and Densities

In this study, the mechanical properties tested were Young's modulus (E *local* or MOE), MOR, shear strength (f_s), and shear modulus (G). The mechanical properties were calculated using equation shown below.

To get Young`s modulus from compression test we use equation (1)

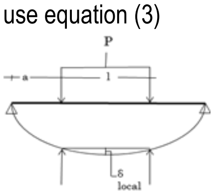
$$MOE = \frac{\Delta P \cdot l^3}{\Delta \delta \cdot bh^3} \tag{1}$$

From three points bending test we will get E_{global} with use equation (2)



$$E_{global} = \frac{l^3 \cdot K_{global}}{48I} \tag{2}$$

From four points bending test we will get E_{local}, and MOR use equation (3)



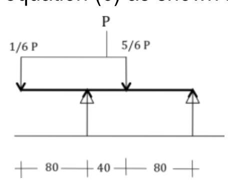
$$E_{local} = \frac{a \cdot l^2}{16I} K_{local} \tag{3}$$

$$MOR = \frac{3P\max \cdot a}{bh^3} \tag{4}$$

Value of E_{global} (equation 2) and E_{local} (equation 3) will used to obtain Shear modulus (G), as shown in equation (5).

$$G = \frac{1.2h^2}{l^2\left(\frac{1}{E_{global}}\right) - \left(\frac{1}{E_{local}}\right)} \tag{5}$$

To get Shear strength from four points shear test we will use equation (6) as shown below.



$$f_s = \frac{5P\max}{4bh} \tag{6}$$

Tables 1 and 2 show mechanical properties of specimens obtained from compression test. The values of mechanical properties shown in the table are the mean value of each 6 duplicates.

Tables 3 and 4 show mechanical properties of specimens obtained from three points bending test, four points bending test and 4 points shear test. The values shown in the table are the mean value of each 6 duplicates.

Comparison of MOE from Compression Test between Each Material

Figures 4 and 5 show comparison of mechanical properties (MOE) of wood materials tested in radial and tangential direction. In these figures, it can be seen that MOE has strong relationship with density, in proportion to the second power of density. Falcata had the lowest for both MOE and density while Ulin had the highest ones. Acacia and Wadang had the second lowest for MOE and density while Ketepeng and Sonokeling had the second highest MOE and density.

Table 1. Mechanical properties of specimens tested in radial direction.

Types of Specimen	A40		A80		A120		A160			
Name of Species	E (N/mm^2)	Yield stress (N/mm^2)	E (N/mm^2)	Yield stress (N/mm^2)	E (N/mm^2)	Yield stress (N/mm^2)	E (N/mm^2)	Yield stress (N/mm^2)	Density (Kg/m^3)	Moisture Content (%)
Acacia	298	5.49	542	7.71	685	9.48	677	9.6	418.06	16.88
Falcata	276	3.65	228	4.97	204	4.65	201	4.64	231.45	12.63
Glued-Acacia	727	12.1	816	16.9	691	13.8	847	18.7	594.59	9.91
Jati	427	9.26	782	16.7	786	12.2	557	14.1	577.56	12.70
Ketepeng	663	13.3	725	17.2	935	17.2	948	17.8	651.25	14.50
Mindi	338	7.17	427	12.2	395	11.2	379	11.6	450.12	11.01
Nangka	493	11.2	662	16.3	745	15.9	542	17.4	488.76	11.50
Sonokeling	693	14.2	725	18.5	986	19.3	957	18.2	680.27	12.50
Ulin	1021	24.3	923	38.9	926	42.7	1002	39.9	925.99	12.13
Wadang	398	7.84	449	12.8	400	11.7	419	9.7	399.27	11.66

Table 2. Mechanical properties of specimens tested in tangential direction.

Types of Specimen	A40		A80		A120		A160			
Name of Species	E (N/mm^2)	Yield stress (N/mm^2)	E (N/mm^2)	Yield stress (N/mm^2)	E (N/mm^2)	Yield stress (N/mm^2)	E (N/mm^2)	Yield stress (N/mm^2)	Density (Kg/m^3)	Moisture Content (%)
Acacia	256	4.70	369	6.70	471	7.43	418	7.21	420.47	17.10
Falcata	165	3.02	182	3.77	159	3.19	130	3.37	233.53	12.68
Glued-Acacia	559	12.5	890	19.4	620	12.4	804	17.9	570.62	9.33
Jati	249	5.40	570	14.0	540	12.4	483	12.2	576.65	12.78
Ketepeng	662	12.8	777	15.7	696	15.2	797	15.8	648.49	14.50
Mindi	357	8.06	406	11.26	347	10.82	314	10.02	444.68	10.99
Nangka	357	10.1	621	15.1	525	13.5	569	15.9	493.15	11.43
Sonokeling	574	13.0	536	15.7	839	17.0	764	15.9	675.90	12.33
Ulin	890	27.7	957	59.4	762	29.2	795	29.0	921.99	12.62
Wadang	331	7.8	328	8.7	260	8.5	282	8.4	389.47	11.25

Table 3. Mechanical properties of specimens tested in radial direction.

