ULTIMATE STRENGTH PREDICTION OF DRM TIMBER BEAMS BY PLASTIC APPROACH: EXPERIMENTAL RESULTS AND DISCUSSIONS

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ABSTRACT: A new stress model is developed to predict the ultimate bending strength of solid timber beams by using the principle of plasticity. The model predicts the actual bending strength of timber beams from the ratio of ultimate tensile and compressive strengths of the beam material. Standard bending, tension and compression tests are conducted on structural sized specimens to verify the proposed stress model using a local hardwood timber, Dark Red Meranti (DRM). The experimental results of 12 beams, 10 tension specimens and 15 compression specimens are used to verify the proposed model. Test results showed that there is a significant non-linear relationship of the load and the deformation for timber in bending and in compression, but the stress-strain relationship is linear in tension. The strain is linearly distributed across the beam section throughout the test, and the neutral axis shifts towards the tension side when the beam is loaded beyond the proportional limit. Although the tensile strength of timber is larger than its compressive strength, modulus of elasticity (MOE) in tension and compression is approximately the same.

Keywords: Timber beams, Ultimate strength prediction, Mathematical stress model, Bending tests, Tension and Compression tests

1.0 INTRODUCTION

During the research, bending, tension and compression tests were conducted on structural sized Dark Red Meranti (DRM) timber specimens in accordance with ASTM standard procedures (D 198-84, 1992). A new stress model was also proposed to predict the ultimate bending strength of DRM timber beams. Then, the model was verified by using the experimental results of bending, tension and compression tests. Ultimate tensile and compressive strengths of test specimens were the input parameters in the model.

During bending tests, the distribution of strain in mid-section wood fibres, the ultimate load, and the deflection of beams were recorded. The ultimate load and the values of strains at certain load levels were recorded during direct tension and compression tests. Moisture content and density of test specimens were also determined according to ASTM D 4442-92 (1992) and D 2395-83 (1992) procedures.

2.0 SELECTION AND PREPARATION OF TEST SPECIMENS

DRM is one of the most commonly used tropical hardwood timbers in Malaysia. It is classified as a light hardwood with an average density of 730 kg/m^3 and specific gravity of 0.47 at 19% moisture content (Choo & Lim, 1983). According to the Malaysian Standard MS 544: Part 2: (2001), it is under the strength group S.G. 5 and the mean value of modulus of elasticity (MOE) is 11200 MPa at moisture content ≤ 19%. Standard structural grade stresses at moisture content ≤ 19% for DRM were described as 14.3 MPa for bending, 8.6 MPa for tension parallel to grain, 11.0 MPa for compression parallel to grain.

Five large pieces (4"x 6"x 15") of Dark Red Meranti timber, which were logged from the area of Bandar Tenggara, Johor, were selected to utilise as the test material (Khin, 2002). They were previously kept to dry naturally in Structural Laboratory for about three years. The pieces were named as A, B, C, D and E. Each piece of timber was then cut into three different portions for bending, tension and compression test specimens.

2.1 Beam Specimens

Beam specimens were fabricated into two different cross-sections with the same length according to ASTM standard (D 198-84). FA, FB, FC, FD and FE group beams were cut from each of A, B, C, D and E timber pieces respectively. Three 50 mm x 100 mm x 2100 mm (2"x 4"x 84") beams were fabricated for each of group FA and FB and two 50 mm x 150 mm x 2100 mm (2"x 6"x 84") beams for each of group FC, FD and FE. All beam specimens were prepared to get 225 mm (9") overhang on each end.

2.2 Tension and Compression Specimens

Tension test specimens were fabricated into five different groups TA, TB, TC, TD and TE based on the dimensions specified by ASTM standard (D 198-84). Each group contained three 800 mm long tension test specimens (including pilot test specimens), with 200 mm grip length and 400 mm in the middle including 250 mm gauge length. The nominal cross sectional dimensions of specimens were 50 mm x 25 mm (2″ x 1″) within the grip length and 25 mm x 25 mm (1″ x 1″) within the gauge length.

Compression test specimens were also fabricated into five different groups CA, CB, CC, CD and CE based on the dimensions specified by ASTM standard (D 198-84, 1992). Each group contained four 50 mm x 50 mm x 150 mm (2" x 2" x 6") compression specimens including pilot test specimens.

