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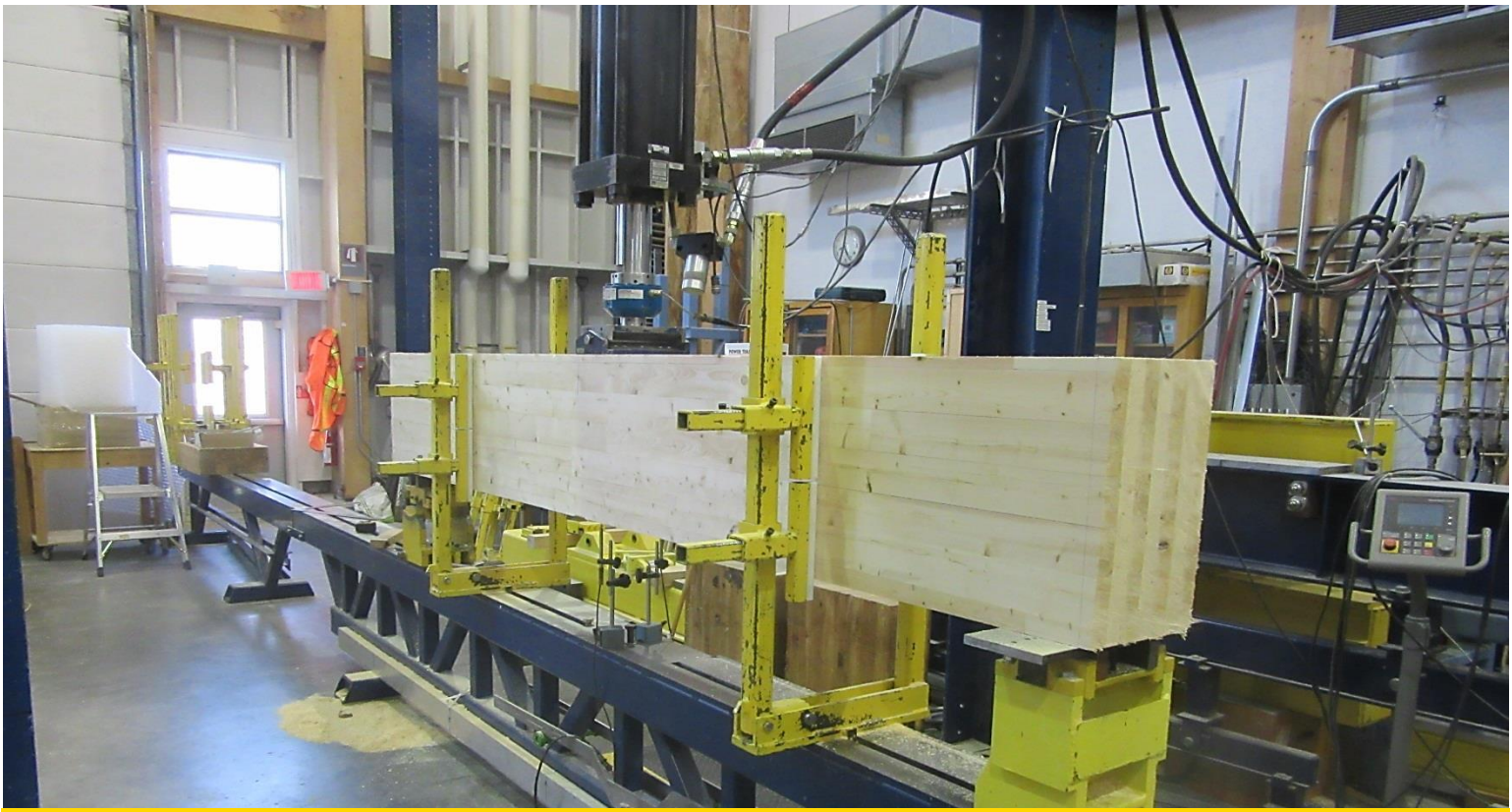

Shear Modulus of CLT: In-plane Loading (REVISED – Version 3)

