EVALUATING WOOD STRENGTH PROPERTIES OF SUBTROPICAL URBAN TREES USING FRACTOMETER II

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TANG AMC, CHU PPL, LEUNG MWK, CHU LM & LIAO WH. 2016. Evaluating wood strength properties of subtropical urban trees using Fractometer II. Estimating the extent and severity of decay during tree risk assessment is essential for evaluating tree defects. A portable device that serves this purpose in the field would enhance decay evaluation. A fractometer is a handy device that breaks increment core at radial and longitudinal dimensions for the measurement of wood strength which enables us to obtain reference data for wood quality. In this study, wood strength properties of 25 healthy common broadleaf tree species in Hong Kong were evaluated using Fractometer II. A total of 2656 sections were tested for radial bending strength and angle and 4779 sections for longitudinal compressive strength. There was significant and positive correlations between radial bending strength and longitudinal compressive strength, suggesting a tight interrelationship in physical arrangement contributing to radial and longitudinal mechanical strengths. The ratio of longitudinal compressive strength to radial bending strength which ranged from 1.82 to 3.58 indicated differences of woody plants in construction investment of wood materials in vertical and radial scale. Hierarchical clustering and multidimensional scaling analysis revealed clear grouping of tree species into different types of wood properties.

Keywords: Bending strength, compressive strength, decay assessment

INTRODUCTION

Trees in urban districts are usually weakened by stress conditions such as restricted planting areas, soil compaction, poor aeration and water drainage, unsuitable pH, nutrient deficiency, interrupted nutrient cycling and low soil organism activity (Craul 1992, Nielsen et al. 2007). Wounds, which often occur in urban areas due to physical damage, facilitate decay, and harsh growing conditions make it harder for trees to respond by compartmentalisation of decay in trees (CODIT). According to CODIT, trees can develop four conceptual walls in the woody tissues around the wound to prevent or slow down decay. Development of fungal decay may increase the likelihood of tree failure and the associated risks. The ability to determine wood quality, especially in the early stages of fungal infection or internal cracks, is an important aid to tree risk assessment (Wang & Allison 2008).

Methods for nondestructive testing of wood in trees have constantly been improved for assessment of standing trees in the field (Johnstone et al. 2010). One of the most convenient and portable field-based wood testing devices is the Fractometer II. The device measures longitudinal compressive strength, radial bending strength and bending angle of wood core sample. Wood compressive strength is a good indicator of wood quality and incipient decay which are highly correlated with decay caused by brown rot and white rot fungi (Chiu et al. 2006, Matsumoto et al. 2010).

Fractometer II is used to evaluate severity of decay in trees by comparing the strength of decayed and sound wood. A database of wood strength values from sound wood in healthy trees would provide reference values and could be compared with results in the field (Spatz

& Pfisterer 2013). Such database allows cross-species comparison by grouping species based on strength of wood. Databases provide tree assessors baseline data of wood strength for healthy trees that can be compared with results from decayed or stressed trees during tree risk assessment. This kind of database is largely unavailable in Asia (Ganesan & Abdul Hamid 2010).

The objectives of this study were to (1) assess wood strength properties of common landscape tree species in Hong Kong, (2) assess potential correlation of radial bending strength with longitudinal compressive strength and (3) categorise tree species into different groups according to their wood properties.

MATERIALS AND METHODS

Study area

Hong Kong, located on the southern coast of mainland China, comprises Kowloon Peninsula and New Territories on the mainland, Hong Kong Island and many other islands with a total area of 1104 km^2. It has a subtropical monsoon climate with hot wet summers and cool dry winters. Mean monthly temperature ranges from 16.3 °C in January to 28.8 °C in July (Anonymous 2015). Roadside trees are mostly planted along pavement in planters or tree pits, tree lawns, raised planting beds, central dividers, traffic islands and roundabouts surrounded by carriageways and spaces below flyovers.

Selection of trees for study

A total of 25 healthy common broadleaf landscape species were included in this study (Table 1). The selected species are widely planted in Hong Kong, South China and Singapore (Jim & Liu 1997, Ganesan & Abdul Hamid 2010). Increment cores were collected from trees in urban parks, housing estates, along roadsides and plantation areas of country parks in various parts of Hong Kong (Table 1). Fifteen trees with dbh (diameter at breast height or 1.3 m from ground level) ranging from 0.20 to 0.35 m were chosen for each species. Only trees with no major defects on the lower trunks were sampled. To avoid possible complications of wood strength in compression and tension sides of leaning trees, sampling was limited to trees growing on flat ground, with trunk lean of 5^o or less, and possessing a balanced tree crown.