3.0 INSTRUMENTATION AND TEST SET-UP

3.1 Beam Tests

The test rig (test-frame) for the bending test was a self-reacting frame made up of four steel boxes, four vertical and four horizontal steel channels. The vertical channels, braced together with horizontal channels by bolts were anchored firmly to the strong floor of by bolts. Two other steel boxes were placed on two lower horizontal channels to act as supports for the beam specimen.

A hydraulic jack, attached to the top horizontal channels of test-frame, was used to apply the load to the beam specimen through the 200 kN Kyowa Load Cell and the load distributor (steel I-beam). Four sets of steel bearing plates with steel rollers were placed between the load distributor and the beam, and also between the beam and the beam support. Lateral guards were also used to prevent the lateral buckling of the beam.

Four 50 mm Omega strain gauges and four 100 mm Omega strain gauges were attached alternately to two opposite sides at the centre of the specimen by solid brass fixing jigs. The jigs were glued to the specimen using 5-minute epoxy glue. The spacing between each strain gauge is 24 mm for 50 mm x 100 mm beams and 38 mm for 50 mm x 150 mm beams. Three Kyowa displacement transducers (LVDT) were placed directly beneath the centre and two loading points of the beam. A Kyowa load cell was placed between the hydraulic jack and the load distributor. Strain gauges, transducers and the load cell were connected to the data-logger to capture the strain, deflections and the load readings during the test.

The rate of loading was about 0.1 kN per second so that the maximum load reached and the specimen failed within 6 to 20 minutes, which is the rate specified by ASTM standard (D 198-84, 1992). The strain for the specified depth was calculated from the average readings of the two strain gauges at the same depth on opposite sides of the beam. After the tests, the beam specimen was cut near the middle span into three 50 mm x 50 mm (2″x 2″) pieces of 25 mm (1″) thickness for moisture content and density tests.

3.2 Tension and Compression Tests

The 5000 kN Dartec universal testing machine with 250 kN loading head was used for tension tests. Wedge grips, instead of normal parallel grips, were used to hold the specimens because of the nature of material and the type of test. The 250 kN Dartec universal testing machine was used for compression tests. The machine had a swivel loading head in order to minimize the eccentricity between the geometric centre of the specimen and the centre line of the loading plates.

Two 100 mm Omega strain gauges were used for tension tests and two 50 mm strain gauges for compression tests. They were attached to opposite sides of the specimen by solid brass fixing jigs, which were glued to the specimen using 5-minute epoxy glue. Strain gauges were connected to the data-logger to capture the strain readings throughout the test. In tension tests, strain gauges were protected by aluminium guard plates because sudden breaking failure of test specimens may cause the damage to gauges.

The rate of loading was fixed at the stroke of 0.05 mm/sec for tension specimens and 0.003 mm/sec for compression specimens. The strain was calculated from the average of two strain gauge readings and the stress from the corresponding load divided by the cross sectional area of the specimen. After the tests, three 25 mm (1″) thick pieces were cut from the end of each specimen for moisture content and density tests.

4.0 TEST RESULTS AND DISCUSSIONS

4.1 Beam Tests

The beams showed the typical bending failure pattern under one-third-point loads. After the applied load passed the proportional limit, the beams started to fail in compression by appearing wrinkles on the compression edge, producing some noises. All wrinkles occurred between the maximum moment region and most wrinkles extended from the upper compression edge to slightly more than one-half of the beam depth. Then further loading beyond the proportional limit caused the redistribution of compressive stresses across the beam depth and the shifting of neutral axis towards the tension edge.

Load-deflection curves for beams [See Figure 1], by using the deflection data at mid span of the beams, show that the beams are stressed well beyond the proportional limit. The curves can be divided into linear portion (elastic stage) and non-linear portion (inelastic stage) with a rising slope. Non-linear portion of the curve occupied a significant amount (over 50%) of total deflection for almost all the specimens.