Date: June 30, 2015

By: Jose Daniel Candelario, Jr. Eng., M.Sc. Researcher,
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PROJECT NO: 301010401
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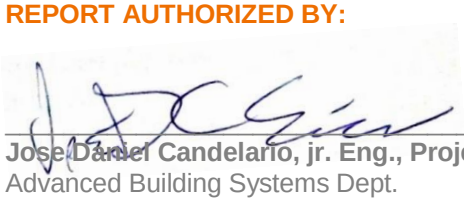

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OBJECTIVES

A testing program was carried out by the Advanced Building Systems (ABS) Department of FPInnovations in response to a request made by Mrs. Julie Frappier of Nordic Engineered Wood Products for the evaluation of the effective shear modulus of eight (8) different Cross-laminated Timber (CLT) configurations or series. The test matrix consisted of a total seventy (70) specimens and each specimen was submitted to four (4) bending tests, resulting in a total two hundred and eighty (280) tests. All specimens were manufactured by Nordic Engineered Wood Products and delivered to FPInnovations' testing facilities in Québec City.

METHOD IDENTIFICATION

The testing procedure for the determination of the shear modulus was performed in accordance with ASTM D198-14 Standard Test Methods of Static Tests of Lumber in Structural Sizes, sections 45 through 52. For composite elements such as CLT, this procedure gives a measure of the effective shear modulus.

Specific Gravity (SG) and Moisture Content (MC) measurements were performed in accordance with ASTM D2395-07 and ASTM D 4442-07, respectively.

DESCRIPTION OF SAMPLES AND SAMPLING METHOD

1.1 Shear Modulus

1.1.1 Test Setup and Parameters

This test procedure covers the determination of the effective shear modulus of rigidity (G) or effective shear modulus of Cross-laminated Timber (CLT) beams.

Eight (8) different series were tested resulting in a total seventy (70) specimens. The descriptions of the series are provided in Table 1 and a sketch of the cross sectional areas for each is presented in Figure 1. Each specimen was tested in center-point loading at four (4) different spans (**L**) measured from the center of one reaction support to the other as shown in the schematic of Figure 2. The spans were selected in function of the depth (**h**) so as to give approximately equal increments of $(\mathbf{h/L})^2$ between them, ranging from approximately 0.035 to 0.0025 as recommended in ASTM D 198, sub-section 50.2.

For each of the four (4) loading spans the specimens were machined in order to ensure that an overhang no greater than 25mm (1 in.) was observed from the edge of the reaction support plates. The two reaction support plates as well as the load-transfer block were 152 mm (6 in.) in length. Pin and roller support reactions were considered in order to prevent translation while ensuring that no restraints were present for the longitudinal deformation and end rotations of the specimens. Figures 3 and 4 present specimens from Series H and B respectively ready for testing at the four (4) different spans.

The load application system had a maximum loading capacity of 250 kN (governed by the load cell). Two (2) linear differential variable transformers (LVDT) were placed to measure deflections at the midspan. Since each specimen was tested at four (4) different spans, the extension limit for the midspan deflection was different for each. Furthermore, the loading rate was selected as a function of the extension limit so as to ensure that the total testing time was no less than four (4) minutes as required by ASTM D 198-14. The extension limits and load rate for each span tested are presented in Tables 2 and 3.

Table 1 - Test matrix for CLT Shear modulus

Series	Specimens	Span, L (mm)				Width, b (mm)	Depth, h (mm)	Outer Layer Orientation
		1	2	3	4			
A	10	9448	3886	2934	2461	105	475	H
B	10	2288	1292	988	836	105	152	V
C	10	9448	3886	2934	2461	175	475	H
D	10	2288	1292	988	836	175	152	V
E	5	9448	3886	2934	2461	78	475	H
F	5	9448	3886	2934	2461	131	475	H
G	10	9448	3886	2934	2461	244	475	H
H	10	9448	3886	2934	2461	244	475	H