Wood strength assessment by the fractometer

Wood strength was assessed using Fractometer type II which determined characteristic values of radial bending strength, radial bending angle and longitudinal compressive strength of wood (Figure 1a). A 400-mm increment borer was used to extract wood core from tree trunks at dbh. The increment borer was regularly sharpened to reduce possible dulling effects. Extracted samples were stored in separate wooden battens in zip-lock plastic

Table 1 Summary of habitat types and their sampled tree species

Sampling location	Tree species
Country park	*Celtis sinensis, Lophostemon confertus, Melaleuca cajuputi* subsp. *cumingiana*
Housing estate	*Acacia auriculiformis, Acacia confusa, Alstonia scholaris, Celtis sinensis, Leucaena leucocephala*
Garden	*Acacia confusa, Alstonia scholaris, Bauhinia × blakeana, Delonix regia, Erythrina variegata, Ficus microcarpa, Ficus virens, Hibiscus tiliaceus, Liquidambar formosana, Senna siamea*
Man-made slope	*Acacia auriculiformis, Albizia lebbeck, Aleurites moluccana, Ficus microcarpa*
Sidewalk	*Acacia auriculiformis, Acacia confusa, Acacia mangium, Albizia lebbeck, Aleurites moluccana, Bauhinia × blakeana, Bombax ceiba, Casuarina equisetifolia, Cinnamomum camphora, Delonix regia, Erythrina variegata, Falcataria moluccana, Ficus microcarpa, Ficus virens, Hibiscus tiliaceus, Khaya senegalensis, Leucaena leucocephala, Liquidambar formosana, Macaranga tanarius* var. *tomentosa, Melia azedarach, Senna siamea*

bags. Samples were analysed in the laboratory within 12 hours.

Wood strength data were taken along the entire core and the same core was used for both bending and compressive tests (Figure 1b). Bending tests were conducted at least six times along the core. Inside the tunnel of the clamping device, wood core was broken at 11 mm from the tip by pushing the two bending levers together. Compressive tests were made after the remaining fragments were cut into 5-mm lengths. Readings were taken at the first failure or kinking of the fibres after force was applied on the grip.

Statistical analysis

All wood strength measurements and the ratio of compressive to radial bending strengths were tested for assumptions of normality using Kolmogorov–Smirnov test. Natural log transformation was applied to the data on radial bending angle and compressive strength:radial bending strength ratio prior to analyses. Interspecific variations of radial bending strength, radial bending angle, longitudinal compressive strength and ratio between longitudinal compressive strength and radial bending strength were investigated by one-way ANOVA followed by Tukey's or Tamhane's post-hoc test. Homogeneity of variance was examined using Levene's test prior to one-way ANOVA analysis. Tukey's HSD post hoc test was applied when variances were assumed equal and Tamhane's post hoc test was applied when variances were not assumed equal.

The association between bending and compressive strengths was tested using Pearson correlation. A Spearman's rank-order correlation was run to determine the relationship between ratio of wood strength properties and dbh of target trees. Patterns of relationships of the three wood strength measurements between species were analysed using non-metric multidimensional scaling (PRIMER version 6, 2006). Hierarchical agglomerative cluster analysis was carried out by complete linkage method.

RESULTS

A total of 2656 sections were tested for radial bending strength and angle and 4779 sections, for longitudinal compressive strength. Mean values for each tree species from no less than 90 measurements for bending strength and angle and 180 measurements for compressive strength