In radial direction	MOE (N/mm^2)	MOR (N/mm^2)	G (N/mm^2)	f_s (N/mm^2)	Density (Kg/mm^3) (220 mm)	Moisture Content (%) (220 mm)	Density (Kg/mm^3) (380 mm)	Moisture Content (%) (380 mm)
Acacia	7844	85.5	732.3	19.0	476	13.2	466	13.4
Falcata	5464	54.1	500.5	8.8	276	11.4	289	11.1
Glued-Acacia	8742	101.2	733.7	21.3	604	9.31	559	9.18
Jati	6753	97.7	810.1	17.1	590	10.7	565	10.7
Ketepeng	7751	94.6	711.3	17.7	661	12.1	689	11.4
Mindi	6455	77.4	595.1	15.0	421	10.8	486	11.1
Nangka	4483	60.8	235.9	20.7	581	12.0	570	10.3
Sonokeling	7924	121.3	886.0	24.3	729	10.0	710	9.7
Ulin	8321	103.2	1053.6	21.6	873	10.6	932	10.0
Wadang	5747	63.0	595.7	14.0	484	13.0	453	11.5

Table 4. Mechanical properties of specimens tested in tangential direction.

In tangential direction	MOE (N/mm²)	MOR (N/mm²)	G (N/mm)	f_s (N/mm²)	Density (Kg/mm³) (220 mm)	Moisture Content (%) (220 mm)	Density (Kg/mm³) (380 mm)	Moisture Content (%) (380 mm)
Acacia	6236	78.7	596.1	19.8	480	13.5	463	13.2
Falcata	3946	47.6	379.7	9.5	278	11.3	277	11.1
Glued-Acacia	7381	108.3	1027.2	24.2	590	9.48	581	8.84
Jati	7125	98.2	695.9	16.4	576	11.0	582	10.5
Ketepeng	6893	87.4	679.7	19.8	624	12.4	676	11.5
Mindi	5639	67.3	507.3	15.6	437	10.7	449	11.3
Nangka	4433	38.1	469.7	19.9	576	10.8	540	10.6
Sonokeling	8842	115.8	726.8	23.3	706	9.9	686	10.1
Ulin	7527	75.5	643.9	15.9	869	10.8	969	9.93
Wadang	4592	56.5	461.7	13.1	476	10.8	383	10.7

