OPTIMUM SLOPE OF LOAD–DEFLECTION CURVE FOR BENDING YOUNG'S MODULUS DERIVATION

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MOHD YUSOUF AL, SUFFIAN M, HASHIM WS & RAFEADAH R. 2015. Optimum slope of load–deflection curve for bending Young's modulus derivation. This paper presents results of a study to assess the optimum slope of load–deflection curve to be used in bending Young's modulus calculation. Bending tests were carried out in accordance with Japanese Agricultural Standard for Plywood to generate data and plots for load versus deflection. Thus, an empirical assessment was designed to determine unstipulated points that would be able to meet the standard requirement. Raw data of the plots were processed to identify the most linear part using standard deviation analysis of compared average slopes. Results of 10 test specimens were presented and discussed. The best-fitted linear line analysis was used to propose delta load and delta deflection preference for practice.

Keywords: Plywood bending test, proportional limit, Japanese Agricultural Standard for Plywood

INTRODUCTION

Plywood panels are manufactured by gluing several plies of wood veneers, normally in odd numbers, with grain direction of each ply perpendicular to the next. As one of the main wood-based panels used as structural material, plywood has traditionally played an important role especially in light-frame construction (Francisco et al. 2008). Qualities of plywood sheets are defined by, but not limited to, its physical and mechanical properties. When there are no requirements with respect to the appearance of the material, plywood with lower-grade veneers may also be suitable for use as temporary formwork without compromising the making of load-bearing members.

Classification for product service performance is assessed according to standards, e.g. the European Standards (EN), Japanese Agricultural Standards (JAS), German Institute for Standardization (DIN) and American Society for Testing Materials (ASTM). Mechanical properties are usually referred to strength tests such as bending, bonding quality, shear and fastener holding capacity. Bending test usually measures bending strength, also referred as modulus of rupture (MOR), and bending Young's modulus result, also known as modulus of elasticity (MOE). The former is calculated when dimensions, bending span and maximum load of test specimen which are applied at bending failure are known. On the other hand, the latter is calculated when the dimensions, bending span and slope of the load versus deflection plot within the elastic zone are known.

For three-point bending, the calculated MOE value is considered as an apparent value, and not the real MOE because the testing method also includes shear during bending (Hrázský & Král 2007). Nevertheless, a proportion of load deflection within the elasticity region must be first determined in order to be applied adequately in the modulus equation (Alam et al. 2012). In EN 310 (1993), the proportional range of load–deflection curve is suggested at 10 and 40% of maximum load. However, there is no proportional range suggested in ASTM (1999) and JAS (2008), thus, the delta load and deflection need to be determined for each test conducted. The objective of this work was to assess, determine and recommend appropriate delta load and delta deflection for Class 1 bending strength test practices according to the JAS for Plywood.

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MATERIALS AND METHODS

Three panels of plywood, labelled as P1, P2 and P3, were used to provide 10 test specimens for this study. Each of the Class 1 structural grade panels composed of five layers of tropical hardwood veneers with overall nominal thickness of 12 mm. They were each 915 mm wide by 1830 mm long. Each panel was cut into three equal segments by length, labelled as S1, S2 and S3, as shown in Figure 1. For P1 and P2, two test specimens were prepared within each of segment S1 and S3 (end segments). For P3, two specimens were prepared within segment S2 (centre segment) only. Bending test specimens were prepared in 50 mm width and 338 mm length size according to JAS (2008). At each segment, one length was parallel to the main grain direction of the surface veneer and the other was perpendicular. The complete test specimens labelling are given in Table 1.

Before testing, test specimens were conditioned at 20 ± 2 °C and 65 ± 5% relative humidity until stable, where the differences in mass at 24-hour intervals were checked so as not to exceed 0.1%. The three-point bending test was carried out using universal testing machine of 50 kN capacity with the setup layout as in Figure 2. Average loading speed was set not to exceed 14.7 MPa min^{-1} with a 36-mm diameter loading block applied to the test specimen in such arrangement that the face veneer was on the compression side. Real-time data were recorded and plotted as load against deflection graph using Trapezium X software, as shown in Figure 3. The raw data were extracted from the operating software and transferred into Microsoft Office Excel for assessment.