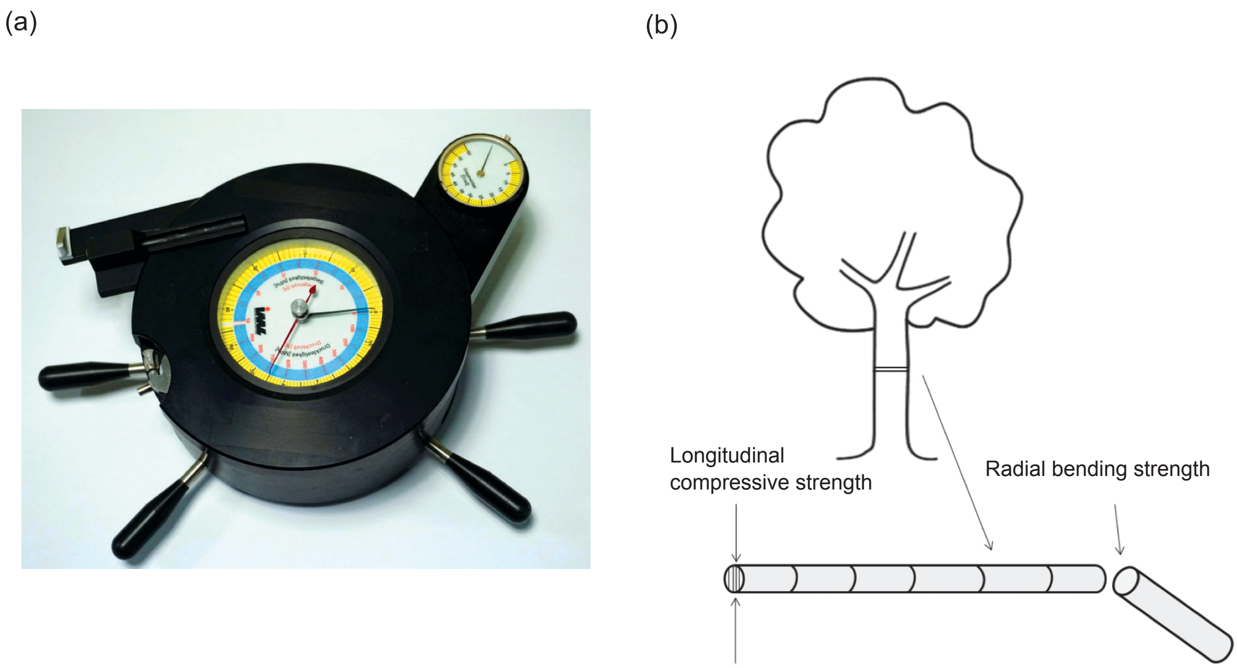

Figure 1 (a) Fractometer II and (b) direction of strength measurements on wood core

are given in Table 2. Kolmogorov-Smirnov test revealed that data sets of radial bending strength and longitudinal compressive strength were normally distributed, while those of radial bending angle and compressive strength:radial bending strength ratio were not and were thus log-transformed.

Radial bending strength

Mean radial bending strength of samples from 25 tree species ranged from 5.9 to 17.0 MPa (Table 2). Since this data set passed the Levene's test, one-way ANOVA followed by Tamhane's post-hoc test was conducted to investigate the interspecific variations and the results are shown in Tables 3 and 4. *Aleurites moluccana*, the species with the lowest mean bending strength, was significantly weaker than most tree species, except for *Bombax ceiba*, *Erythrina variegata*, *Melia azedarach* and *Falcataria moluccana* (one-way ANOVA, $F_{(24, 348)} = 24.83$, $p < 0.05$, Tamhane's test, $p < 0.05$) (Tables 3 and 4). *Acacia confusa,* with the highest mean bending strength, was significantly stronger than most tree species, except for *Casuarina equisetifolia*, *Celtis sinensis*, *Ficus microcarpa*, *Leucaena leucocephala* and *Liquidambar formosana*.

Radial bending angle

Mean radial bending angle of 25 tree species ranged from 8.5° to 16.2° (Table 2). Since the data set did not pass Levene's test, one-way ANOVA followed by Tukey's post-hoc test were carried out to investigate the interspecific variations. *Acacia auriculiformis*, *Alstonia scholaris, Bauhinia × blakeana, Bombax ceiba, Erythrina variegata*, *Lophostemon confertus* and *F. moluccana* formed a homogenous subset that had significantly smaller bending angle ranging from 8.5° to 9.1° (one-way ANOVA, $F_{(24, 348)} = 15.26$, $p < 0.05$, Tukey's test, $p < 0.05$) (Tables 3 and 4). *Cinnamomum camphora* and *C. sinensis* had significantly larger bending angle (Tukey's test, $p < 0.05$).

Longitudinal compressive strength

Mean longitudinal compressive strength measurements of 25 tree species ranged from 13.3 to 42.3 MPa (Table 2). Since this data set passed Levene's test, one-way ANOVA followed by Tamhane's post-hoc test was conducted to investigate the interspecific variations. Specifically, *Aleurites moluccana* and *Erythrina variegata* had significantly smaller mean longitudinal compressive strength than the rest of the species (one-way ANOVA, $F_{(24, 348)} = 72.72$, $p < 0.05$, Tamhane's test, $p < 0.05$ for each comparison) (Tables 3 and 4). *Acacia auriculiformis, A. confusa, C. equisetifolia, L. leucocephala* had significantly higher mean longitudinal compressive strength than the rest of the species (Tamhane's test, $p < 0.05$).

