STRENGTH AND STIFFNESS OF REMNANTS OF FRACTURED TIMBER

AW Mohd Jamil* & MK Mohamad Omar

Forest Research Institute Malaysia, 52109 Kepong, Selangor Darul Ehsan, Malaysia

Received October 2013

MOHD JAMIL AW & MOHAMAD OMAR MK. 2015. Strength and stiffness of remnants of fractured timber. The reliability of timber becomes a major concern when the material has been stressed to fracture limit. Information on the structural integrity of the remnant is not available due to the practice of cutting and reusing undamaged timber sections. Without knowledge of the mechanical properties of the remnants, utilisation of the plank is rather doubtful. This article compares the strength and stiffness between unused wood and remnants of fractured plank. Bending tests were conducted on two tropical hardwood species, *Scorodocarpus borneensis* and *Endospermum malaccense*. Large-sized planks were bent to rupture limit by monotonic loading. Undamaged sections were distinguished visually and salvaged. Three-point bending test was conducted on the undamaged sections and modulus of elasticity as well as modulus of rupture was measured. For comparison, prior testing on unused wood was performed. Results indicate that the breakage of timber has trivial effect on the strength and stiffness of the remnants. There was no reduction in modulus of rupture. Fracture damage on timber plank demonstrated a localised effect. Visual assessment was sufficient to differentiate between clear and fractured sections.

Keywords: Recycled timber, visual inspection, residual

INTRODUCTION

Fractured timbers have highly variable qualities. Often they may not be utilised as construction material due to the incurred macro- and micro-damages (Jakubowski et al. 2011). However, fractured planks are often used for structural applications once the broken parts are discarded and the risk of strength deterioration is frequently neglected.

For instance, reclaimed planks from deconstruction and demolition works are often damaged and the wood material ends up broken (Falk 1999). However, these timbers are commonly used as components in building construction. Minimal energy consumption for recycling timber compared with cement, steel, aluminium and other metals has made it an affordable and attractive option for building material. There is a need to evaluate the mechanical properties of damaged timber for reuse.

In cases of repairing and restoring damaged timber buildings caused by earthquake and other natural hazards, the commonly applied method is by splicing additional material to the damaged sections (Gerwick et al. 2010). This involves removing the broken section of the structural component and then splicing a new section of timber onto the existing component. While it can be demonstrated that the strength of that particular section has been restored, the effects from stresses on the reliability of the remaining structures become uncertain. This architectural repair keeps the breakage tight and stiff, but it does not restore the strength of the remaining sections.

In fact, improper logging, primary processing and handling often result in overstressing and breakage of the timber material. One of the issues addressed in plantation forest includes damage to logs during harvesting. Dykstra (2007) reported that broken logs were cut into shorter pieces while removing the damaged sections. Small logs tend to break or suffer significant damage easier than larger logs. This is influenced by equipment and logging methods that are beyond the operator's control.

*mohdjamil@frim.gov.my

Crushing resulting from grapple and choker chain is also observed. Despite these, the normal practice of simply removing damaged fractions without accurate knowledge of the remnants may lead to doubtful qualities and risk in utilisation of the timber.

Preparation of research specimens from fractured planks has also been reported. Alik and Badorul Hisham (2006) prepared smaller specimens from the remnants of larger specimens following a destructive test. Thus, specimens were prepared from samples that were subjected to destructive stresses. The objective of the study was to compare the strength and stiffness of two different sizes. It is questionable as to whether such specimen, which is cut from fractured specimen, is comparable in terms of strength and stiffness.

This article demonstrates the most comprehensive mechanical property evaluation on fractured tropical timber. The data are essential to assess the strength and stiffness of the remnants of fractured timber and minimising risk in structural design. The primary objective of this study was to determine whether strength of unused material and remnant segments of fractured timbers differed from each other.

MATERIALS AND METHODS

Species studied

Two tropical hardwood species, *Scorodocarpus borneensis* and *Endospermum malaccense* or kulim and sesendok respectively, were selected as samples. The timbers are grouped in SG3 and SG7 respectively. Modulus of rupture (MOR) and modulus of elasticity (MOE) of kulim are 107 and 14,900 N mm^{-2} respectively at approximately 15% moisture content (MC). MOR and MOE of sesendok reported in green condition are 39 and 8500 N mm^{-2} respectively (Lee et al. 1993). Results for dried specimens are not available. Kulim timber is classified as medium hardwood with air-dry density ranging from 640 to 975 kg m^{-3}. The timber is popular for a wide range of structural applications. Sesendok is a favoured timber for non-structural components such as match splints and boxes. It is classified as light hardwood with air-dry density ranging from 305 to 655 kg m^{-3} (Wong 1982).

Preparations of specimens

A total of 145 large planks of *S. borneensis* and *E. malaccense* were cut into two sizes of 51 mm × 152 mm × 2896 mm and 51 mm × 51 mm × 762 mm. The larger test piece is referred to as structural size specimen and the latter as small clear specimen. Small clear specimen is defined as specimen with no visible defect over the length. Either one or two pieces of small clear specimens were prepared accompanying each structural size specimen. Figure 1 shows the cutting pattern for the specimens.

Destructive bending test

Small clear specimens were tested based on three point bending principle. Two supports were adjusted to produce a span of 711 mm. The speed applied was 2.5 mm min^{-1} throughout the test. Figure 2 illustrates the three point bending test arrangement for small clear specimens. The specimen was positioned so that the load will be applied to the tangential surface nearest the pith. A total of 277 small clear specimens were tested.

The bending strength of wood is presented as bending MOR which is the equivalent stress in the extreme fibres of the specimen at a point of failure. The MOR in three-point bending is calculated based on the following equation:

$$MOR = \frac{3Pl}{2wd^2}$$

where P = applied load (N), l = span (mm), w = width (mm) of the specimen and d = depth (mm) of the specimen.