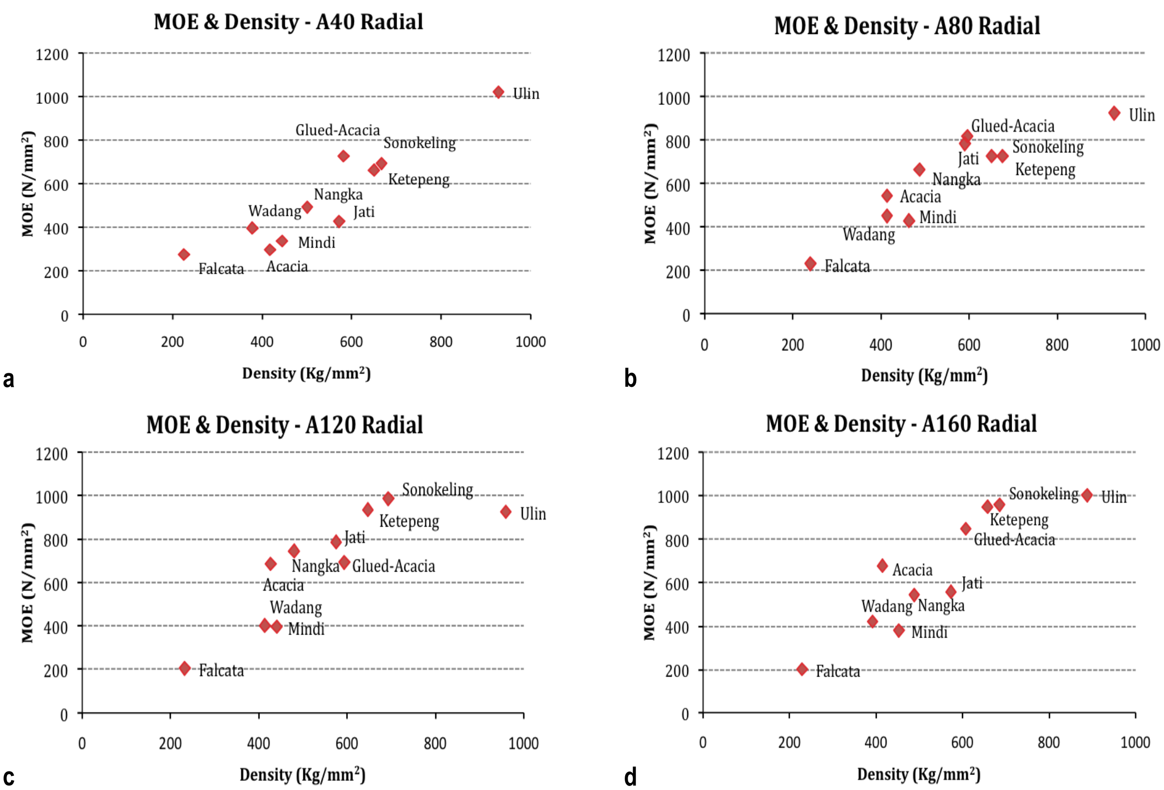


Figure 4. Comparison of MOE from compression test in radial direction.

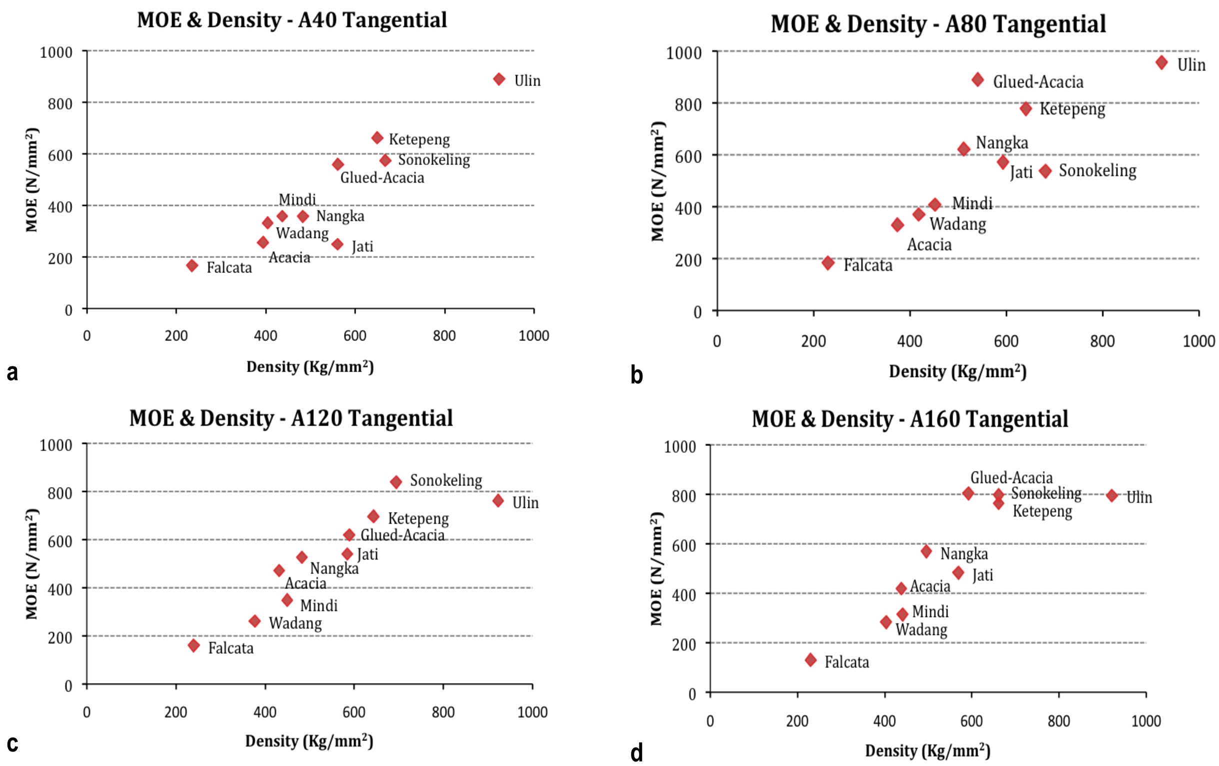


Figure 5. Comparison of MOE from compression test in tangential direction.