Combined analyses of wood strength properties

Pearson correlation analysis revealed significant positive correlations between bending strength and compression strength ($r = 0.635$, $p < 0.05$, $n = 373$) (Figure 2), and bending strength and bending angle ($r = 0.289$, $p < 0.05$, $n = 373$). No correlation between bending angle and compression strength was found. The ratio range of longitudinal compressive strength to radial bending strength was 1.82–3.58:1. Since this data set passed Levene's test, one-way ANOVA followed by Tamhane's post-hoc test was conducted to investigate the interspecific variations. *Falcataria moluccana* had significantly higher ratio than *C. sinensis* (one-way ANOVA, $F_{(24, 348)} = 12.323$, $p < 0.05$, Tamhane's test, $p < 0.05$) (Tables 3 and 4). Spearman's rank-order correlation revealed significant negative correlation between ratio and dbh ($r_s = -0.184$, $p < 0.001$, $n = 373$).

Multivariate analysis of wood strength measurements between species, including hierarchical clustering and multidimensional scaling analysis (Figure 3), identified three main groups, each with > 80% within-group similarity (2D stress: 0.04). Similarity between groups 2 and 3 was 77%, while that between group 1 and the other two groups was 59%. Within group 1 there was further separation of two species, namely, *A. moluccana* and *E. variegata* from the rest of the species.

DISCUSSION

Comparison of wood strength values, including radial bending strength, radial bending angle and longitudinal compressive strength, from

Table 2 Summary measurements of the 25 tree species studied

Species	Height (m)	Dbh (mm)	Spread (m)	Radial bending strength (MPa)	95% confidence interval	Radial bending angle (degree)	95% confidence interval	Longitudinal compressive strength (MPa)	95% confidence interval	Ratio of longitudinal compressive strength: radial bending strength
Acacia auriculiformis	9.1 ± 1.6 (15)	230 ± 29 (15)	4.3 ± 1.2 (15)	12.9 ± 4.3 (90)	± 0.90	8.5 ± 2.8 (90)	± 0.59	42.3 ± 7.1 (180)	± 1.04	3.41 ± 0.68
Acacia confusa	8.1 ± 0.3 (15)	268 ± 109 (15)	4.1 ± 2.1 (15)	17.0 ± 5.5 (91)	± 1.15	13.1 ± 2.8 (91)	± 0.59	37.2 ± 5.4 (180)	± 0.79	2.26 ± 0.46
Acacia mangium	9.1 ± 1.1 (15)	269 ± 30 (15)	3.6 ± 0.9 (15)	13.3 ± 3.8 (90)	± 0.79	10.8 ± 2.3 (90)	± 0.48	35.3 ± 6.2 (180)	± 0.91	2.66 ± 0.39
Albizia lebbeck	7.0 ± 1.6 (15)	283 ± 44 (15)	5.4 ± 1.5 (15)	12.7 ± 3.7 (90)	± 0.78	11.0 ± 2.6 (90)	± 0.54	33.5 ± 5.2 (180)	± 0.76	2.72 ± 0.50
Aleurites moluccana	6.5 ± 1.8 (15)	237 ± 24 (15)	3.4 ± 1.4 (15)	5.9 ± 1.8 (90)	± 0.38	11.0 ± 3.8 (90)	± 0.80	13.3 ± 2.8 (180)	± 0.41	2.26 ± 0.20
Alstonia scholaris	7.2 ± 1.1 (15)	253 ± 44 (15)	3.8 ± 1.0 (15)	9.9 ± 2.6 (90)	± 0.55	9.9 ± 3.0 (90)	± 0.63	20.9 ± 4.4 (180)	± 0.65	2.13 ± 0.47
Bauhinia × blakeana	6.4 ± 0.7 (15)	222 ± 19 (15)	4.3 ± 0.9 (15)	11.4 ± 3.2 (93)	± 0.67	9.5 ± 2.8 (93)	± 0.58	30.2 ± 4.9 (178)	± 0.73	2.65 ± 0.43
Bombax ceiba	7.2 ± 0.8 (15)	245 ± 44 (15)	3.9 ± 0.7 (15)	7.4 ± 2.0 (90)	± 0.43	10.0 ± 2.0 (90)	± 0.42	18.1 ± 5.6 (180)	± 0.82	2.49 ± 0.35
Casuarina equisetifolia	8.0 ± 1.9 (15)	248 ± 60 (15)	4.5 ± 1.8 (15)	15.1 ± 5.2 (90)	± 1.10	10.8 ± 2.6 (90)	± 0.54	41.3 ± 11.0 (180)	± 1.62	2.89 ± 0.92
Celtis sinensis	7.4 ± 2.2 (15)	278 ± 64 (15)	5.3 ± 2.4 (15)	14.4 ± 5.3 (165)	± 0.82	14.6 ± 3.9 (165)	± 0.60	25.4 ± 5.2 (211)	± 0.70	1.82 ± 0.51
Cinnamomum camphora	6.6 ± 0.9 (15)	261 ± 43 (15)	4.4 ± 0.9 (15)	12.3 ± 2.7 (104)	± 0.53	16.2 ± 3.9 (104)	± 0.77	25.1 ± 5.2 (189)	± 0.75	2.07 ± 0.28
Delonix regia	6.2 ± 0.8 (15)	248 ± 30 (15)	4.2 ± 0.8 (15)	10.1 ± 4.7 (90)	± 0.98	11.2 ± 2.6 (90)	± 0.55	23.2 ± 6.2 (180)	± 0.92	2.42 ± 0.55
Erythrina variegata	5.4 ± 2.1 (15)	266 ± 47 (15)	4.2 ± 1.8 (15)	6.9 ± 1.9 (110)	± 0.36	9.1 ± 2.9 (110)	± 0.55	14.0 ± 2.7 (195)	± 0.38	2.17 ± 0.45
Falcataria moluccana	6.9 ± 1.1 (15)	255 ± 31 (15)	6.0 ± 1.0 (15)	6.4 ± 2.3 (90)	± 0.47	9.8 ± 2.1 (90)	± 0.44	22.4 ± 4.7 (180)	± 0.69	3.58 ± 0.65
Ficus microcarpa	5.6 ± 1.0 (15)	254 ± 43 (15)	3.9 ± 1.0 (11)	14.6 ± 4.5 (90)	± 0.94	10.3 ± 2.5 (90)	± 0.52	28.6 ± 5.5 (180)	± 0.81	2.00 ± 0.40
Ficus virens	6.6 ± 0.9 (15)	262 ± 43 (15)	4.8 ± 1.1 (15)	11.2 ± 2.5 (104)	± 0.49	11.9 ± 3.1 (104)	± 0.60	23.1 ± 4.3 (191)	± 0.61	2.11 ± 0.32
Hibiscus tiliaceus	5.4 ± 1.5 (15)	243 ± 29 (15)	4.8 ± 0.9 (15)	11.4 ± 3.2 (121)	± 0.58	10.2 ± 2.7 (121)	± 0.49	26.9 ± 4.2 (196)	± 0.60	2.46 ± 0.36