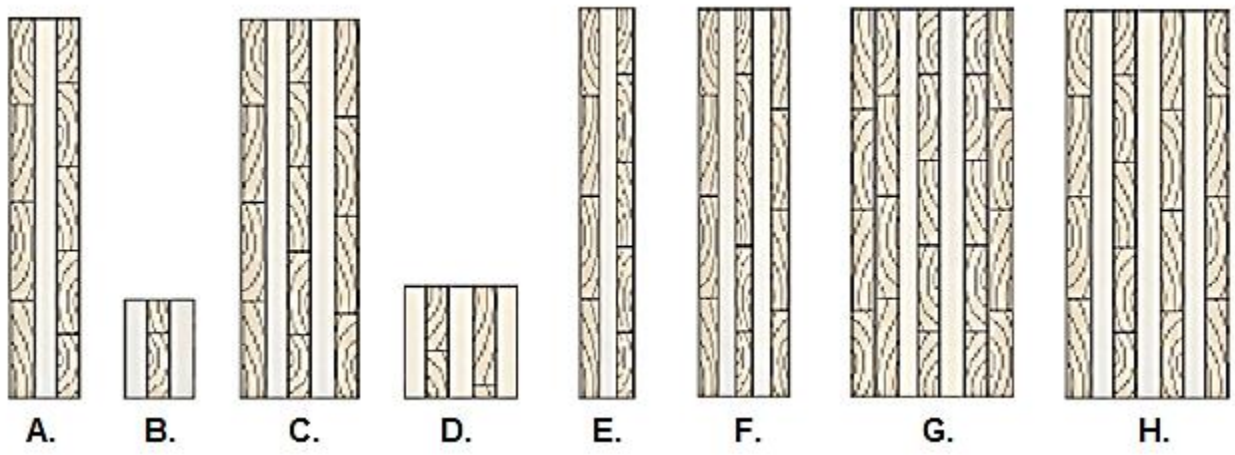

Figure 1. Section view sketch of the eight (8) series tested

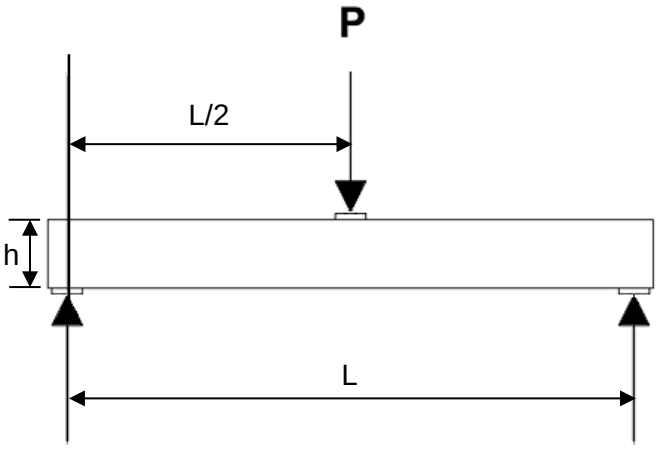

Figure 2. Schematic of Center-point loading setup

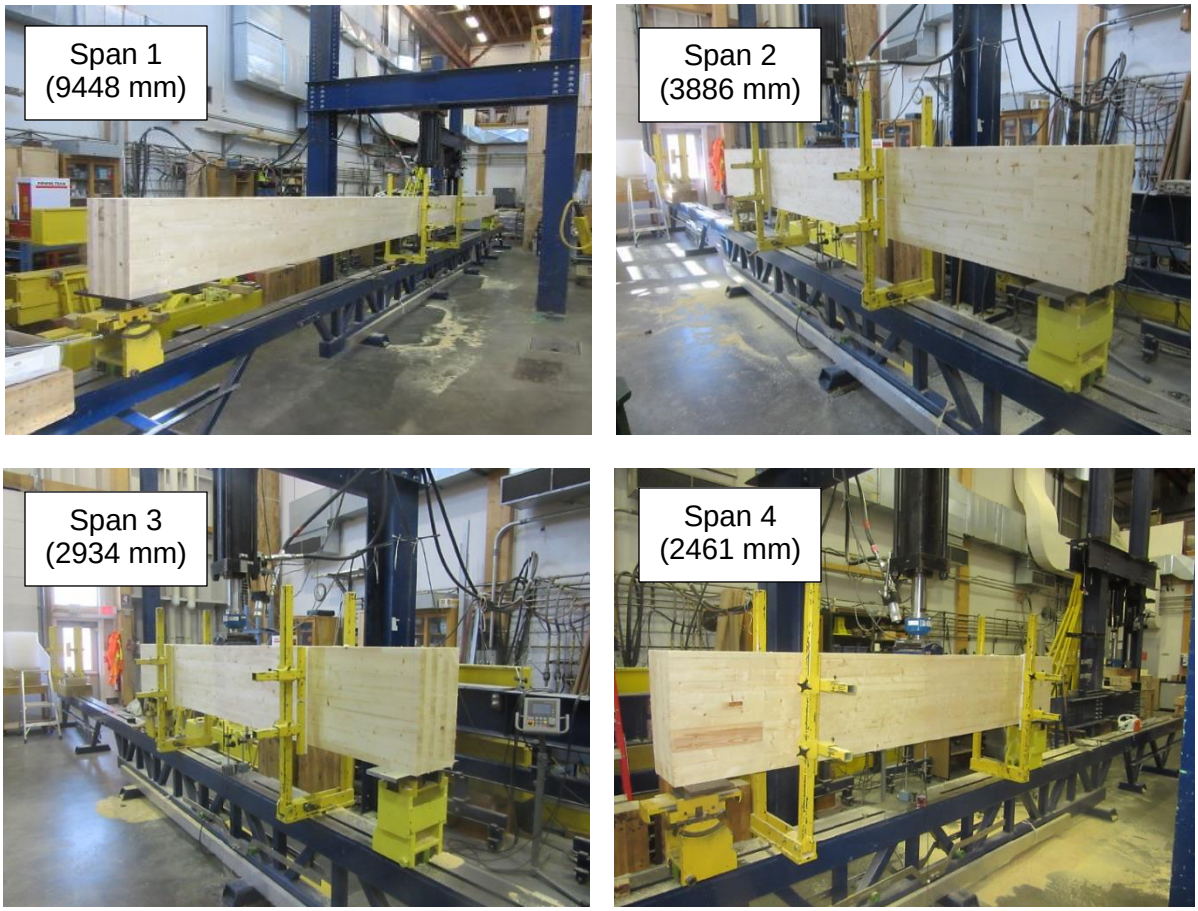

Figure 3. Specimen from Series H tested at the four (4) different spans

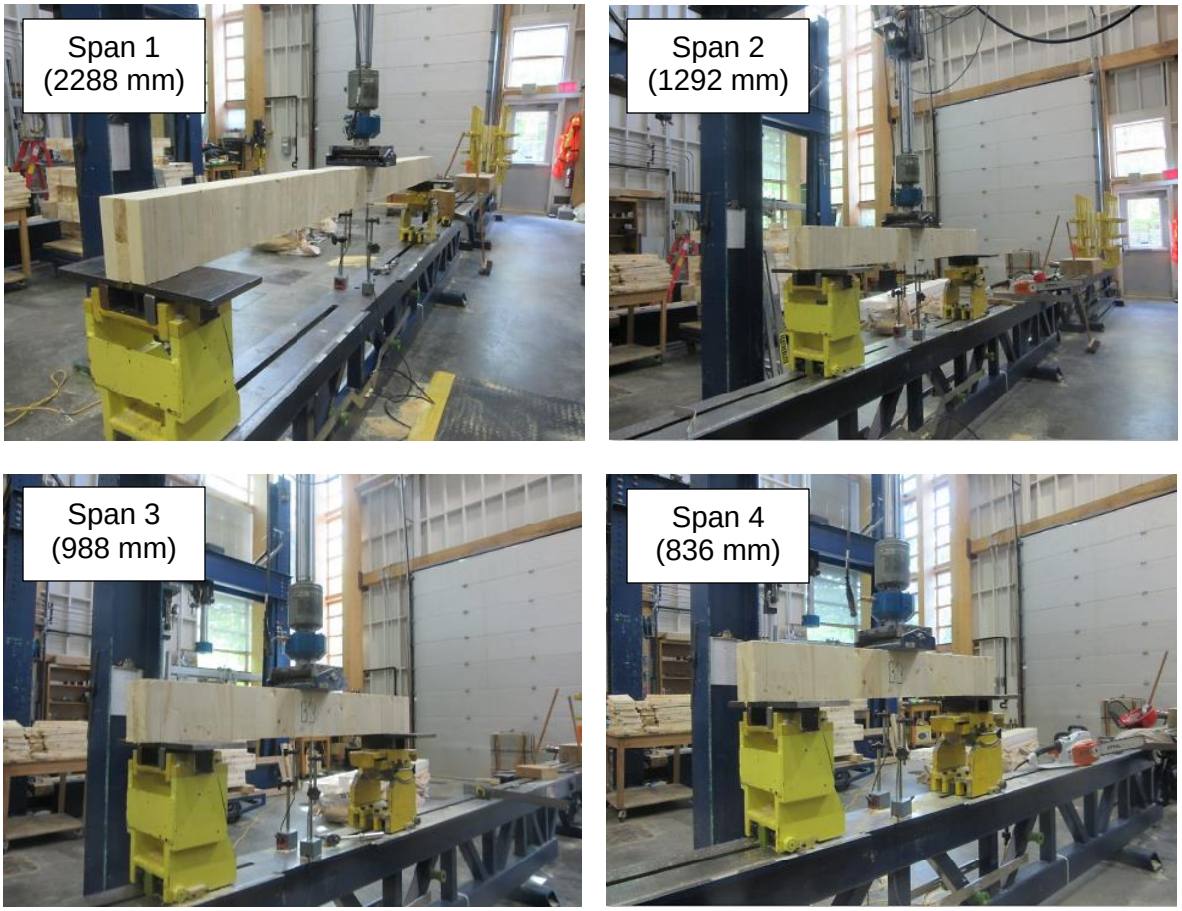

Figure 4. Specimen from Series B tested at the four (4) different spans

Table 2 - Extension limit and load speed for the four spans of Series A, C, E, F, G, and H

Span name	Span length (mm)	Max Disp. (mm)	Load Speed (mm/min)
1	9448	10	2.500
2	3886	3	0.750
3	2934	2	0.500
4	2461	1.5	0.375