The JAS for Plywood has given bending Young's modulus equation as the following:

$$\text{Bending Young's modulus} = \frac{\Delta P.l^3}{4.b.h^3.\Delta y} \quad (1)$$

where l = span (mm), b and h = width and thickness of test specimen (mm) respectively, ΔP = difference between upper limit and lower limit of load within the proportional range (N), and Δy = deflection difference in the centre of test span corresponding to ΔP (mm).

To determine the upper and lower limits in equation 1, deflection values were extracted from the raw data that corresponded to the designated load percentages which were set from 0 to 100% of maximum load at 10% interval. At this stage, delta load, i.e. ΔP was defined as $P_i - P_{i-10}$ where i = percentage of maximum load. The same definition was applied to delta deflection or Δy. Taking specimen C as example, calculation of ΔP at 50% was $P_{50\%} - P_{40\%}$, where the values were 595 and 476 N respectively making ΔP equivalent to

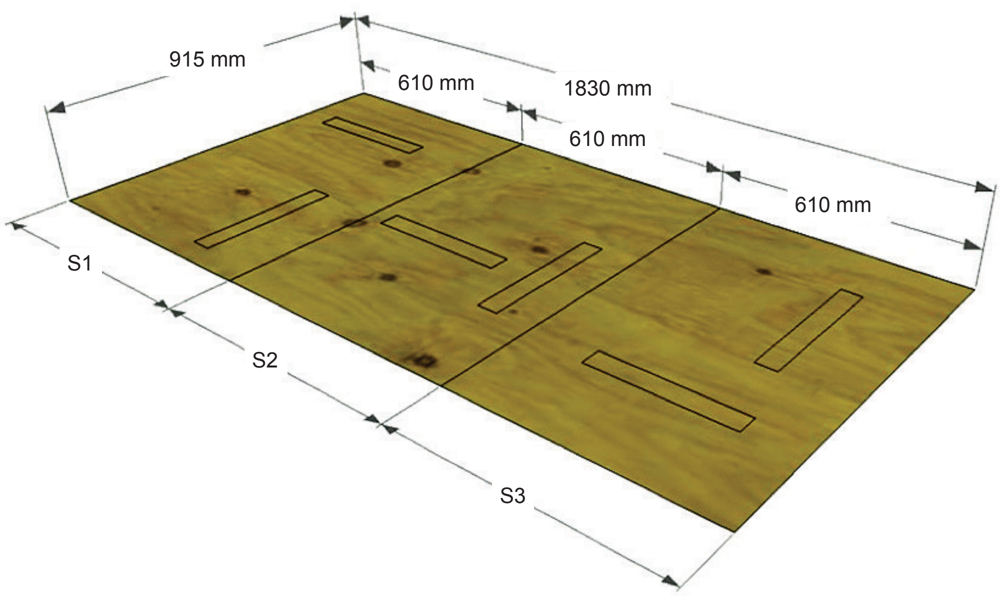

Figure 1 Test specimens of 50 mm × 338 mm were prepared from segments S1, S2 and S3 according to panel cutting

Table 1 Preparation of 10 test specimens from three panels of plywood and its alphabetical labelling at specified segment

Item and description	Label								
Plywood panel (915 mm × 1830 mm)		P1			P2			P3	
Equal segment (915 mm × 610 mm)	S1	S2	S3	S1	S2	S3	S1	S2	S3
Parallel test specimen (50 mm × 338 mm)	A	–	B	C	–	D	–	E	–
Perpendicular test specimen (50 mm × 338 mm)	F	–	G	H	–	I	–	J	–