MOE of small clear specimen was measured simultaneously. Universal testing machine recorded the load-deflection graphs. The equivalent stresses and strains in the load versus deflection increments were determined. MOE in three-point bending is calculated using the following equation:

$$MOE = \frac{P'l^3}{4\Delta' wd^3}$$

where P' = applied load at the limit of proportionality (N), l = span (mm), Δ' = deflection at the limit of proportionality (mm), w = width (mm)

Figure 1 Cutting pattern for the preparation of structural size and small clear specimens from one original plank; L = length of structural size specimen (2896 mm), D = thickness of structural size specimen (152 mm), l = length of small clear specimen (762 mm), w = width of small clear specimen (51 mm) and d = thickness of small clear specimen (51 mm)

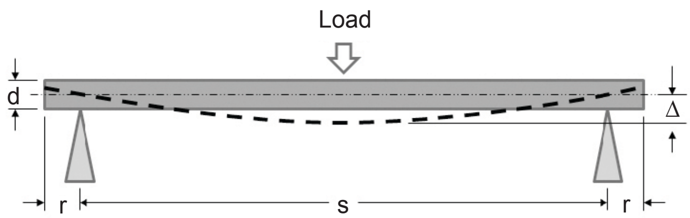

Figure 2 Three-point bending test arrangement; d = depth of specimen (51 mm), s = bending span (711 mm), r = overhang (25 mm) and Δ = bending deflection

of the specimen and d = depth (mm) of the specimen.

The viability for rupture limit determination is through force versus deflection monitoring. Thus, similar loading test was conducted on structural size plank to attain the rupture stress. Test set up for measuring the elasticity of structural size specimen is illustrated in Figure 3. The test piece was symmetrically loaded at two points over a span of 18 times the depth. The test piece was simply supported with an overhang of approximately 76 mm on each side. The distance between the two loading points was equal to the distance between one loading point and the nearest support. Deflection was measured within the gauge length on both sides of the specimen using dial gauges. Small steel plates were inserted between the specimens and the loading points to minimise the local indentation. The tension edge of the piece was selected at random. A total of 145 specimens were tested.

The modulus of elasticity for structural size specimen (MOE_f) was calculated from the following equation:

$$MOE_f = \frac{a l_1^2 P'}{16\, I \Delta'}$$

where a = distance (mm) between a loading point and the nearest support, l_1 = gauge length (mm), I = second moment of area (mm^4), P' = increment of load (N) and Δ' = increment of deformation (mm) corresponding to P'.

Bending strength was determined by bending the plank to failure through similar loading point arrangement. The modulus of rupture for structural size specimen (MOR_f) was calculated from the following equation:

$$MOR_f = \frac{F_{max} a}{2W}$$

where F_{max} = maximum load (N), a = distance (mm) between an inner load point and the nearest support and W = section modulus (mm^3).

MC and density were determined from 25 mm cross-cut sections of each tested specimen. Oven-dry method was conducted to determine the MC of each specimen. The formulas are:

$$MC = \frac{m_1 - m_0}{m_0} \times 100\%$$

where m_1 = mass of the specimen (g) at test and m_0 = oven-dry mass (g) of specimen.

$$Density = \frac{m_t}{V_t}$$

where m_t = mass of the specimen (kg) at test and V_t = volume of the specimen (m^3) at test.

Remnant parts of fractured timber

Test pieces of similar size as small clear specimens of 51 mm × 51 mm × 762 mm were cut from the remaining parts of tested structural size specimen. Cracks and damages were distinguished and the clear sections were selected through visual inspection while avoiding the fractured segments. The distance between the visible breakage and the specimen was between 10 and 50 mm. Figure 4 shows the cutting pattern for the test pieces. These test pieces are referred to as remnant specimens. Cracks on some structural size specimens were so extensive that there was no remaining specimen. Remnant specimen test was similar to small clear specimen test. MOR and MOE calculations were also identical. Remnant specimen test was conducted on a total of 143 test pieces.

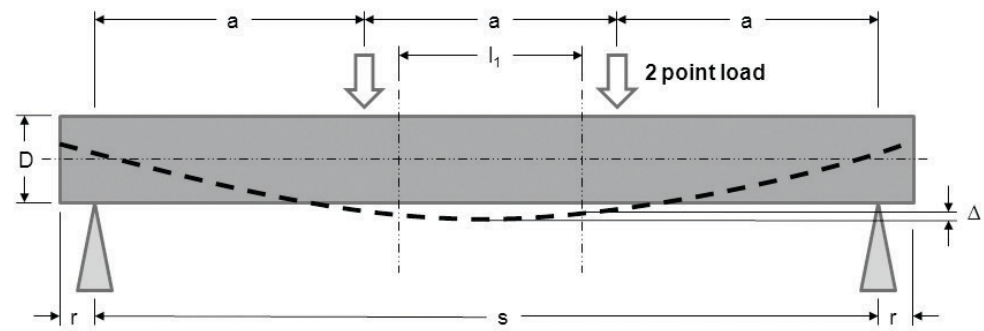

Figure 3 Structural size bending test arrangement; D = depth of specimen (152 mm), s = bending span (2743 mm), r = overhang (76 mm), a = distance between a loading point and the nearest support, l_1 = gauge length (762 mm) and Δ = bending deflection