Table 3 - Extension limit and load speed for the four spans of series B, and D

Span name	Span length (mm)	Max Disp. (mm)	Load Speed (mm/min)
1	2288	5	1.25
2	1292	2.5	0.625
3	988	2	0.500
4	836	1.5	0.375

1.1.2 Computations for Determination of Shear Modulus and Modulus of Elasticity

The experimental setup described in 3.1.1 allows for the measurement of the load-deformation (P/Δ) behaviour for each specimen.

For every specimen, the apparent Modulus of Elasticity (**E,app**) was determined for each of the four different spans as:

$$\mathrm{E,app} = \frac{\mathrm{PL}^3}{4\mathrm{bh}^3\Delta}$$

where:

L = span from center to center of reactions,

b = specimen width and,

h = specimen depth.

The reciprocal of the **E,app** determined for each of the four spans was then plotted against the square of the depth to length ratio **(h/L)^2**, as shown in Figure 5 for Specimen 2 of Series H. The Shear Modulus (**G**) was calculated from the slope of the plot ($\boldsymbol{K_1}$) as:

$$\mathbf{G} = \frac{6}{5\mathbf{K_1}}$$

for a rectangular cross section.

The 'true' or 'shear free' Modulus of elasticity (**E**) was also computed for each specimen as:

$$\mathrm{E,app} = \frac{3\mathrm{PL}^3}{4\mathrm{bh}^3\Delta(1 - \frac{\mathrm{PL}}{10\mathrm{bhG}\Delta})}$$