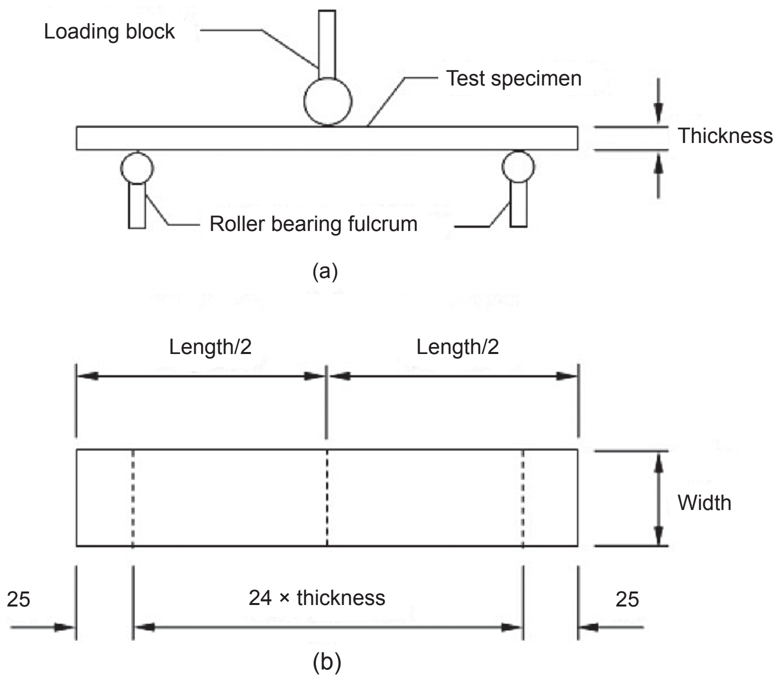

Figure 2 (a) Front view of specimen arrangement during bending strength Class 1 test and (b) top view of specimen with dimensions in mm

119 N, and Δy was $y_{50\%} - y_{40\%}$ or 6.08 – 5.39 mm = 0.69 mm. Therefore, delta load divided by delta deflection was calculated as:

$$\frac{\Delta P}{\Delta y} = \frac{(595 - 476)}{(6.08 - 5.39)} = \frac{119}{0.69} = 172.46 \text{ N mm}^{-1} \quad (2)$$

Equation 2 also gave the slope of the load–deflection curve. Calculations for slope values for each percentage range and test specimen are shown in Table 2.

Calculated slopes were plotted against the percentage of maximum load to visualise and help select the range options for further assessment. Based on the results, three potential options were considered for optimal proportional range assessment, namely, 20–60, 20–50 and 10–40%, where average slope was calculated at each option and plotted as bar chart. The highest average slope with lowest standard deviation (SD) value represented the optimum proportional range and used as constant m to form y = mx + c linear equation for each specimen. Using the best-fitted linear model, a simplified diagram was produced to present the recommended proportional range.

Table 2 Extracted raw data of load and deflection for calculation of slope ($\Delta P/\Delta y$) at 10% load interval