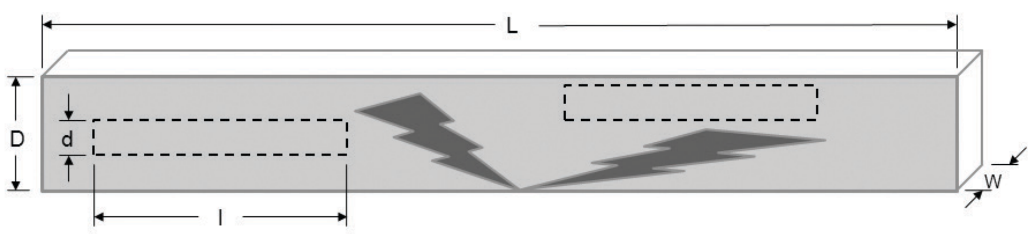

Figure 4 Selection and preparation of remnant specimens from structural size test piece; L = length of structural size specimen (2896 mm), W = width of structural size specimen (51 mm), D = thickness of structural size specimen (152 mm), l = length of small clear specimen (762 mm) and d = thickness of small clear specimen (51 mm)

RESULTS AND DISCUSSION

This study was designed to evaluate two contrasting conditions of tropical timber: the new unused specimen and the remnant section from plank subjected to fracture stress. Immediate appraisal of the strength values was inappropriate due to variation of MC in each specimen (Madsen 1975). There is insignificant change in strength of timber with change of MC above the fibre saturation point (Engku 1971, Desch & Dinwoodie 1996). Below the fibre saturation point, however, the strength increases with reduction in MC. The MC of timbers in air-dry state in Malaysia is within the range of 15 to 19% (Wong 1982).

Lavers (1983) has developed a set of data showing percentage change in some mechanical properties of timber per 1% reduction in MC. The complete table was published by Desch and Dinwoodie (1996). Table 1 presents percentage changes of MOR and MOE for 1% reduction in MC. MOR and MOE values from the present tests were adjusted by considering 25% MC as the fibre saturation point. MC of 16% is the targeted reference condition for relevant comparison with existing data for both kulim and sesendok timbers (Lee et al. 1993). The adjustment was conducted on each specimen. Table 2 shows the average values of MOR and MOE after MC adjustment. Average values of MC and density at test were also presented.

MOR and MOE results of small clear specimens of kulim were equivalent to the existing record. The values were formerly obtained from 30 specimens with similar testing method (Lee et al. 1993). Thomas (1940) first reported on the mechanical properties of kulim timber. Hence, the current results demonstrated the reliable quality of the present kulim timber supply. In general, it raises confidence in the existing mechanical data of overall Malaysian timbers. Since Malaysian timber classifications were derived from previous test values, these results partly verified both the A to D and SG1 to 7 groupings (Mohd Jamil et al. 2012). Besides, these values were the foundation for the development of The Malaysian Standard Code of Practice for Structural Use of Timber.

Comparison of the present test with existing records proves that timbers of equivalent quality are still available. These statistical evidences explain numerous enquiries regarding the quality of timber that will be available from forests over time (Gagliano 2001, Gardiner & Mochan 2009). Early testing on kulim timbers was conducted latest in the year 1940 (Thomas 1940). With subsequent present test, equal strength and stiffness were obtained after more than 70 years. Comparatively, this numerical information will support technical and marketing decisions of the wood industry. Unfortunately, test results on dried sesendok timbers were not presented in Lee et al. (1993) for comparison. Lee and Chu (1965) explained that a number of air-dried specimens were lost during the World War II period.

In this study, small and structural size specimens showed substantial differences in MOR and MOE values, despite being cut from the same plank (Table 2). Average MOR value of small clear specimens was higher than structural size, whereas the MOE value was lower. Results were the same for both kulim and sesendok. The variation between these two sets of data is reasonable since size effect in bending test has

Table 1 Percentage changes in MOR and MOE per 1% change in moisture content

Mechanical property	Moisture range (%)		
	6–10	12–16	20–24
Modulus of rupture (MOR)	4.2	3.3	2.4
Modulus of elasticity (MOE)	0.21	0.18	0.15

Table 2 Results of average values of MOR, MOE, MC and density

Timber species (trade name)	Specimen (number of specimens, n)	At test				Estimated at 16% MC	
		Modulus of rupture (N mm^{-2})	Modulus of elasticity (N mm^{-2})	Moisture content (%)	Density (kg m^{-3})	Modulus of rupture (N mm^{-2})	Modulus of elasticity (N mm^{-2})
Scorodocarpus borneensis (kulim)	Small clear (n = 192)	93 (15.7)	12680 (2197)	21 (2.7)	946 (60.3)	107 (17.8)	12789 (2214)
	Structural size (n = 96)	74 (13.1)	16438 (2797)	22 (2.7)	937 (64.6)	86 (15.9)	16504 (2684)
	Remnant (n = 54)	97 (14.2)	12558 (1761)	20 (1.8)	913 (55.5)	107 (15.9)	12667 (1860)
Endospermum malaccense (sesendok)	Small clear (n = 85)	52 (7.6)	6790 (1577)	18 (1.9)	452 (64.6)	55 (8.4)	6812 (1584)
	Structural size (n = 49)	40 (9.9)	9455 (2396)	19 (1.7)	454 (68.4)	43 (10.6)	9497 (2411)
	Remnant (n = 89)	53 (7.8)	6670 (1360)	17 (1.1)	451 (62.8)	55 (8.4)	6708 (1352)

MOR = modulus of rupture, MOE = modulus of elasticity, MC = moisture content; values in parentheses are standard deviations

been reported significant (Madsen & Buchanan 1986, Desch & Dinwoodie 1996). A study on mixed tropical timber species indicated that larger specimen produced lower MOR and higher MOE (Mohd Jamil et al. 2013). Small clear specimens were selected without any visible deviation along the length, whereas for the preparation of structural size specimens, defects were present. Besides, the extended length of structural size specimens introduced deviation in the grain angle. Additionally, the different methods of three-point and four-point loadings plus the distinction in dimension of the specimens gave considerable horizontal shear force difference between structural size and small clear tests. Brancheriau et al. (2002) reported the relationship of MOE between three-point and four-point bending tests. They concluded that the results were not only influenced by the shear effect but also by supports and loading head indentation.