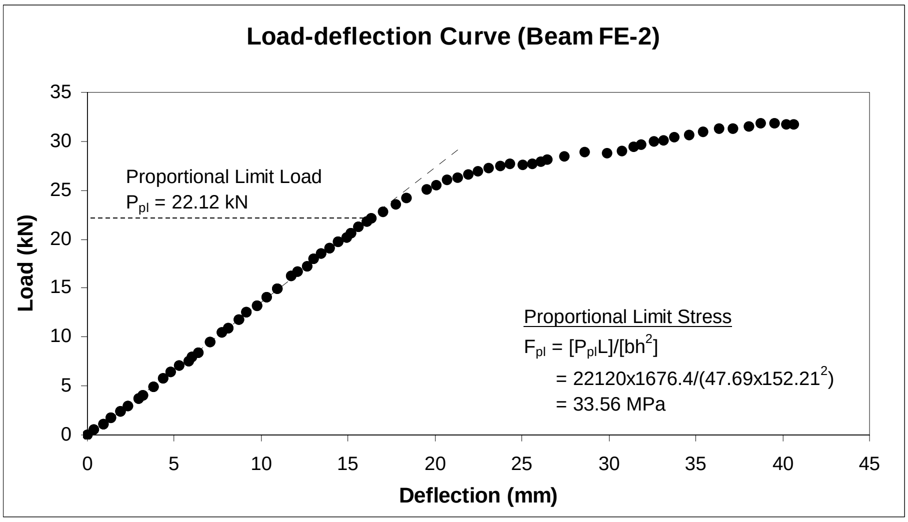

Figure 1: Typical load-deflection curve for timber beams

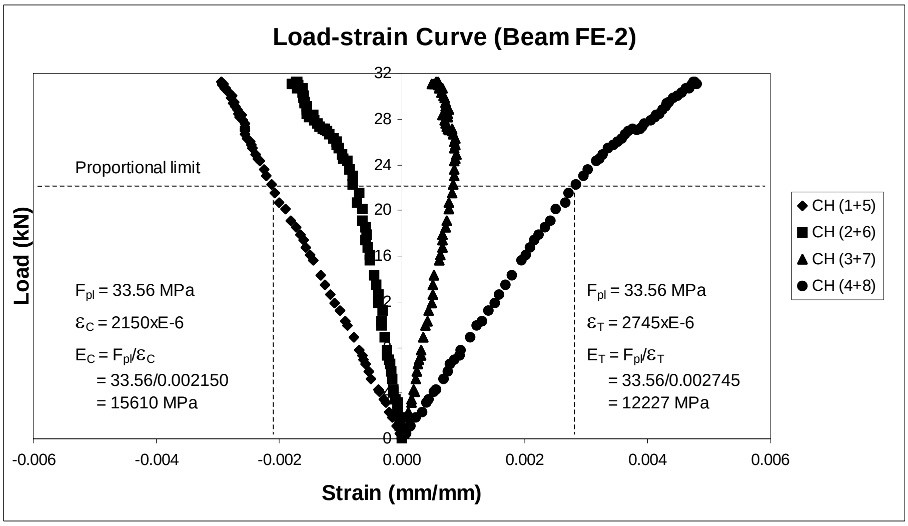

Figure 2: Typical load-strain curve for timber beams

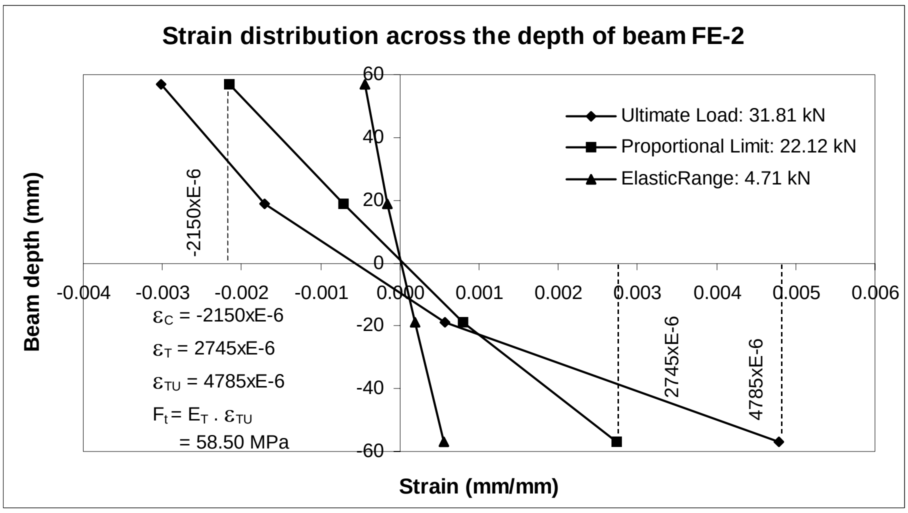

Figure 3: Typical strain distribution diagram for timber beams

Load-strain curves for beams [See Figure 2] are drawn using the average data from eight strain gauges. The curves show non-linear relationship between the load and the strain in the inelastic stage of loading. As a result of the downward movement of neutral axis and the redistribution of compressive stresses, tension fibres are subjected to relatively increased tensile stresses to maintain the equilibrium of the beam. These increased stresses are no longer proportional to the load on the beam. As the neutral axis moves progressively towards the tension side due to the redistribution of stresses, the fibres close to the neutral axis of the beam and originally strained in tension are strained later into compression [See channel CH (3+7) of Figure 2].

Strain distribution diagrams [See Figure 3] across the beam depth were also drawn at three different loading stages: the elastic stage, the proportional limit stage and the inelastic stage at ultimate load. Satisfactory results of linearly distributed strains across the beam depth were shown for all loading stages. Deviation of strain from the linear distribution in some cases, especially at ultimate loading stages, may be due to wrinkles, which appeared near mid span during the inelastic range of loading and interfered the action of strain gauges.

When the applied load was small within the elastic range, it was observed that the initial position of neutral axis was slightly above or below the mid-depth of the beam. At proportional limit load, the position of neutral axis still remained in the same position as in the elastic range. Then the neutral axis moved towards the tension edge of the beam until the ultimate load was reached. Position of neutral axis was described as the neutral axis position factor (γ) [See Table 1].