Test specimen with P_{max} value in parenthesis		Percentage, i (%)										
		0	10	20	30	40	50	60	70	80	90	100
A (1051)	P_i	0	105	210	315	420	526	631	736	841	946	1051
	y_i	0.60	1.28	1.90	2.53	3.17	3.83	4.53	5.36	6.55	8.11	10.27
	$\Delta P/\Delta y$	n.a.	154.56	169.52	166.83	164.22	159.24	150.14	126.63	88.32	67.37	48.66
B (1100)	P_i	0	110	220	330	440	550	660	770	880	990	1100
	y_i	1.80	2.54	3.15	3.80	4.48	5.19	5.97	6.87	7.97	9.39	12.28
	$\Delta P/\Delta y$	n.a.	148.65	180.33	169.23	161.76	154.93	141.03	122.22	100.00	77.46	38.06
C (1190)	P_i	0	119	238	357	476	595	714	833	952	1071	1190
	y_i	2.65	3.40	4.06	4.72	5.39	6.08	6.81	7.68	8.81	10.19	12.07
	$\Delta P/\Delta y$	n.a.	158.67	180.30	180.30	177.61	172.46	163.01	136.78	105.31	86.23	63.30
D (1169)	P_i	0	117	234	351	468	585	701	818	935	1052	1169
	y_i	3.48	4.18	4.79	5.40	6.03	6.65	7.29	7.95	8.68	9.63	11.32
	$\Delta P/\Delta y$	n.a.	167.00	191.64	191.64	185.56	188.55	182.66	177.12	160.14	123.05	69.17
E (1096)	P_i	0	110	219	329	438	548	658	767	877	986	1096
	y_i	4.51	5.14	5.68	6.23	6.78	7.33	7.89	8.46	9.07	9.76	10.74
	$\Delta P/\Delta y$	n.a.	173.97	202.96	199.27	199.27	199.27	195.71	192.28	179.67	158.84	111.84
F (764)	P_i	0	76	153	229	306	382	458	535	611	688	764
	y_i	5.67	6.21	6.65	7.11	7.59	8.06	8.56	9.07	9.62	10.29	11.36
	$\Delta P/\Delta y$	n.a.	141.48	173.64	166.09	159.17	162.55	152.80	149.80	138.91	114.03	71.40
G (900)	P_i	0	90	180	270	360	450	540	630	720	810	900
	y_i	6.38	7.12	7.72	8.33	8.96	9.59	10.26	10.98	11.84	12.99	14.81
	$\Delta P/\Delta y$	n.a.	121.62	150.00	147.54	142.86	142.86	134.33	125.00	104.65	78.26	49.45
H (921)	P_i	0	92	184	276	368	461	553	645	737	829	921
	y_i	7.45	8.19	8.76	9.33	9.92	10.53	11.16	11.86	12.71	14.02	16.75
	$\Delta P/\Delta y$	n.a.	124.46	161.58	161.58	156.10	150.98	146.19	131.57	108.35	70.31	33.74
I (1004)	P_i	0	100	201	301	402	502	602	703	803	904	1004
	y_i	8.73	9.52	10.12	10.78	11.46	12.16	12.92	13.80	14.91	16.76	19.34
	$\Delta P/\Delta y$	n.a.	127.09	167.33	152.12	147.65	143.43	132.11	114.09	90.45	54.27	38.91
J (984)	P_i	0	98	197	295	394	492	590	689	787	886	984
	y_i	9.70	10.32	10.85	11.41	11.98	12.56	13.16	13.81	14.60	15.68	17.02
	$\Delta P/\Delta y$	n.a.	158.71	185.66	175.71	172.63	169.66	164.00	151.38	124.56	91.11	73.43

Load in Newton (N), deflection in millimetres (mm) and n.a. = not applicable

RESULTS AND DISCUSSION

Plots showed similar load–deflection patterns for all specimens (Figure 3). Parallel test specimens resulted in higher maximum loads than perpendicular specimens. It can be observed that test specimens A, B, C, D, E and I had maximum loads exceeding 1000 N while F, G, H and J, less than 1000 N. In specimens A, B, C, D and E, of five plies, three (first, third and fifth veneers) were in parallel grain to the bending span which contributed to better strength. On the other hand, test specimens F, G, H, I and J had only two plies (second and fourth veneers) in parallel direction to the bending span. Early research had discussed the effect of veneer arrangement in plywood to MOR and MOE results (Freas 1964). Properties of plywood are dependent