Figures 5 and 6 show the distributions of MOR and MOE values of each species. Each graph illustrates three sets of results simultaneously. Equivalent distributions of remnant and small clear specimens were observed. The equations of linear regression of the small clear and remnant specimens were fairly similar. The linear regression equations of MOR versus MOE values of small clear and remnant specimens of kulim were $y = 0.0067x + 21.1$ and $y = 0.0051x + 42.2$ respectively. Similarly, the linear regression equations of MOR versus MOE values of small clear and remnant specimens of sesendok were $y = 0.0051x + 21.0$ and $y = 0.0047x + 22.7$ respectively. The distribution differences between small clear, remnant and structural size specimens are presented as cumulative functions in Figures 7 and 8. In general, the values of strength and stiffness of the remnant fractions for both kulim and sesendok timbers were equivalent to small clear specimens. When both high and low density timbers reveal similar results, we can assume that regardless of density, MOR and MOE of remnant sections are not affected by fracture stresses.

Plots of pairing specimens further explain the correlation between small clear and remnant specimens. Figures 9 and 10 show comparison for MOR and MOE respectively. The deviations between small clear and remnant specimens of

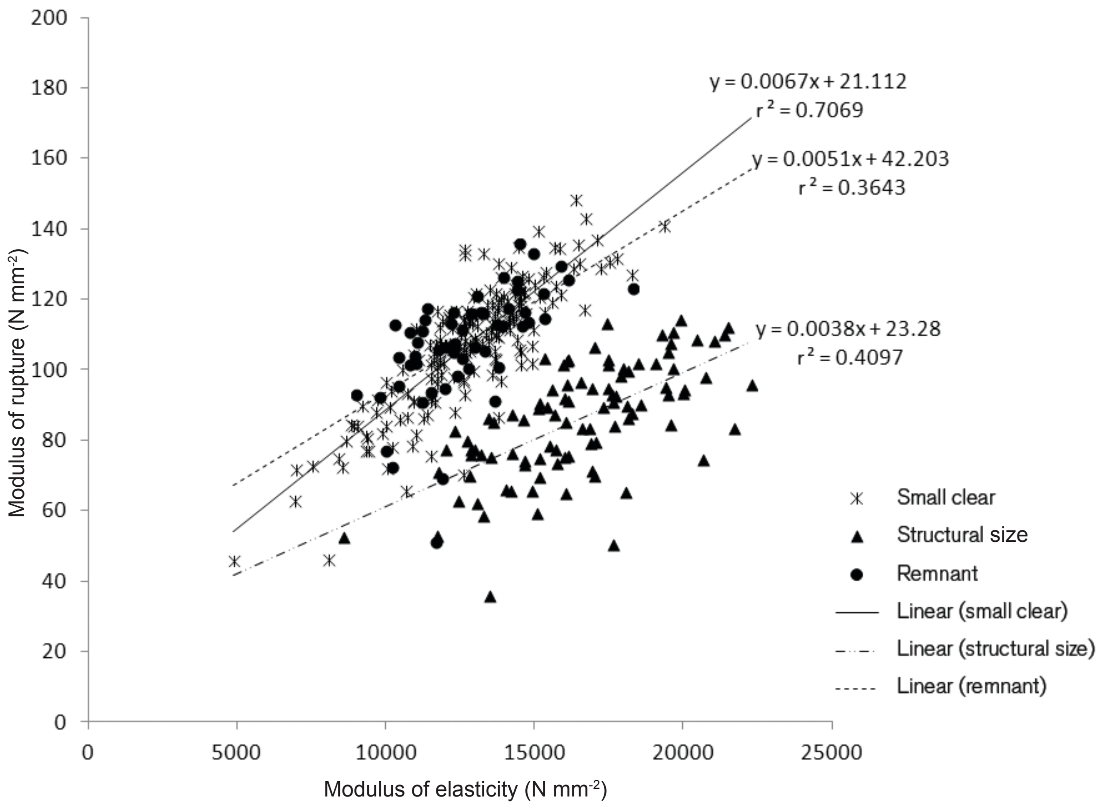

Figure 5 Distribution of modulus of elasticity and modulus of rupture for kulim

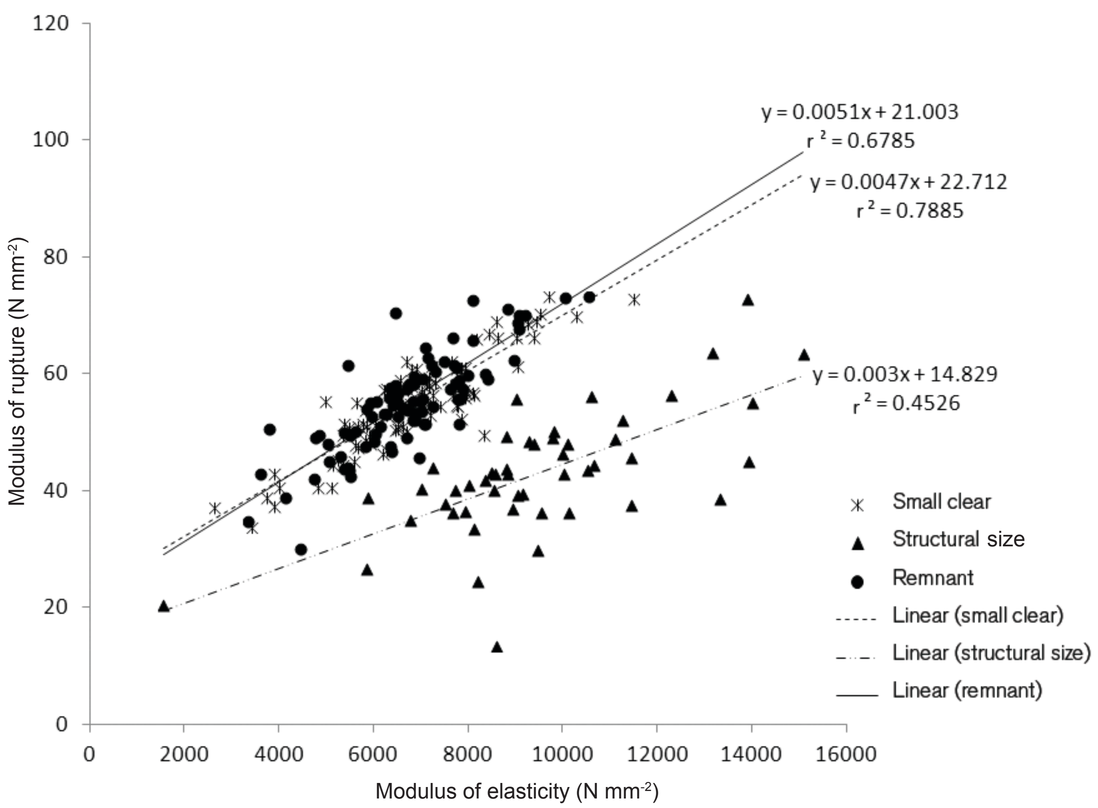

Figure 6 Distribution of modulus of elasticity and modulus of rupture for sesendok

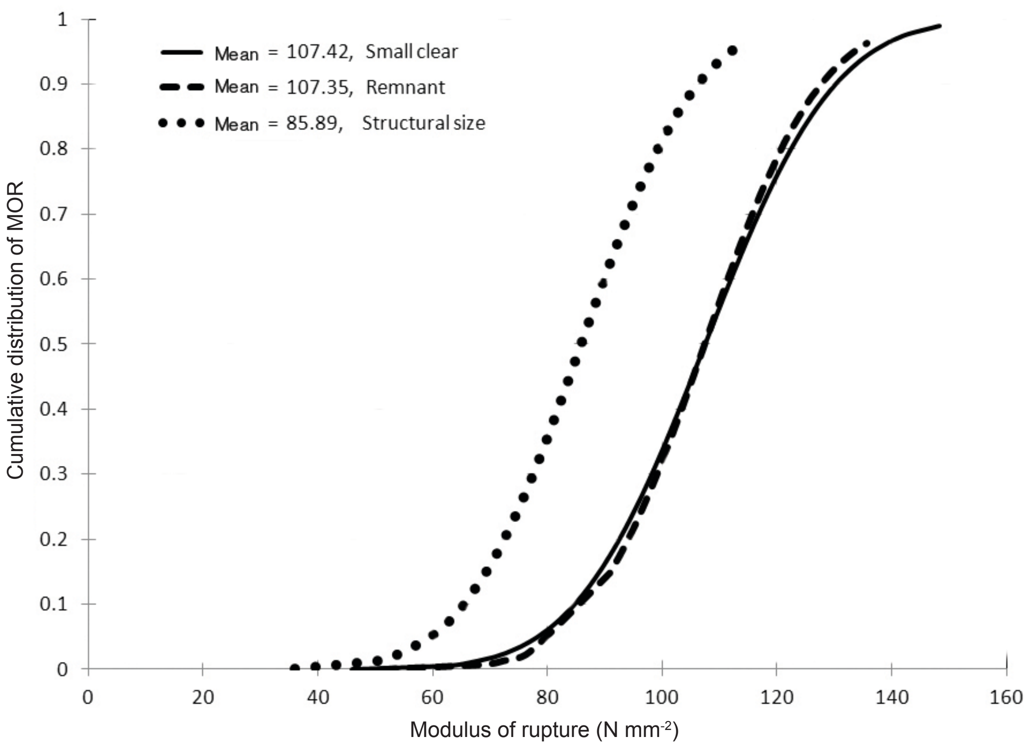

Figure 7 Comparison between cumulative distributions of MOR (modulus of rupture) of kulim