(continued)

(Table 2 continued)

Species	Height (m)	Dbh (mm)	Spread (m)	Radial bending strength (MPa)	95% confidence interval	Radial bending angle (degree)	95% confidence interval	Longitudinal compressive strength (MPa)	95% confidence interval	Ratio of longitudinal compressive strength: radial bending strength
Khaya senegalensis	8.0 ± 1.1 (15)	241 ± 25 (15)	4.0 ± 0.6 (15)	12.7 ± 3.4 (90)	± 0.72	11.5 ± 3.2 (90)	± 0.66	28.0 ± 4.8 (180)	± 0.70	2.25 ± 0.35
Leucaena leucocephala	8.4 ± 1.8 (15)	225 ± 22 (15)	3.8 ± 1.6 (15)	15.8 ± 4.9 (90)	± 1.02	10.6 ± 2.2 (90)	± 0.47	39.6 ± 6.5 (180)	± 0.95	2.57 ± 0.44
Liquidambar formosana	8.6 ± 1.4 (11)	302 ± 77 (11)	4.4 ± 1.2 (11)	16.5 ± 5.3 (82)	± 1.16	11.9 ± 3.0 (82)	± 0.66	29.2 ± 5.8 (146)	± 0.95	1.92 ± 0.28
Lophostemon confertus	7.5 ± 1.9 (15)	246 ± 29 (15)	3.7 ± 1.2 (15)	11.8 ± 4.2 (107)	± 0.82	9.0 ± 2.9 (107)	± 0.56	34.9 ± 6.3 (190)	± 0.90	3.03 ± 0.62
Macaranga tanarius var. *tomentosa*	5.8 ± 1.6 (15)	233 ± 45 (15)	5.9 ± 1.7 (15)	9.5 ± 4.1 (115)	± 0.77	10.5 ± 2.7 (115)	± 0.50	21.1 ± 6.2 (168)	± 0.95	2.36 ± 0.79
Melaleuca cajuputi subsp. *cumingiana*	6.8 ± 1.2 (16)	250 ± 24 (16)	2.9 ± 0.6 (16)	12.9 ± 3.3 (177)	± 0.49	11.6 ± 2.2 (177)	± 0.34	31.7 ± 5.1 (301)	± 0.57	2.41 ± 0.42
Melia azedarach	6.3 ± 0.9 (16)	237 ± 47 (16)	4.3 ± 1.0 (16)	8.2 ± 3.2 (217)	± 0.43	13.7 ± 3.5 (217)	± 0.47	27.2 ± 5.6 (294)	± 0.67	3.47 ± 0.63
Senna siamea	6.1 ± 1.2 (15)	247 ± 31 (15)	3.1 ± 0.9 (15)	12.3 ± 3.2 (90)	± 0.68	9.9 ± 2.6 (90)	± 0.55	34.1 ± 6.0 (180)	± 0.88	2.77 ± 0.51