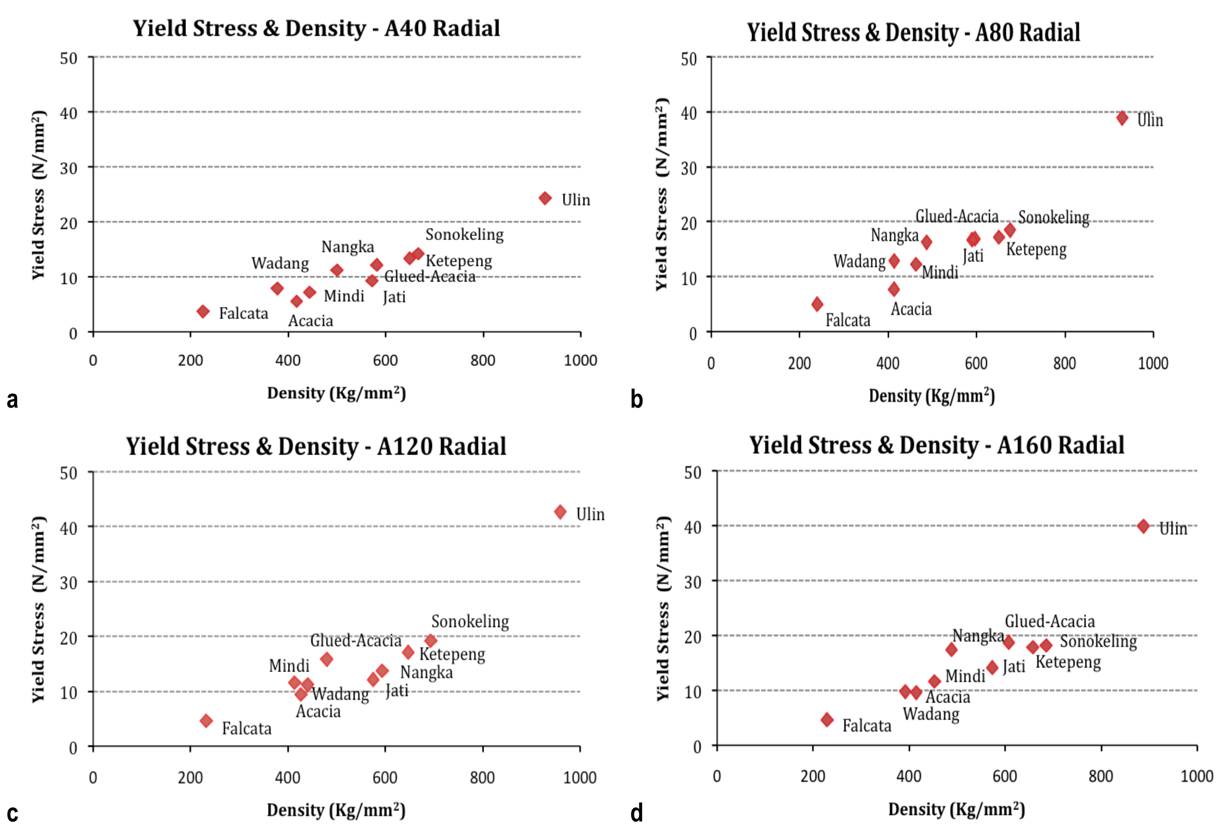


Figure 6. Comparison of yield stress from compression test in radial direction.