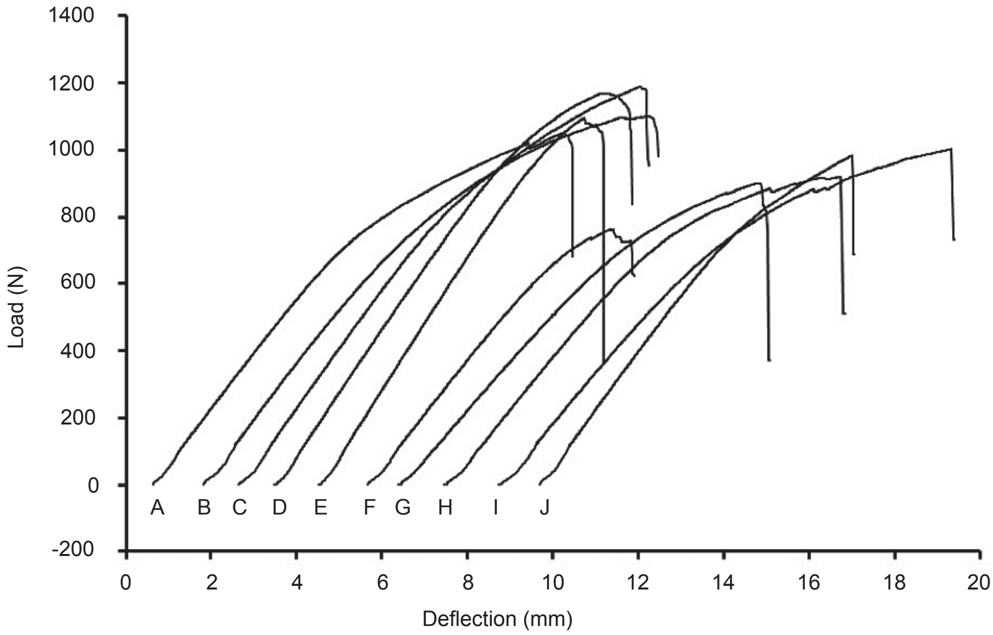

Figure 3 Plot of load against deflection for test specimens

on properties in the span direction of each ply besides the thickness and number of plies of the plywood.

Options for proportional ranges were selected based on Figure 4. Slopes for all test specimens below 20% of maximum load were still developing and increasing to achieve constant values. Plots of slopes for test specimens D, E, I and J were about the same from 20 to 60% of maximum load. For test specimens D and E, the slopes were almost constant, i.e. 185 and 200 N mm^{-1} respectively. Slopes of the rest of the test specimens were forming almost straight lines from 20 to 50% of maximum load. Slopes declined after 50 or 60% towards ultimate failure, which meant that specimens were moving out of elastic range and entering plastic range of the bending. Either of these ranges (20 to 50% or 20 to 60%) can be considered the ideal proportional range. The ranges were slightly deviated from the 10–40% proportional range recommended in EN 310. Thus, the three ranges, namely, 20–60, 20–50 and 10–40% were further analysed by comparing average slopes and SD values for each test specimen.

Average slopes were about the same for load ranges 20–60 and 20–50% (Figure 5). The average slopes for load range 10–40% were generally the lowest compared with the other two ranges. Therefore, high SD values were expected when lower limit was considered at 10%. For test specimen C, average slopes and SD values (in parentheses) were 175 (3.7), 177 (1.9) and 174 N mm^{-1} (5.2) at ranges 20–60, 20–50 and 10–40% respectively. For test specimen D, average slopes and SD were 188 (2.0), 189 (1.5) and 184 (5.8) N mm^{-1} respectively. For test specimen E, average slopes and SD were 199 (1.3), 200 (0.9) and 194 (6.7) N mm^{-1} respectively. The highest average slope with lowest SD value was obtained at 20–50%.

Though limited numbers of test specimens were presented in this paper, the main aim was to show the optimum proportional range for determination of MOE. Since the optimum proportional range occurred at 20–50% of maximum load, the slope was used as the constant to form linear equation for each test specimen. The best-fitted linear lines were developed and found graphically adequate to demonstrate the proportional range of the load–deflection curve (Figure 6). The range can also be written as 0.2 of maximum load for the lower limit and 0.5 of maximum load for the upper limit. This range