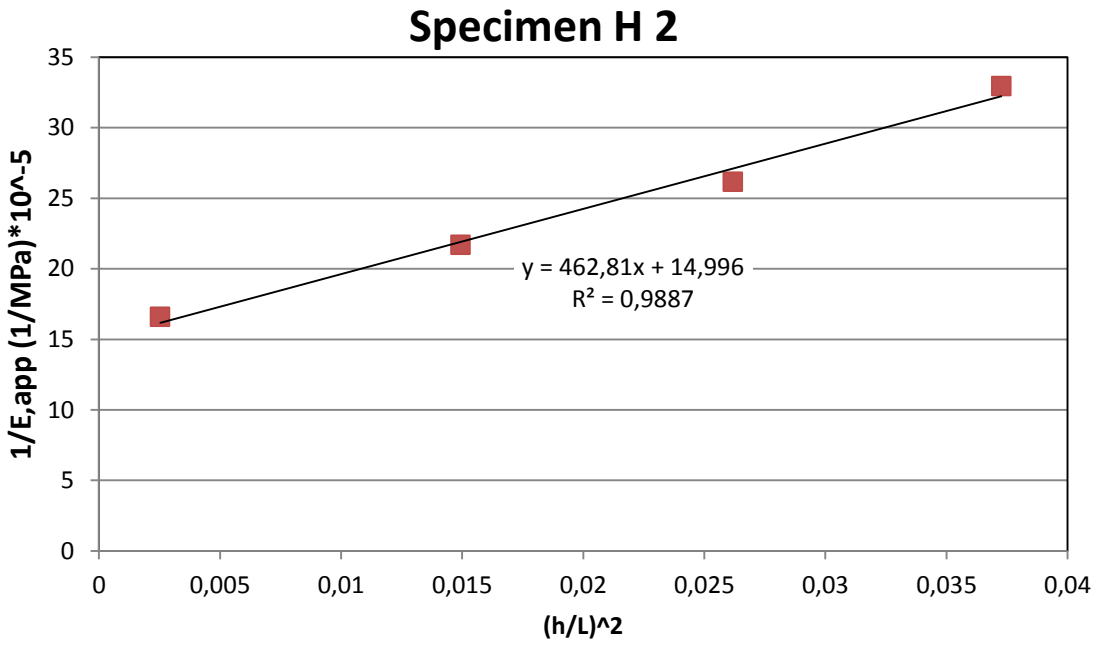

Figure 5. Plot for determination of Shear Modulus for Specimen 2 of Series H

1.2 Specific Gravity and Moisture Content

A slice of the beam cross section of approximately 25 mm long (see Figure 6) was cut immediately upon testing at approximately one-third of the length for the determination of Specific Gravity (**SG**) and Moisture Content (**MC**) as per ASTM D2395-07a and ASTM D 4442-07, respectively.

Figure 6. Transversalslices for Series C used for Moisture Content and Specific Gravity

TECHNICAL TEAM

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Sylvain Gagnon, Eng.,	Associate Research Leader, Advanced Building Systems
Olivier Baës,	Principal Technologist, Advanced Building Systems
Anes Omeranovic,	Principal Technologist, Advanced Building Systems

DATE OF RECEPTION OF SAMPLES

The specimens were received on April 13, 2015 at FPInnovations' laboratory in Québec City.

DATES OF TESTING

Testing commenced on April 15, 2015 and concluded on May 25, 2015.

RESULTS

1.3 Shear Modulus

The effective shear modulus (**G**) and shear corrected Modulus of Elasticity (**E**) obtained for each series are presented in Table 4. The Minimum (**Min.**), Maximum (**Max.**), and Average (**Avg.**) Shear Moduli for each series are presented as a bar chart in Figure 7.

Individual results for the four (4) spans tested for every specimen are provided in the Appendix.

Table 4 - Results for Shear Modulus and shear-corrected Modulus of elasticity for all series

	Avg. Shear Corrected Modulus of Elasticity MPa (E)	Effective Shear Modulus MPa (G)				
		Min.	Max.	Avg.	Std. dev.	CV (%)
A	7440	233	318	274	27	9.87
B	3782	213	468	317	81	25.51
C	7461	207	298	259	23	8.99
D	5013	227	333	276	40	14.55
E	8992	319	400	378	33	8.80
F	8259	291	341	319	20	6.25
G	8641	250	292	268	13	5.00
H	7131	232	283	256	16	6.11