Valued are reported as means ± standard deviations; dbh = diameter at breast height; values within parentheses are total number of samples in the measurements healthy with non-defective trees can help tree risk assessors determine the strength of wood sample. However, wood strength values of trees widely planted in the tropical or subtropical areas are scarcely available in references such as the United States Department of Agriculture (USDA) wood handbook (Kretschmann 2010). In this study, 15 individual trees from 25 common landscape trees species were sampled and tested using Fractometer II. Our results suggested that, with this sample size, the fractometer could provide statistically valid values of radial bending and longitudinal compressive strengths. This represents a step forward in validating the usefulness of this device in decay assessment.

The range of mean radial bending strength for different species was generally consistent with the results of a similar study in Singapore (Ganesan & Abdul Hamid 2010). Mean bending strengths of the common species in both studies, namely, *A. auriculiformis*, *Delonix regia*, *F. moluccana* (syn. *Paraserianthes falcataria*) and *Khaya senegalensis*, were similar. For example, mean radial bending strength values of *D. regia* were 10.1 ± 4.7 and 12.5 ± 5.8 MPa in the current and Singapore studies respectively, while they were 12.9 ± 4.3 and 15.0 ± 3.9 MPa for *A. auriculiformis*.

Direct reference to mechanical properties of wood in Kretschmann (2010) was not possible because there was no overlap between temperate

Table 3 One-way ANOVA for radial bending strength, bending angle, longitudinal compression strength and compressive strength:radial bending strength ratio

Wood strength parameter	Source of variation	Sum of squares	df	Mean square	F value	Sigmoid
Radial bending strength	Between groups	3361.61	24	140.067	24.832	< 0.001
	Within groups	1962.92	348	5.641		
	Total	5324.53	372			
Radial bending angle	Between groups	1.63	24	0.068	15.261	< 0.001
	Within groups	1.55	348	0.004		
	Total	3.18	372			
Longitudinal compressive strength	Between groups	22011.00	24	917.125	72.715	< 0.001
	Within groups	4389.21	348	12.613		
	Total	26400.21	372			
Compressive strength:radial bending strength ratio	Between groups	2.19	24	0.091	12.323	< 0.001
	Within groups	2.57	348	0.007		
	Total	4.76	372			

df = degree of freedom, data of radial bending angle was under natural log transformation

Table 4 Levene's test for equality of variances

Wood strength parameter	Levene's statistic	df1	df2	Sigmoid
Radial bending strength	5.685	24	348	< 0.001
Radial bending angle	1.381	24	348	0.112
Longitudinal compressive strength (compressive strength)	4.453	24	348	< 0.001
Compressive strength:radial bending strength ratio	2.340	24	348	< 0.001

df1 = numerator degrees of freedom is one of the two parameters that specifies exactly which F-distribution applies, df2 = denominator degrees of freedom is the second parameter for the F-distribution

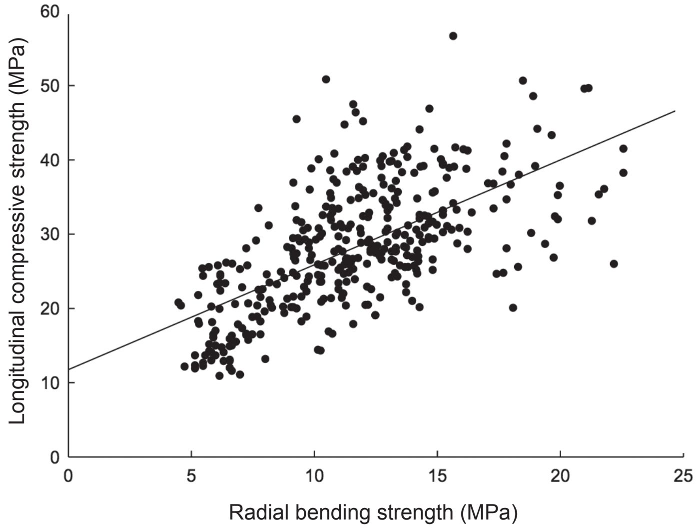

Figure 2 Relationship between longitudinal compressive strength and radial bending strength; Pearson correlation, r = 0.635, $p < 0.05$, n = 373

and tropical species. However, comparison of data from similar species can be made. The USDA wood handbook has been regarded as an important reference for wood strength data and comparison with the closest relative within the book is worthwhile. For example, compression parallel to grain of *Ceiba pentandra* was 16.4 MPa (with 12% moisture) in Kretschmann (2010), which is comparable with 18.1 MPa for compressive strength of *B. ceiba* in our study. In contrast, modulus of rupture of the former was 29.6 MPa but the latter was 7.4 MPa.