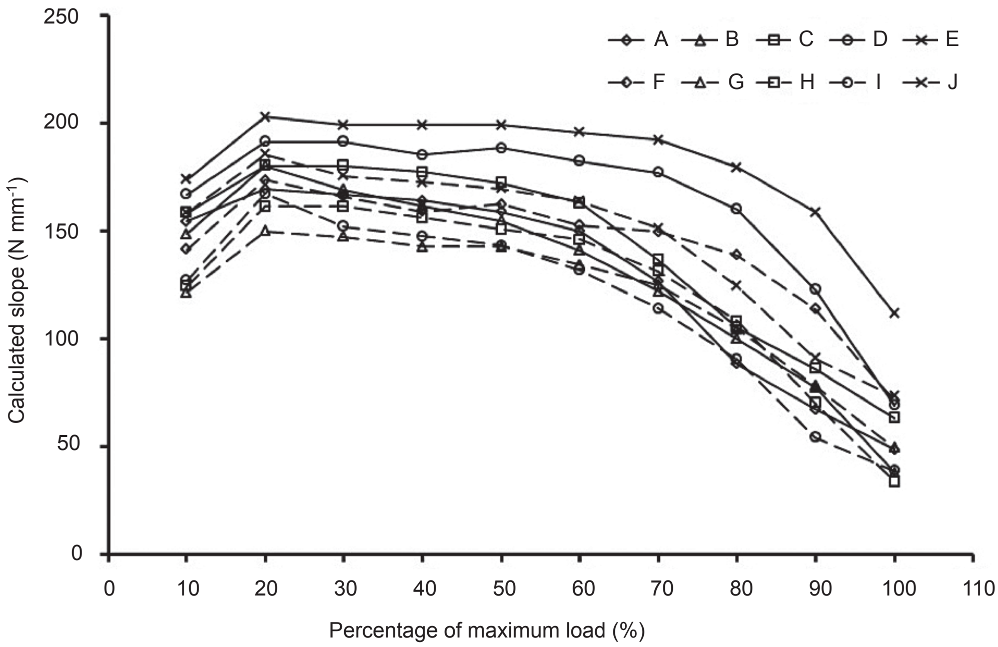

Figure 4 Calculated slope against percentage of maximum load for test specimens A–J

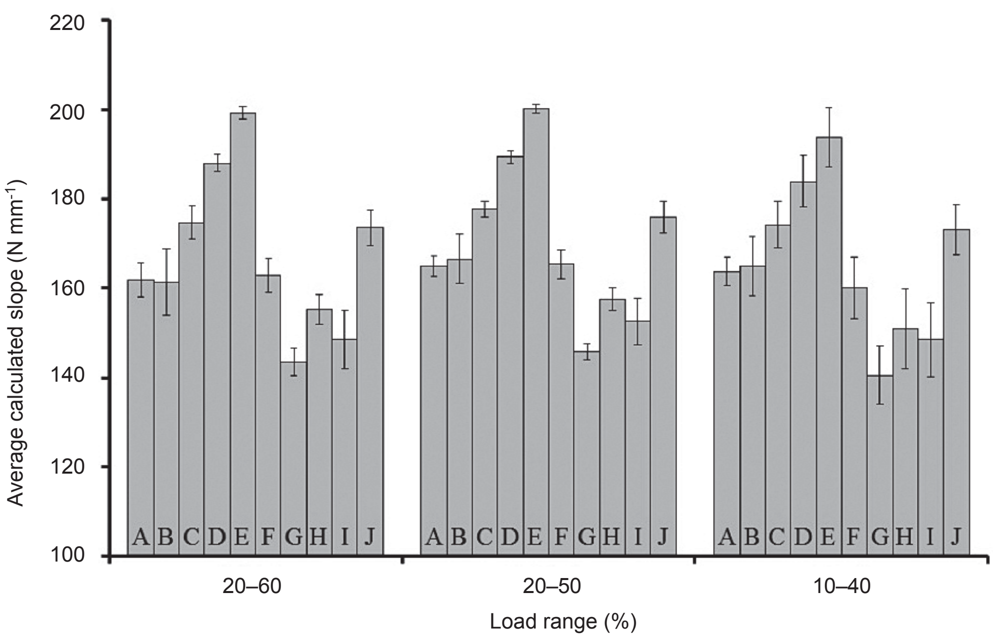

Figure 5 Average calculated slope against load range in percentage of maximum load, with standard deviation indicators for each test specimen