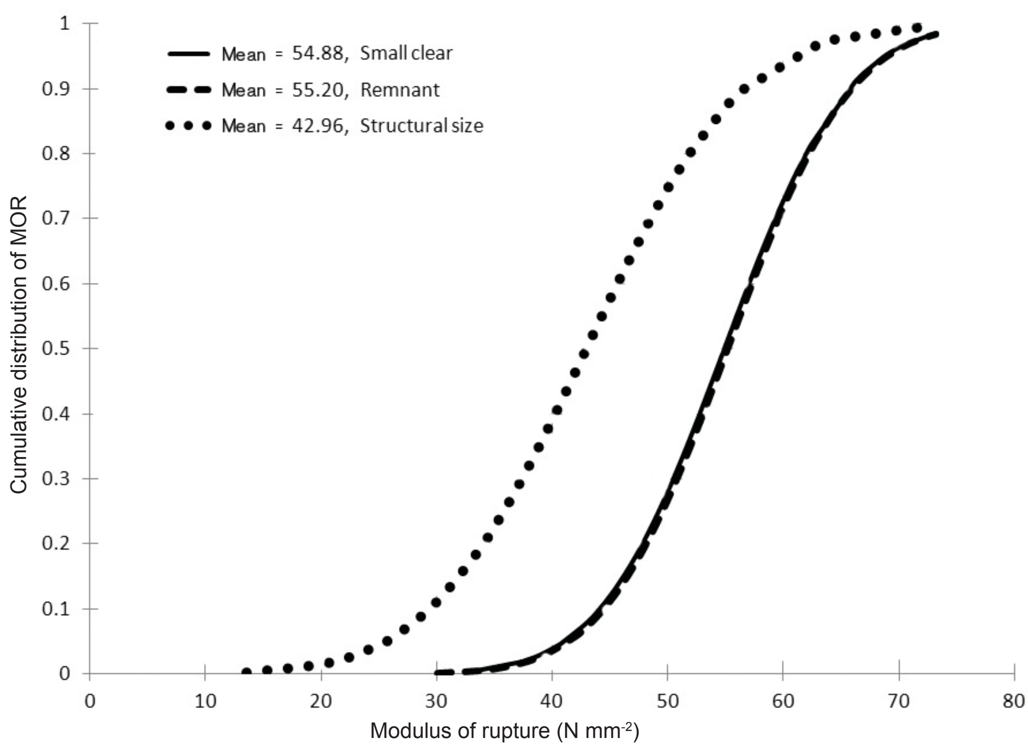

Figure 8 Comparison between cumulative distributions of MOR (modulus of rupture) of sesendok

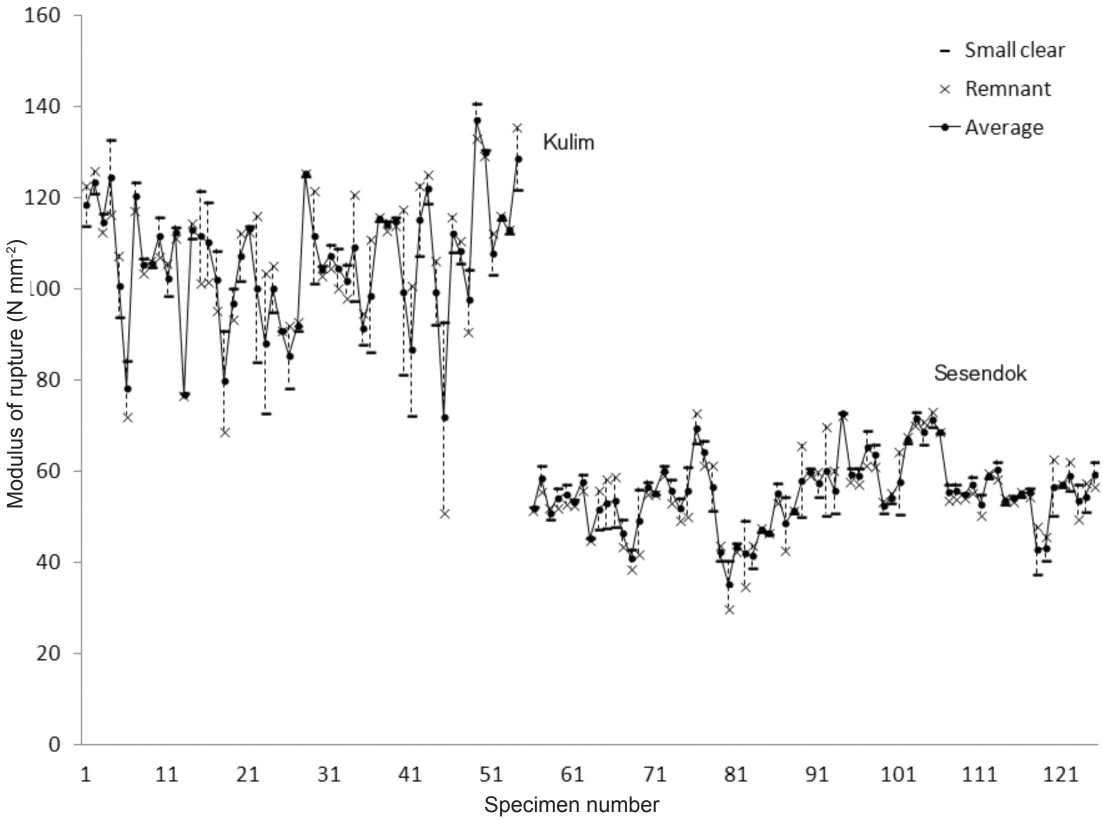

Figure 9 Modulus of rupture correlation between small clear and remnant specimens