Table 1: Summary of beam test results

				At Proportional Limit Load				At Ultimate Load			
Beam Label	[E_C] (MPa)	[E_C/E_T]	[E_T] (MPa)	[F_{pl}] (MPa)	[ε_C] (xE-6)	[ε_T] (xE-6)	[γ_{pl}]	[M_u] (kN-m)	[ε_{TU}] (xE-6)	[F_t] (MPa)	[γ_u]
FA-1	13913	0.91	15363	39.79	2860	2590	0.49	3.65	2960	45.48	0.34
FA-2	15069	0.95	15809	30.59	2030	1935	0.45	2.33	1970	31.14	0.45
FA-3	14941	1.03	14463	38.47	2575	2660	0.50	3.88	4575	66.17	0.44
FB-1	16308	0.93	17592	41.34	2535	2350	0.49	5.49	5270	92.71	0.41
FB-2	19911	1.18	16909	48.78	2450	2885	0.48	5.68	5555	93.93	0.40
FB-3	20982	1.23	17119	40.92	1950	2390	0.49	5.56	5585	95.61	0.40
FC-1	20880	0.93	22343	54.18	2595	2425	0.49	14.77	6195	138.42	0.45
FC-2	18371	1.02	18024	47.76	2600	2650	0.49	12.47	5800	104.54	0.46
FD-1	24003	1.24	19409	49.69	2070	2560	0.50	13.45	5290	102.67	0.45
FD-2	12614	0.84	14970	47.68	3780	3185	0.47	12.15	5840	87.42	0.36
FE-1	14330	1.11	12910	28.02	1955	2170	0.49	6.25	3140	40.54	0.45
FE-2	15610	1.28	12227	33.56	2150	2745	0.49	8.89	4785	58.50	0.44

The proportional limit stress (F_{pl}) for each beam is estimated from the corresponding load-deflection curves [See Figure 1 and Table 1]. First, a straight line was drawn passing through the points within the linear portion of the curve. Then the point of inflection was defined as the proportional limit load (P_{pl}). Then the proportional limit stress (F_{pl}) was calculated from the proportional limit load, the moment arm and the section properties of the beam.

Assuming there is a linear stress-strain relationship for extreme tension fibres of the beams, extreme fibre tensile stress (F_t) for each timber beam is calculated from MOE of extreme tension fibres (E_T) and the maximum tensile strain (ε_{TU}) [See Figure 3 and Table 1]. The MOE of extreme tension fibres (E_T) is calculated by dividing the proportional limit stress (F_{pl}) with the tensile strain at proportional limit (ε_T), which corresponds to the proportional limit load (P_{pl}) [See Figure 2 and Table 1].