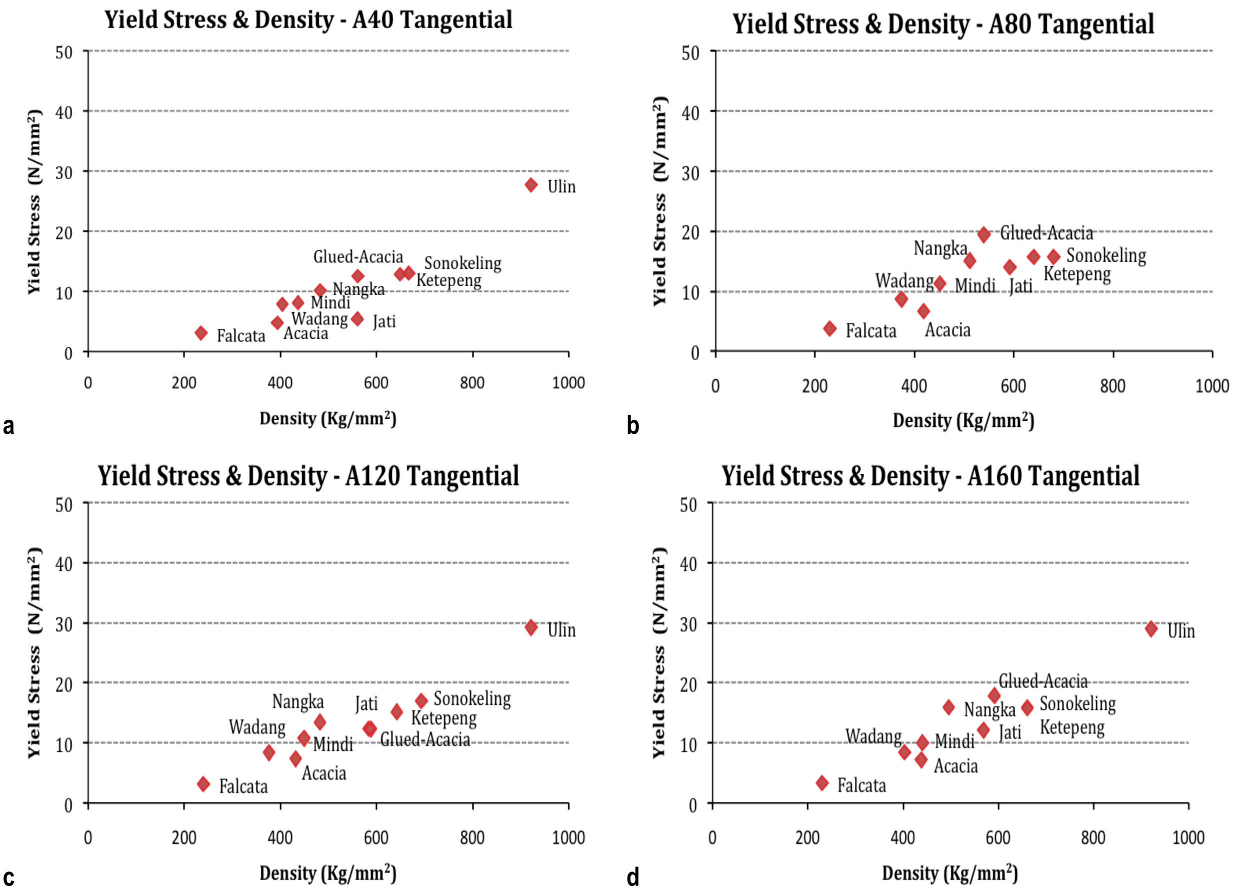


Figure 7. Comparison of yield stress from compression test in tangential direction.

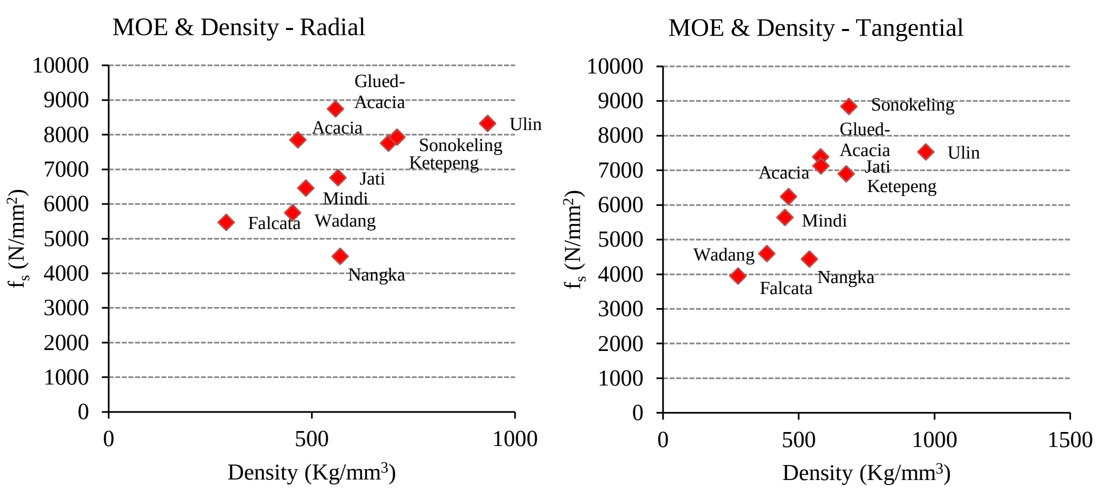


Figure 8. Comparison of MOE in four points bending test between each materials.