There were concerns that results from Fractometer I may not be consistent with those from accepted methods for measuring wood properties (DIN 52-186) (Gruber & Hagemann 2000). The Fractometer II, however, includes measurement of compressive strength which may provide data on wood resistance against buckling. A recent study showed that compressive strength measurements obtained from Fractometer II were highly correlated with degree of white rot and brown rot decay whereby, the device could detect decrease in compressive strength at relatively early stage of decay (Matsumoto et al. 2010).

We found positive and significant correlation between radial bending and longitudinal compressive strengths. This may suggest strong interrelationship in physical arrangement contributing to radial and longitudinal mechanical strengths. However, the remaining unexplainable proportion of the correlation and the spread of points at higher values in the scattered plot showed that other independent factors, such as genetic traits, were also important in explaining the additional strength of strong tree species.

In this study, the ratio of longitudinal compressive strength to radial bending strength was 1.82–3.58:1. This was in contrast to the ratio of 2:1 reported by Bethge et al. (1996). The ratio obtained in this study implied that combined strengths in longitudinal and radial directions might contribute to architectural design of trees. Negative and significant correlation between dbh and the ratio of compressive strength to radial bending strength suggested slender trees were also longitudinally stronger. For example, high ratio in *A. auriculiformis, F. moluccana* and *M. azedarach* may be associated with stronger resistance to vertical self-loading and capability to develop more slender yet stiffer trunk (Anten & Schieving 2010, Read et al. 2011). Compressive strength is positively correlated with lignin content and is positively related to stiffness and resistance to cell deformation (Gindl & Teischinger 2002). Relationship between compressive strength and lignin may be very weak in species with small ratios (*C. sinensis*

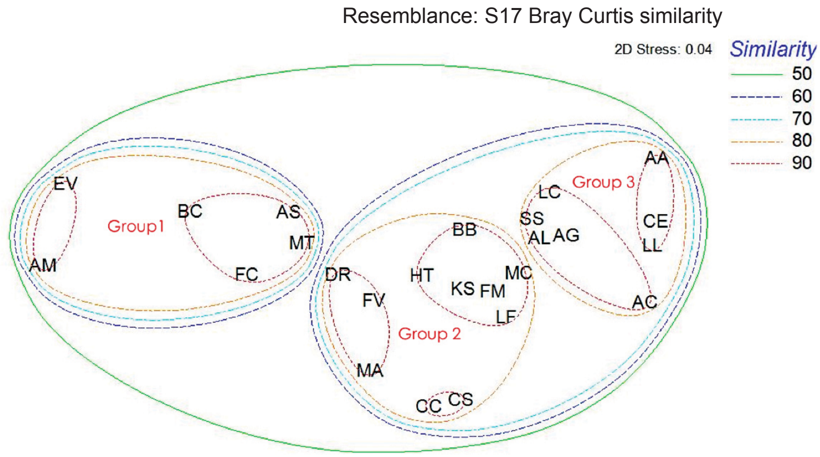

Figure 3 Relationship of wood strength properties between tree species by cluster analysis and multidimensional scaling; AA = *Acacia auriculiformis*, AC = *Acacia confusa*, AG = *Acacia mangium*, AL = *Albizia lebbeck*, AM = *Aleurites moluccana*, AS = *Alstonia scholaris*, BB = *Bauhinia* × *blakeana*, BC = *Bombax ceiba*, CE = *Casuarina equisetifolia*, CS = *Celtis sinensis*, CC = *Cinnamomum camphora*, DR = *Delonix regia*, EV = *Erythrina variegata*, FC = *Falcataria moluccana*, FM = *Ficus microcarpa*, FV = *Ficus virens*, HT = *Hibiscus tiliaceus*, KS = *Khaya senegalensis*, LL = *Leucaena leucocephala*, LF = *Liquidambar formosana*, LC = *Lophostemon confertus*, MT = *Macaranga tanarius* var. *tomentosa*, MC = *Melaleuca cajuputi* subsp. *cumingiana*, MA = *Melia azedarach* and SS= *Senna siamea*

and *L. formosana*). Our result indicated that different ratios of longitudinal compressive and radial bending strengths represented different dimensions of wood investment and provided some advantages to overall tree fitness. In fact, the nature of vertical and radial dimensions of wood development were inseparable, i.e. they were not separate traits.