Modulus of elasticity (MOE) for extreme tension and compression fibres of each beam is evaluated based on proportional limit stress (F_{pl}) from load-deflection curves and respective strain at proportional limit from load-strain curves. The values of MOE in compression and tension fibres (E_C and E_T), and the ratio (E_C /E_T) of compression and tension fibres are described in Table 1. According to Table 1, it can be assumed that MOE in compression fibres is equal to MOE in tension fibres.

Ultimate bending moment (M_u) of beam specimens under one third point loading is calculated from the maximum applied load (P_u) and span length. The maximum load (P_u) was taken from the peak point of load-deflection curve. The values of ultimate bending moment and maximum load for 50 mm x 100 mm beams (group A and B) and for 50 mm x 150 mm beams (group C, D and E) are described in Table 2.

Table 2: Properties of beam specimens

Group	Specimen Label	Moisture Content	Density (kg/m^3)	Maximum Load (P_u) (kN)
A	FA-1	15.79%	551.4	13.07
	FA-2	17.14%	474.3	8.35 (N.A)
	FA-3	19.33%	567.8	13.90
	Mean	**17.42%**	**531.2**	**13.49**
B	FB-1	17.25%	876.0	19.64
	FB-2	17.29%	858.5	20.34
	FB-3	17.00%	851.7	19.89
	Mean	**17.18%**	**862.1**	**19.96**
C	FC-1	16.95%	840.3	52.85
	FC-2	18.28%	842.9	44.62
	Mean	**17.62%**	**841.6**	**48.74**
D	FD-1	17.66%	849.3	48.13
	FD-2	17.86%	765.4	43.48
	Mean	**17.76%**	**807.4**	**45.81**
E	FE-1	17.41%	501.3	22.7 (N.A)
	FE-2	16.69%	530.9	31.81
	Mean	**17.05%**	**516.1**	**31.81**
Overall Mean		**17.41%**	**711.7**	N.A = not account

4.2 Tension Tests

Almost all the specimens showed the same failure pattern by a combination of tension and shearing parallel to grain. The failure of tension specimens was initiated as compression perpendicular to grain failure by crushing wood fibres between the wedge grips producing some noises. Then the specimen started to fail along the edge of upper wedge grips, where stress concentrations occur. The failure extended towards the middle gauge length along the grain of the specimen. Finally, the specimen suddenly broke by a combination of tension and shear parallel to the grain producing a loud noise.

Stress-strain curves of all tensile test specimens show linear relationship up to maximum stress [See Figure 4]. As there is no non-linear portion of the stress-strain curve like in compression test specimens, the behaviour of tensile specimens showed brittle nature. Maximum tensile strength parallel to the grain (F_{tu}) of each tension specimen is determined from the peak point of stress-strain curves.

Average values of ultimate tensile strength, and the maximum and minimum tensile strength values for tension specimens are described in Table 3. A wide range between maximum tensile strength and minimum tensile strength of tension specimens may be due to the variation of density for each group of specimens. Modulus of elasticity (MOE) for each of tension specimens is determined from the slope of their stress-strain curves. The average, maximum and minimum MOE values for tension specimens are described in Table 3.

Table 3: Properties of tension specimens

Group	Specimen Label	Moisture Content	MOE (MPa)	Max. Tensile Strength (F_{tu}) (MPa)
A	TA-1	19.05%	10508	41.09
	TA-2	20.00%	10390	51.76
	Mean	**19.53%**	**10449**	**46.43**
B	TB-1	16.13%	12900	58.78
	TB-2	17.14%	12420	53.66
	Mean	**16.64%**	**12660**	**56.22**
C	TC-1	15.63%	10233	54.12
	TC-2	17.24%	14354	53.12
	Mean	**16.44%**	**12294**	**53.62**
D	TD-1	15.79%	12051	56.65
	TD-2	17.14%	11847	62.73
	Mean	**16.47%**	**11949**	**59.69**
E	TE-1	16.67%	8184	37.01
	TE-2	15.38%	9004	57.00
	Mean	**16.03%**	**8594**	**47.01**
Overall Mean		**17.02%**	**11189**	**52.59**