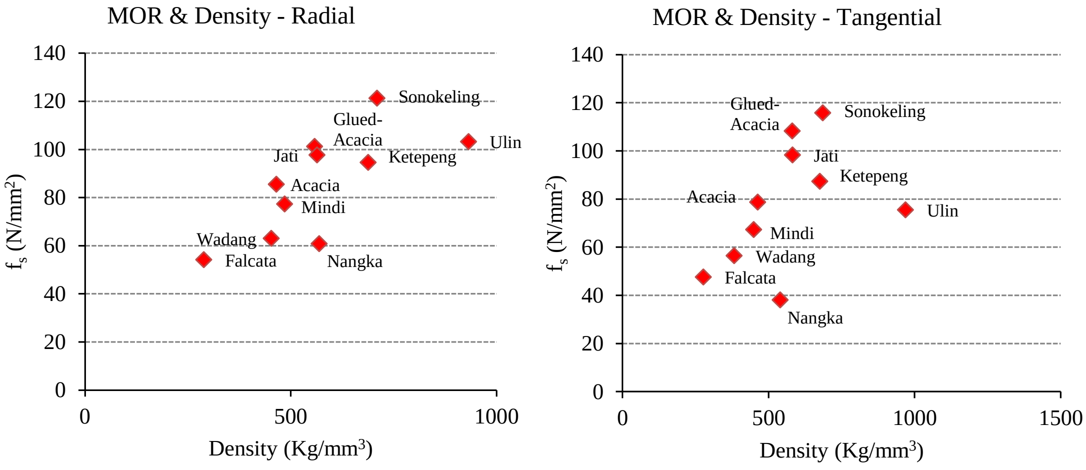


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Figure 9. Comparison of MOR from four points bending test.

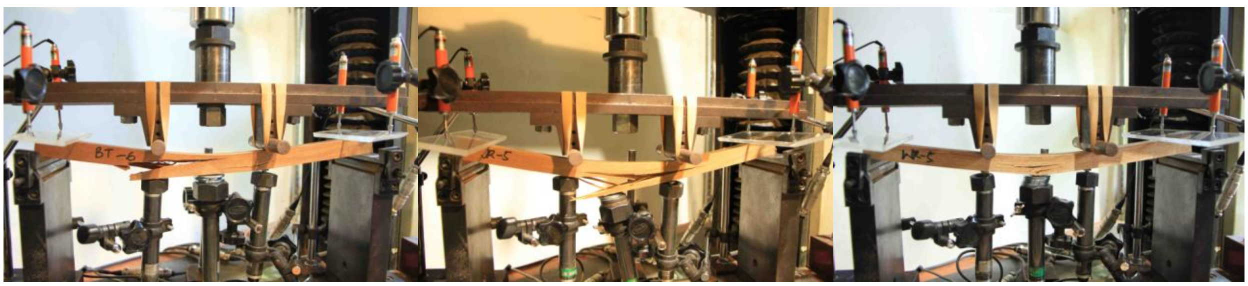

Figure 10. Failure mode of specimen from four point bending test.

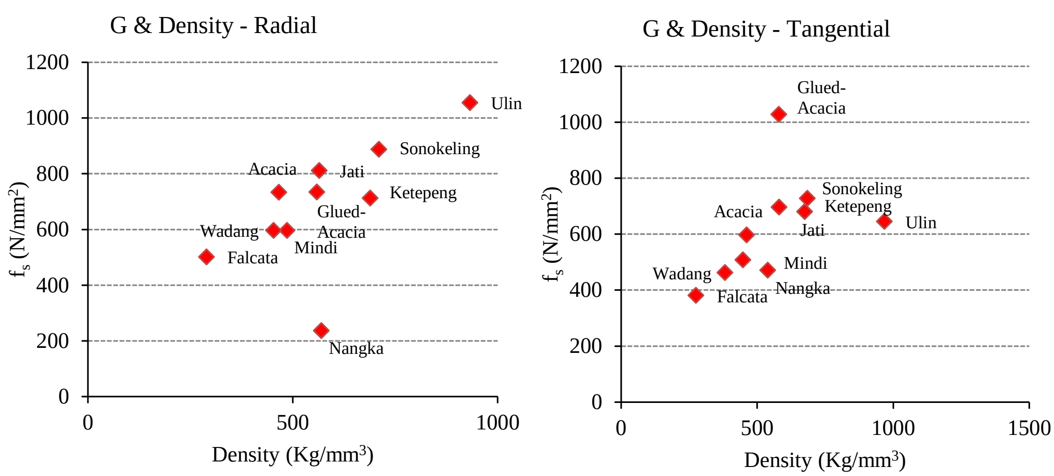

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Figure 11. Comparison of G among materials.