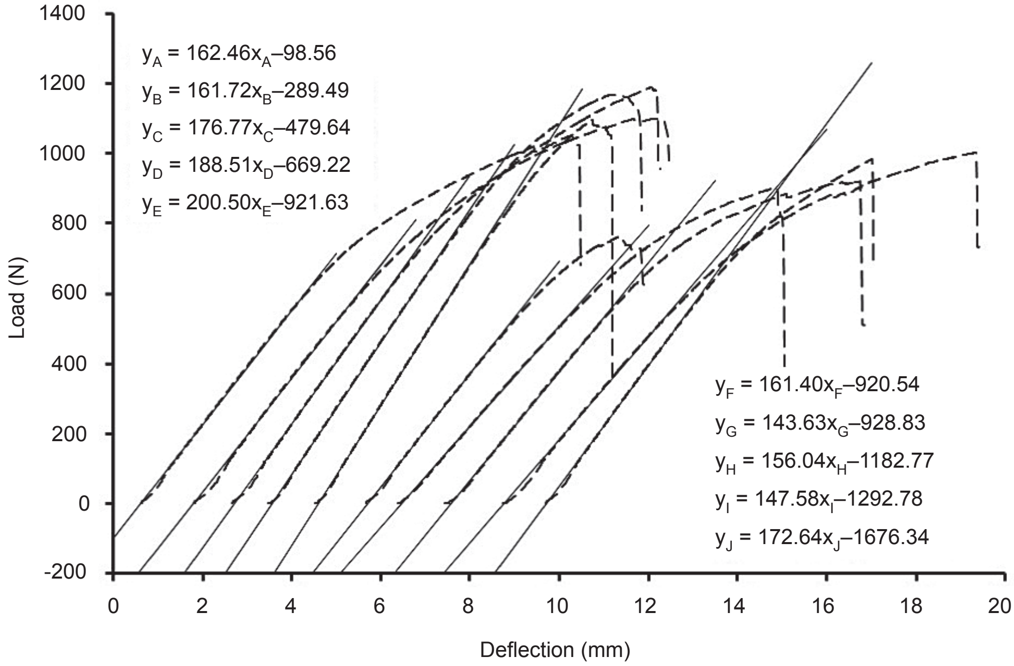

Figure 6 Constructed best-fitted linear lines with equations for test specimens A, B, C, D, E, F, G, H, I and J from left to right accordingly

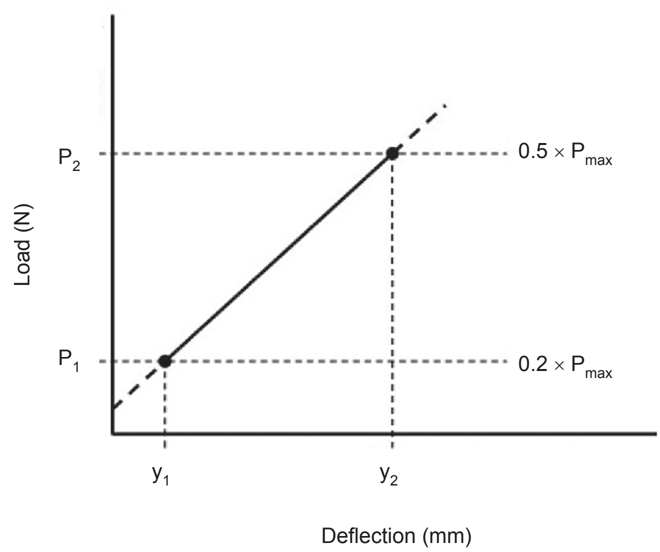

Figure 7 Recommended load and deflection range for bending Young's modulus calculation according to Japanese Agricultural Standards for Plywood

can be recommended for use in bending Young's modulus calculation when Class 1 bending test is carried out according to JAS for Plywood, as simplified in Figure 7.

CONCLUSION

The optimum slope for Young's modulus when JAS for Plywood was referred for bending strength Class 1 test could be obtained between 20 and 50% of the maximum load.

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