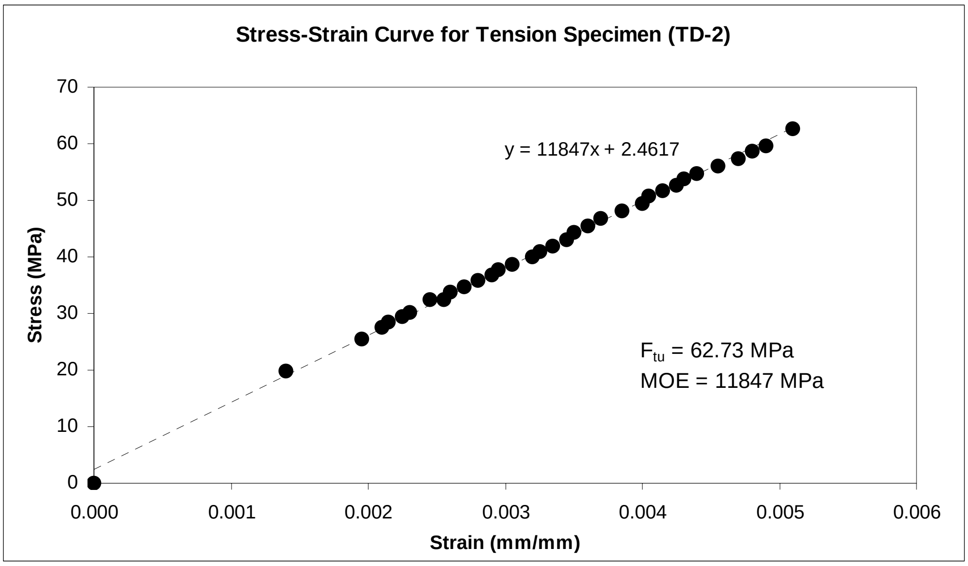

Figure 4: Typical stress-strain curve for tension specimens

4.3 Compression Tests

All specimens showed typical compression failures conforming to the American Standard ASTM D-143-83 (1992), without splitting or end rolling but a combination of crushing or wedge splitting or compression and shearing parallel to grain. Most specimens yielded in compression by appearing wrinkles near the edge and the middle of the specimen, after the maximum load had reached but the specimens never broke apart completely. This phenomenon can be explained from the fact that wood cells behave as a pack of straws (or hollow tubes) and they are very efficient for resisting a compressive force parallel to the grain Mohamed (1991).

Table 4: Properties of compression specimens

Group	Specimen Label	Moisture Content	Density (kg/m^3)	MOE (MPa)	Max. Comp. Strength (F_{cu}) (MPa)
A	CA-1	13.64%	460.2	9120	29.08
	CA-2	15.00%	452.0	11311	28.87
	CA-3	15.00%	434.4	10286	30.07
	Mean	**14.55%**	**448.9**	**10239**	**29.34**
B	CB-1	17.37%	812.9	13328	42.54
	CB-2	16.67%	735.9	11156	39.64
	CB-3	14.43%	749.2	12109	43.12
	Mean	**16.16%**	**766.0**	**12198**	**41.77**
C	CC-1	16.13%	804.0	10995	49.55
	CC-2	18.36%	794.6	13022	43.61
	CC-3	17.84%	811.7	15444	46.81
	Mean	**17.44%**	**803.4**	**13154**	**46.66**
D	CD-1	15.40%	707.8	11513	47.69
	CD-2	16.01%	700.4	14191	46.50
	CD-3	17.83%	708.5	13168	42.57
	Mean	**16.41%**	**705.6**	**12957**	**45.59**
E	CE-1	15.52%	476.1	11816	28.49
	CE-2	16.67%	478.3	10116	29.12
	CE-3	16.67%	480.6	10730	27.20
	Mean	**16.29%**	**478.3**	**10887**	**28.27**
Overall Mean		**16.17%**	**640.4**	**11887**	**38.33**