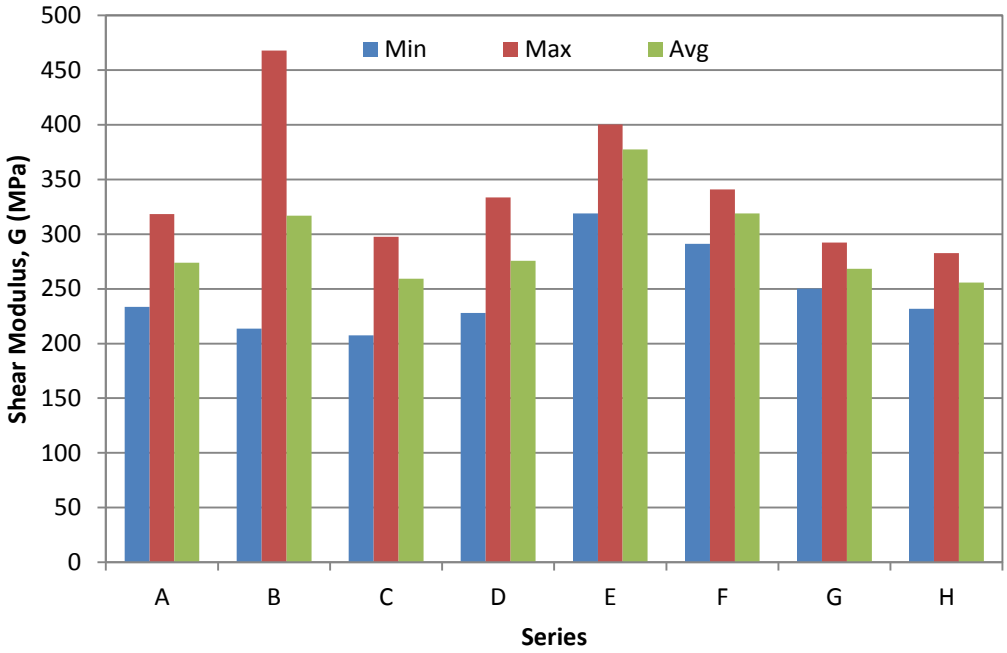


Figure 7. Minimum, Maximum, and AverageShear Moduli

1.4 Specific Gravity and Moisture Content

The average (Avg.), Standard Deviation (Std. dev.), and Coefficient of Variation (CV) for the Specific Gravity (SG) and Moisture Content (MC) of all specimens tested are presented in Table 5.

Table 5 - Specific Gravity and Moisture Content results

Assembly	Item	MC %	SG
A	Avg.	17.0	0.495
	Std. dev.	3.9	0.037
	CV %	22.9	7.475
B	Avg.	15.8	0.501
	Std. dev.	1.3	0.024
	CV %	8.2	4.790
C	Avg.	14.9	0.505
	Std. dev.	1.1	0.007
	CV %	7.4	1.386
D	Avg.	17.3	0.501
	Std. dev.	0.8	0.017
	CV %	4.6	3.393
E	Avg.	11.7	0.508
	Std. dev.	0.6	0.010
	CV %	5.1	1.969
F	Avg.	12.1	0.487
	Std. dev.	0.6	0.017
	CV %	5.0	3.491
G	Avg.	15.7	0.504
	Std. dev.	1.0	0.010
	CV %	6.4	1.984
H	Avg.	14.4	0.493
	Std. dev.	1.4	0.014
	CV %	9.7	2.840

CONCLUSIONS AND OBSERVATIONS

A testing program was performed at FPInnovations' ABS testing facilities in Québec City for Nordic Engineered Wood with the objective of evaluating the effective Shear Modulus (G) of Cross-laminated Timber beams subjected to in-plane loading. The study was composed of eight (8) Series, and (70) specimens. Each specimen was subject to four (4) center point loading tests for a total two hundred and eighty (280) data points.

Based on the analysis and observations made during the course of this study, the following conclusions and observations can be made:

- The linear relationship between the reciprocal of the apparent Modulus of Elasticity (**E,app**) and the square of the depth to length ratio **(h/L)^2** was evidenced by coefficients of determination ($\mathbf{R^2}$) ranging from 0.92 to 1.00,
- The highest Average Effective Shear Modulus was observed for Series E at **378 MPa** and the lowest was observed for Series H at **256 MPa**.

It is to be noted that all results and discussions presented in this report refer exclusively to the specimens submitted to this test schedule.