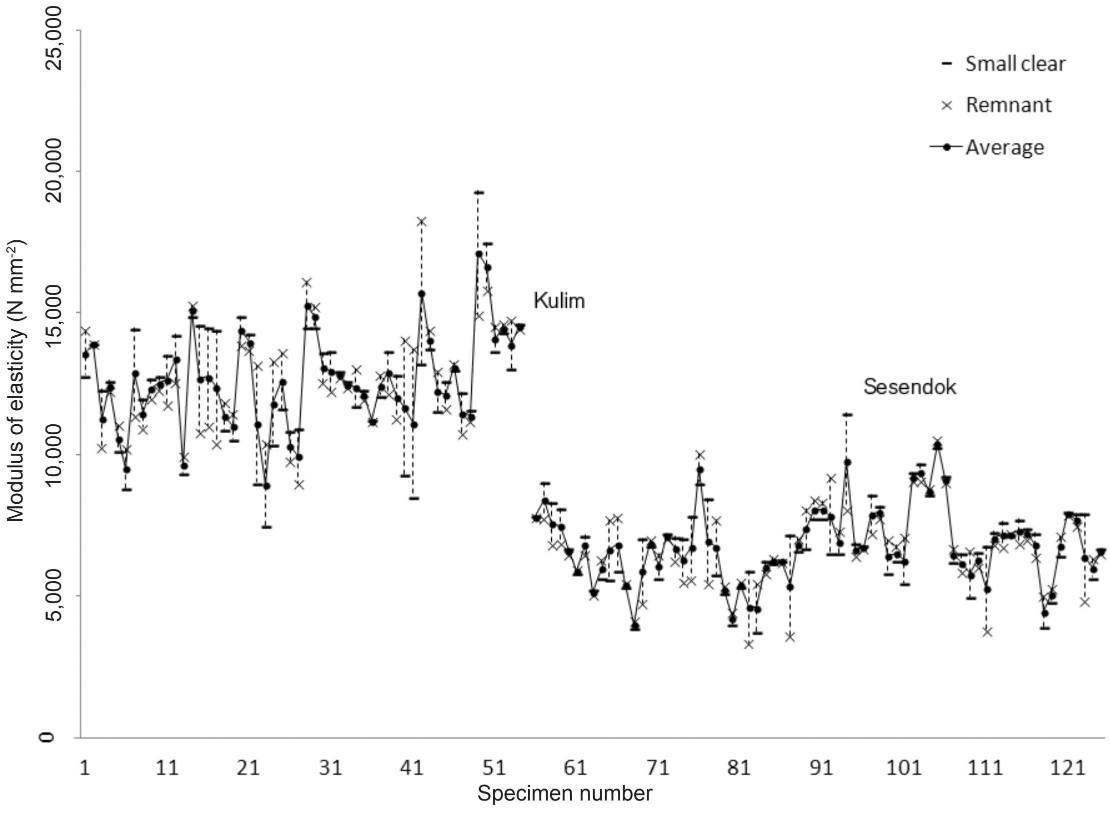

Figure 10 Modulus of elasticity correlation between small clear and remnant specimens

each MOR and MOE were plotted as vertical dashed-lines with solid lines connecting the average values. Changes were unnoticed for both MOR and MOE comparisons. Reduction of strength or stiffness due to stressing was not confirmed. Most of the differences were trivial and inconsistent, with regard to which was higher between small clear and remnant values. Furthermore, Table 2 shows that average MOR value is unchanged with a trivial drop in the average MOE value. Thus, it could be summarised that the effect of fracture stress on strength and stiffness of undamaged remnant fractions was insignificant.

Nevertheless, slight disparities between pairing specimens which originated from the same plank were observed. A clear specimen is supposed to be sound wood without natural or processing defect along the specimen length. However, for tropical timber, sound wood is difficult to distinguish. In practice, the grain angle deviation is not easy to determine (Geert & van de Kuilen 2010). Besides, variability in mechanical properties even among clear and straight-grain specimens is expected (Gromala 1985). Based on our experience, for small clear bending tests of tropical timber, only 20–30% of specimens failed by splintering separation, which is an indication of straight-grain timber. The percentage was lower for structural size bending, around 10%. The remainder failed as a result of various defects arising from the preparation of specimens, mostly slope of grain. However, the percentage of splintering failures slightly increased with higher density timber.

Figures 5 and 6 reveal the dispersal differences between small clear, remnant and structural size specimens. Distributions of small clear and remnant specimens were narrower than structural size. MOR and MOE distributions of remnant specimens is close to those of small clear specimens. Structural size specimens portrayed a more scattered distribution. These distributions are to be expected since small clear and remnant specimens are approximated to sound wood. High variation in structural size specimens are a consequence of the presence of defects and crossed grain.

Visual inspection method is practical to distinguish between clear and fractured fractions. In bending, fracture path normally initiates on the tension face of the beam. Timber often fractures in horizontal shear thus crack propagations are normally noticeable (Alam et al. 2009). Hence, removing damaged parts of timber for reuse of undamaged sections is practical via visual assessment. However, the effectiveness of visual inspection depends critically on the skill and experience of the practitioner.

Average density values showed slight reduction in density of remnant specimens (Table 2). Moisture release reduces the mass of the timber, thus reducing its density. Normally, laboratory comparison of timber density is made at zero MC through oven drying at 103 ± 2 °C until constant mass is obtained and this property is referred to as specific gravity (Desch & Dinwoodie 1996). On the contrary, we were comparing the densities of timber at the time of test. Thus, the density reduction of the remnant specimens is explicable.

Overall, timber subjected to fracture limit stress showed localised damage progression. Thus, the breakage path restricted the effect of strength weakening. Cracks always begin at a defect point on the tension surface, followed by breakages that take the mechanically weakest path. Hence, when fracture initiates in timber, it tends to work its way and propagates through the fibre. In that sense, a clear-straight grain specimen often shows a centre splintering type breakage, with the assumption that it has no critical weak point to initiate crack spread. Although timber damage occurs in various modes of failure such as gouging, splitting, slabbing, scraping as well as breakage, bending test result is a satisfactory and adequate guide to relative strength qualities of timber (Thomas 1931). Indeed, the basis for the establishment of safe working stresses is often partly derived from bending test results.

An understanding of the degree of damage at which a timber tolerates and consequently the rate to which strength and stiffness are affected is a topic that is practically relevant in timber utilisation. Timbers endure certain amount of stresses and occasionally end up with fracture. It happens along the processing line and sometimes during operation. Data obtained from this experiment has shown some very important conclusions in timber applications.

Nevertheless, the hypothesis was based on the macroscopic observation of test specimens, thus it is valid only for engineering purposes. From a scientific point of view, the microscopic progress due to high stresses is not satisfactorily explained through this test and requires anatomical investigation. The effects of timber damage in relation to the introduction of insects and fungi should be conducted in future study. Aho et al. (1983) reported that timber injuries, even a tiny size, are susceptible to infection by fungi and prone to attack by insects. Similarly, timber fracture due to age and environment needs to be studied.