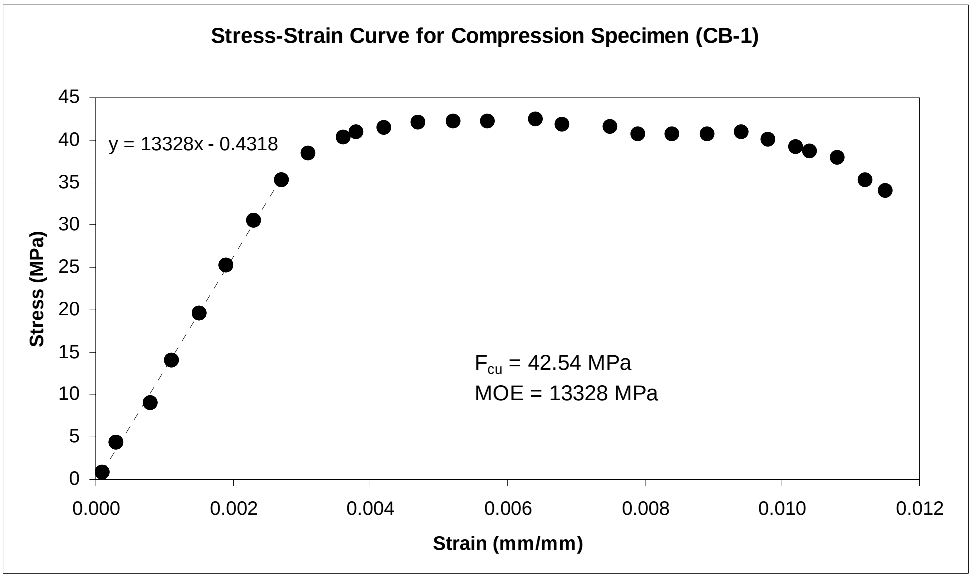

Figure 5: Typical stress-strain curve for compression specimens

Stress-strain curves of compression test specimens can be divided into linear and non-linear parts [See Figure 5]. Linear portion up to proportional limit shows elastic behaviour, and non-linear portion from proportional limit until failure shows ductile (plastic) behaviour of wood in compression. Non-linear portion of the stress-strain curve occupies a significant amount (over 50%) of total strain for most specimens. Maximum compressive strength parallel to the grain (F_{cu}) of each compression specimen is determined from the peak point of the corresponding stress-strain curves. The average, maximum and minimum values of ultimate compressive strength for compression specimens are described in Table 4.

Modulus of elasticity (MOE) for each of compressive test specimens is determined from their stress-strain curves. A straight line was drawn through a group of points within the linear portion of the stress-strain curve and the slope of the line was taken as MOE of the corresponding specimen. The average, maximum and minimum MOE values for compression specimens are described in Table 4.

5.0 CONCLUSION

The results of bending, tension and compression tests have been discussed in previous sections. For bending tests, it can be concluded that the strain is linearly distributed across the beam depth almost up to failure, and the neutral axis shifted towards the tension edge as the load passed the proportional limit. Load-deflection curves showed a combination of linear and significant non-linear (plastic) relationship with the rising slope. Average values of MOE for tension and compression fibres are approximately the same. Beam stresses, i.e. proportional limit stress (F_{pl}) and extreme fibre tensile stress (F_t), are calculated from load-deflection curves and load-strain curves. Tension specimens showed almost linear stress-strain relationship with brittle nature while compression specimens showed a combination of linear and significant non-linear stress-strain relationship with plastic behaviour. Ultimate tensile strength of tension specimens is higher than ultimate compressive strength of compression specimens. Average MOE in axial tension is approximately equal to average MOE in axial compression.

6.0 ACKNOWLEDGEMENT

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NOMENCLATURE

E_C = modulus of elasticity for extreme compression fibres of the beam
E_T = modulus of elasticity for extreme tension fibres of the beam
F_{cu} = ultimate compressive strength of the beam material obtained from compression tests
F_{pl} = proportional limit stress of the beam
F_t = maximum tensile stress in extreme tension fibres of the beam
F_{tu} = ultimate tensile strength of the beam material obtained from tension tests
M_u = ultimate bending moment capacity of the beam
n = the strength ratio or the ratio of ultimate tensile strength to ultimate compressive strength of the beam material ($n = F_{tu}/F_{cu}$ and $n > 1$)
P_{pl} = proportional limit load obtained from the load-deflection curve
γ = neutral axis position factor of the beam measured from the tension edge
γ_{pl} = neutral axis position factor of the beam at proportional limit
γ_u = neutral axis position factor of the beam at ultimate load
ε_C = compressive strain of beam fibres at proportional limit
ε_T = tensile strain of beam fibres at proportional limit
ε_{TU} = maximum tensile strain of beam fibres at ultimate load
ψ = moment coefficient of stress models

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