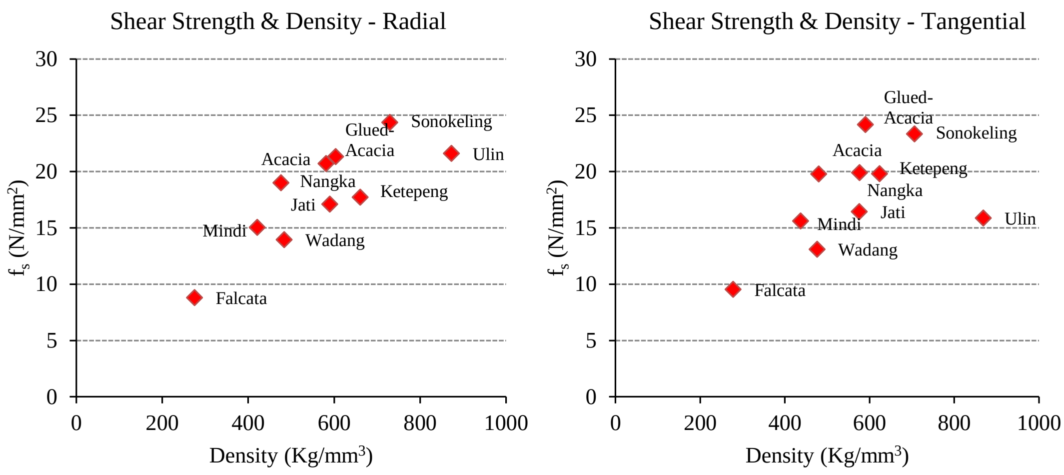

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Figure 12. Comparison of f_s among materials.

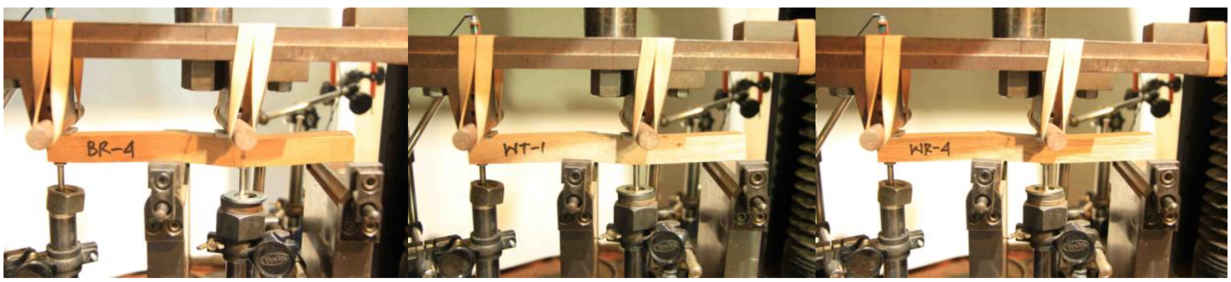

Figure 13. Failure mode of specimen from four points shear test.

From Figure 4, it can be seen that Jati has higher density than that of Nangka, but the MOE of Nangka is higher than Jati. Figure 5b shows that Nangka has higher MOE and density than that of Jati and Acacia. Jati and glued-Acacia have similar MOE, but glued-Acacia has higher density than that of Jati. From Figure 5b, 5c and 5d, it can be seen that Jati has higher MOE and density than that of Nangka. Figure 5a shows that Nangka has higher density than that of Jati, but the MOE of Nangka is a little bit lower than that of Jati. It can be seen from these figures that MOE and density of Acacia are lower than that of Jati and Nangka. Regarding to promoting substitute materials for Javanese wooden structures, woods having similar mechanical properties to Jati are in search. In these figures, mechanical properties of Acacia and Nangka are located close to Jati.

Comparison of Yield Stress from Compression Test

Figures 6 and 7 show the comparison of yield stress of the timbers tested in radial and tangential directions. In these figures, yield stress also showed relatively proportional correlation with density. Falcata has the lowest yield stress and density while Ulin has the highest. Sonokeling has the second highest yield stress and density while Acacia has the second lowest for those properties.

From Figure 6, it can be seen that glued-Acacia has higher yield stress and density than that of Acacia. Nangka has higher density than Jati even though Jati has the higher yield stress than Nangka. Figure 7 shows Nangka has higher yield stress than Jati and Acacia. If this is to find timber with similar mechanical properties to Jati, mechanical properties of glued-Acacia and Nangka are seen to be close to that of Jati.

Comparison of MOE from Four Points Bending Test

Figure 8 show comparison of mechanical properties (MOE) of the timbers tested in radial and tangential directions. In this figure, it can be seen that MOE has weak relationship with density, in proportion to the second power of density. Falcata has the lowest density and Nangka has the lowest MOE. Ulin has the highest density and glued-Acacia has the highest MOE while Falcata and Wadang have second lowest MOE and density. Ulin and Sonokeling have the second highest for MOE and density. From Figure 8, it can be seen that Jati has relatively similar density to Nangka, but the MOE of Jati was much higher than that of Nangka. Since finding substitute materials for Javanese wooden structures having similar mechanical properties to Jati was in search, the results show that Acacia has mechanical properties that are close to that of Jati.