Jakubowski et al. (2011) investigated the mechanical properties of wind-broken trees of Scots pine, but this occurrence was very seldom reported for tropical hardwood. Trees exposed to frequent winds resulted in distorted fibres, which remained as weak points in the wood (Arnold & Steiger 2006).

CONCLUSIONS

The presence of defects and slope of grain resulted in lower structural size MOR compared with small clear specimens. The MOE of structural size specimens was higher than small clear specimens due to difference in horizontal shear effect. Although the material had been subjected to fracture stress (the force limit of the specimen), it did not deteriorate the strength and stiffness of the remnant. Timber subjected to fracture stress in bending showed localised destructive effect which was restricted only to breakage paths. Distinguishing clear and damaged fractions from fractured timber via visual inspection was practical.

ACKNOWLEDGEMENTS

The research was financed by the Ministry of Science, Technology and Innovation Malaysia. We are indebted to F Che Muhammad and A Syarmiza for assisting in the mechanical testing.

REFERENCES

Aho PE, Fiddler G & Srago M. 1983. *Logging Damage in Thinned, Young-Growth True Fir Stands in California and Recommendations for Prevention.* Research Paper PNW-RP-304. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland.

Alam P, Ansell MP & Smedley D. 2009. Mechanical repair of timber beams fractured in flexure using bonded-in reinforcements. *Composites* Part B 40: 95–106.

Alik D & Badorul Hisham AB. 2006. Strength performance of full-size structural timber of *Dryobalanops* species of Sarawak, Malaysia. *Proceeding of the Ninth World Conference on Timber Engineering.* 6–10 August 2006, Portland.

Arnold M & Steiger R. 2006. The influence of wind-induced compression failures on the mechanical properties of spruce structural timber. *Materials and Structures* 40: 57–68.

ASTM. 1952. Standard D 143-52. Standard methods of testing small clear specimens of timber. *Annual Book of ASTM Standards.* American Society for Testing Materials, Philadelphia.

Brancheriau L, Bailleres H & Guitard D. 2002. Comparison between modulus of elasticity values calculated using 3 and 4 point bending tests on wooden samples. *Wood Science and Technology* 36: 367–383.

Desch HE & Dinwoodie JM. 1996. *Timber—Structure, Properties, Conversion and Use.* Seventh edition. McMillan, Basingstoke.

Dykstra DP. 2007. Influence of forest operations on timber quality. *Proceedings of the International Conference on Forest Growth and Timber Quality: Crown Models and Simulation Methods for Sustainable Forest Management.* 7–10 August 2007, Portland.

Engku ARC. 1971. Basic and grade stresses for some Malaysian timbers. *Malayan Forester* 34: 131–134.

Falk RH. 1999. The properties of lumber and timber recycled from deconstructed buildings. *Proceedings of the Pacific Timber Engineering Conference.* 14–18 March 1999, Rotorua.

Gagliano JM. 2001. *An Improved Method for the Fracture Cleavage Testing of Adhesively-Bonded Wood.* Virginia Polytechnic Institute and State University, Blacksburg.

Gardiner B & Mochan S. 2009. Timber quality assessment. *Proceedings of the Improved Conifer Timber Quality Through Plant Selection and Silviculture.* 11 February 2009, Dunkeld.

Geert R & van de Kuilen JW. 2010. Comparison of methods of strength classification of tropical hardwood timber. *Proceedings of the Eleventh World Conference on Timber Engineering.* 20–24 June 2010, Riva Del Garda.

Gerwick JW, Trenkwalder TW & Kearney JW. 2010. Practical repair of timber structures. *Proceedings of the 12th Ports: Building on the Past, Respecting the Future.* 25–28 April 2010, Jacksonville.

Gromala DS. 1985. Determination of modulus of rigidity by ASTM D-198 flexural methods. *Journal of Testing and Evaluation* 13: 352–355.

Jakubowski M, Jelonek T & Tomczak A. 2011. Modulus of rupture in twin samples (wet and absolutely dry) coming from wood of wind-broken trees of Scots pine (*Pinus sylvestris* L.). *Forestry and Wood Technology* 74: 110–114.

Lavers GM. 1983. *The Strength Properties of Timber.* Third edition. Construction Research Communications Limited, Peterborough.

Lee YH & Chu YP. 1965. The strength properties of Malayan timbers. *Malayan Forester* 28: 307–319.

Lee YH, Engku ARC & Chu YP. 1993. *The Strength Properties of Some Malaysian Timbers*. Timber Trade Leaflet No. 34. Malaysian Timber Industry Board, Kuala Lumpur.

Madsen B. 1975. Moisture content–strength relationship for lumber subjected to bending. *Canadian Journal of Civil Engineering* 2: 466–473.

Madsen B & Buchanan AH. 1986. Size effects in timber explained by a modified weakest link theory. *Canadian Journal of Civil Engineering* 13: 218–232.

Mohd Jamil AW, Mohd Zamin J & Mohamad Omar MK. 2012. Statistical technique for grouping tropical timbers into similar strength groups. *Modern Applied Science* 6: 73–80.

Mohd Jamil AW, Mohd Zamin J & Mohamad Omar MK. 2013. Relationship between mechanical properties of structural size and small clear specimens of timber. *Journal of Tropical Forest Science* 25: 12–21.

Thomas AV. 1931. Some notes on timber testing. *Malayan Forester* 1: 56–59.

Thomas AV. 1940. Malayan timbers tested in a green condition. *Malayan Forester* 9: 151–157.

Wong TM. 1982. A *Dictionary of Malaysian Timbers*. Malayan Forest Records No. 30. Forest Department Peninsular Malaysia, Kuala Lumpur.