Hierarchical clustering and multidimensional scaling analysis placed the test species into three groups based on their wood properties (Figure 3). Group 1, characterised by poor strength but high stiffness, was consistent with our general observation of brittle wood. Similar low bending strength was reported for *F. moluccana* (syn. *Paraserianthes falcataria*) which was known to snap easily (Ganesan & Abdul Hamid 2010). Wood of *F. moluccana* is inherently weak and not recommended for planting as roadside tree (Corner 1952). Two group 1 species, *A. moluccana* and *E. variegata*, were further separated, suggesting that they developed particularly weak wood. *Aleurites moluccana* is a fast-growing species with softwood and relatively high susceptibility to decay (Krisnawati et al. 2011). Since the species has been widely planted on roadsides in the tropics and subtropics (e.g. Indo-Malaysia regions, South China, Pacific Islands) (Krisnawati et al. 2011), suspected trees should be carefully monitored and managed to reduce potential risks of snapping. *Erythrina variegata*, on the other hand, has long been recognised as having weak wood. A case of fatal collapse of this species in 2008 in Hong Kong has provoked widespread concern for the need to improve tree risk assessment and standards of tree assessors.

Group 2 was characterised by moderate bending and compressive strength. Within this group, *C. camphora* and *C. sinensis* clustered into a subgroup, characterised by having relatively ductile wood (due to high bending angle). They are both native trees, but the former is an evergreen whereas the latter, deciduous. Although they can attain large final dimensions, most of them are yet to approach potential maximum size in Hong Kong. Their low compressive to bending strength ratios indicated their tendency to develop horizontal dimensions and ductile wood, which suggested resistance to trunk breakage. Another group, including *D. regia*, *Ficus virens* and *M. azedarach* demonstrated relatively weak bending strength. Group 3 was characterised by moderate stiffness and high compressive strength and represented by many strong tree species. Within the group, *C. equisetifolia* possessed exclusively hard wood. The wood of this species is extremely heavy, hard and difficult to saw, and the tree species is often planted as windbreak.

Standard wood strength information collected from structurally sound trees allowed comparison with results from trees with either obvious or suspected decay. Tree risk assessors will find this information useful for judging potential risks of trunk breakage. However, one should bear in mind that there is much variation in wood properties within stems of trees according to genera, species and individuals (Niklas 1997). Tree assessors may use the confidence interval (95%) to account for variability of the mean. For example, radial bending strength of *A. auriculiformis* was 12.9 ± 4.3 MPa and confidence interval (95%) was ± 0.90 MPa. Therefore, the true population mean of the species fell within the range of 11.95 to 13.75 MPa.

Nevertheless, wood properties are only one factor contributing to mechanical stability of trees (Read & Stokes 2006, Read et al. 2011). Resistance to failure of a tree is much more complex than whether a tree produces strong or weak wood (Read et al. 2011). To understand more about mechanical stability of tree trunks, the types of load that trees may experience should be taken into consideration (James et al. 2006). Diameter is an important factor since bending and torsional stresses are inversely proportional to the cube of diameter. If trunk diameter of one tree is twice that of another, stress will only be one-eighth of the stress value (Larjavaara & Muller-Landau 2010). In addition, tree architecture (shape and structure) greatly influences its mechanical stability under dynamic loading (James et al. 2006).

Assessment of tree stability should consider the following: (1) general wood strength properties of tree species, which require a broad database with threshold values of sound wood in healthy trees; (2) cross-sectional strength in relation to internal decay, which can be determined by fractometer or other relevant methods; (3) presence of structural defects such as trunk cracks, crotch splits, lean with root movement, unbalanced crown, over-extended branches, weak branch attachment; (4) existing and potential loads, including crown density, stress concentration (e.g. cankers, cracks and bends), wind strength and direction, precipitation and location of load or any extra loads related to tree condition; (5) site factors, including patterns of previous tree failures, wind patterns, soil characteristics and drainage patterns, land disturbances, restricted root growth conditions and land-use history and recent change and (6) response growth of the tree, including crown vigour, bark integrity, wound wood development around cracks and openings, wood growth near structural defect, growth adaptation to compensate internal decay, demarcations between health and damaged tissue, root flare compensation and trunk lean correction (Dunster et al. 2013).

CONCLUSIONS

When assessing the likelihood of tree failure, the presence and severity of decay must be evaluated. This study provided reference values of radial bending strength, radial bending angle and longitudinal compressive strength of 25 tropical tree species. The data will help arborists to evaluate wood strength in comparison with standard values from undecayed wood of the same species. Wood strength values give general information on wood brittleness.

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