Comparison of MOR from Four Points Bending Test

Figure 9 shows that Sonokeling has the highest MOR though Ulin has the highest density. In radial direction, Falcata has the lowest MOR and density while Nangka has the lowest MOR and Falcata has the lowest density in tangential direction. Nangka, Jati and glued-Acacia have quite similar density but glued-Acacia has the highest MOR. In this figure, yield stress also demonstrated weak proportional relationship with density. In order to seek substitute materials for Javanese wooden structures, materials having similar mechanical properties to Jati were in search. In this figure, mechanical properties of glued-Acacia are located close to that of Jati.

Figure 10 shows failure mode of specimens from four points bending test. In this figure, it can be seen the failure started from one or both of bending points and it came from the center of loading.

Comparison of Shear Modulus from Four Points Shear Test

Figure 11 shows the comparison of shear modulus of timber tested in radial and tangential direction. In this figure, shear modulus also showed weak proportional relationship with density. Nangka is the lowest for G and Ulin is the highest one in radial direction. Falcata is the lowest for G and glued-Acacia is the highest one in tangential direction. Falcata and Wadang have the second lowest yield stress and density and Sonokeling has the second lowest for yield stress and density.

From this figure, it can be seen that glued-Acacia has highest shear modulus but Ulin has the highest density. Nangka has quite similar density to Jati although Jati has higher shear moudlus. In this figure, mechanical properties of Acacia and Sonokeling are located nearby Jati.

Comparison of Shear Strength from Four Points Shear Test

Figure 12 shows comparison of shear strength from four points test of material tested in radial and tangential direction. In this figure, shear modulus also showed weak proportional relationship with density. Falcata is the lowest for shear modulus and density and Sonokeling and glued-Acaia are the two most highest while Ulin has the highest density. Sonokeling and glued-Acacia have the second highest yield stress and density while Wadang has the second lowest for yield stress and density. Here, mechanical properties of Acacia and Nangka were located nearby Jati.

Figure 13 shows failure mode of specimens from four points shear test. There are 2 types of failure mode: (1) failure by bending with the failure comes from point of bending and (2) failure by shear force.

Conclusions

Compression test, three point bending, four point bending and four points shear tests for 9 tropical timbers have been done. It was found that some comparisons showed relationship among parameters related to mechanical properties.

MOE showed strong relationship with densities. There was a clear trend that smaller density indicates smaller MOE. Yield stress has strong relationship with densities. Ulin wood has the best mechanical properties while Falcata has the poorest while tested in radial direction.

MOE and MOR show quite strong relationship with densities. Shear strength and shear modulus show quite strong relationship with densities. In terms of shear modulus, Acacia, Jati and Nangka have quite similar mechanical properties. For shear strength, Nangka is located nearby jati. Glued-Acacia has equal mechanical properties to Jati in the matter of MOR.

Considering the results of MOE, MOR, yield stress, shear modulus, shear strength and density, Acacia, Jati and Nangka have similar mechanical properties. Acacia and Nangka are recommended to substitute Jati to be used in Javanese wooden house reconstruction.

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References

Leerdam, B.F.V. 1995. Architect Henry Maclaine Pont, Een Speurtocht-naar-het-Wezenlijke van de Javaanse Architectuur. Dissertation at Technische Universiteit Delft.

Jogja Heritage Society (JHS). 2007. Kotagede Heritage District, Yogyakarta, Indonesia: Home Owners's Conservation Manual, UNESCO Bangkok-UNESCO Jakarta. p 121-145.

Pendidikan Industri Kayu Atas (PIKA). 1981. Mengenal Sifat-sifat Kayu Indonesia dan Penggunaannya. Penerbit Kanisius, Yogyakarta.

Prihatmaji, Y.P.; A. Kitamori; K. Komatsu. 2011. In Search of Substitution Material for Traditional Javanese Wooden Houses. Wood Research Journal 2(1): 33-40.

Prihatmaji, Y.P.; A. Kitamori; K. Komatsu. 2010a. The Impact of Tongue and Gulls Connection System for Earthquake Resistance for Javanese Wooden House. Proceeding of the World Conference on Timber Engineering, Trentino, Italy. p 415 (II).

Prihatmaji, Y.P.; K. Aryati; I. Suprijanto. 2010b. Reading on Lembur Wood (*Pterocarpus indicus*) in Manggarai Traditional Building, Flores (Mbaru Niang Mbowang). Proceeding of National Seminar of MAPEKI, Bali.

Yahmo, I. 2007. Current State of Wooden Architecture in Indonesia. Asian Forum for Wooden Architecture, Tokyo, Japan. p. 2.

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