REFERENCE

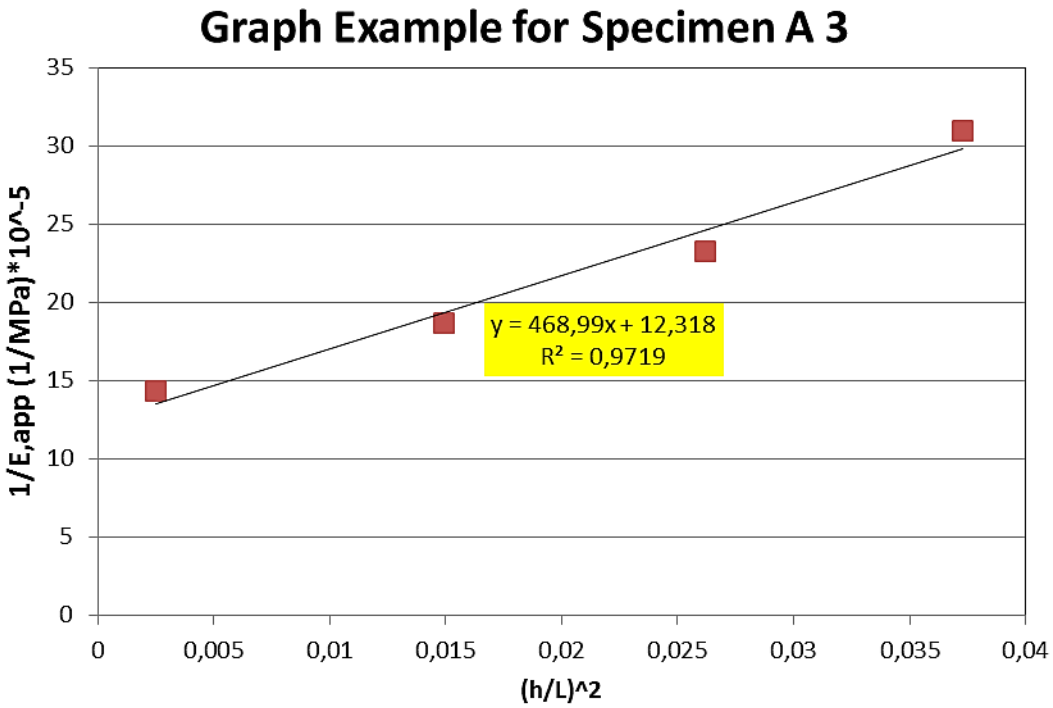
ASTM 2014. Annual Book of ASTM Standards, Volume 04.10 Wood. ASTM, Philadelphia, Pa.

APPENDIX

Specimen A; 3ply - 105

	E,app (MPa)				E,app^-1 (1/MPa)x10^-5				Slope	R^2	G	E,true (Mpa)
	hx19.9	hx8.2	hx6.2	hx5.2	hx19.9	hx8.2	hx6.2	hx5.2	(1/Mpa) 10^-5		(Mpa)	
A1	6194.77	4730.50	3836.61	3009.85	16.14	21.14	26.06	33.22	485.13	0.99	**247.32**	7000.62
A2	6641.20	4834.09	3887.07	3013.00	15.06	20.69	25.73	33.19	513.64	0.99	**233.60**	7552.62
A3	6963.23	5363.10	4295.67	3232.33	14.36	18.65	23.28	30.94	469.06	0.97	**255.87**	8177.89
A4	6636.60	4787.82	3923.46	3158.19	15.07	20.89	25.49	31.66	470.57	1.00	**254.92**	7274.46
A5	6892.57	5473.92	4428.02	3621.06	14.51	18.27	22.58	27.62	377.05	0.99	**318.27**	7633.38
A6	6779.67	4878.71	4022.79	3247.89	14.75	20.50	24.86	30.79	454.31	1.00	**264.14**	7394.49
A7	6854.78	5153.85	4337.83	3359.21	14.59	19.40	23.05	29.77	425.07	0.98	**282.29**	7658.22
A8	6447.58	4928.54	4128.62	3333.87	15.51	20.29	24.22	30.00	409.92	0.99	**292.81**	7042.37
A9	6789.61	5209.58	4202.90	3519.62	14.73	19.20	23.79	28.41	394.81	1.00	**303.82**	7383.71
A10	6801.40	4953.95	4086.27	3406.59	14.7	20.19	24.47	29.35	417.84	1.00	**287.12**	7287.34

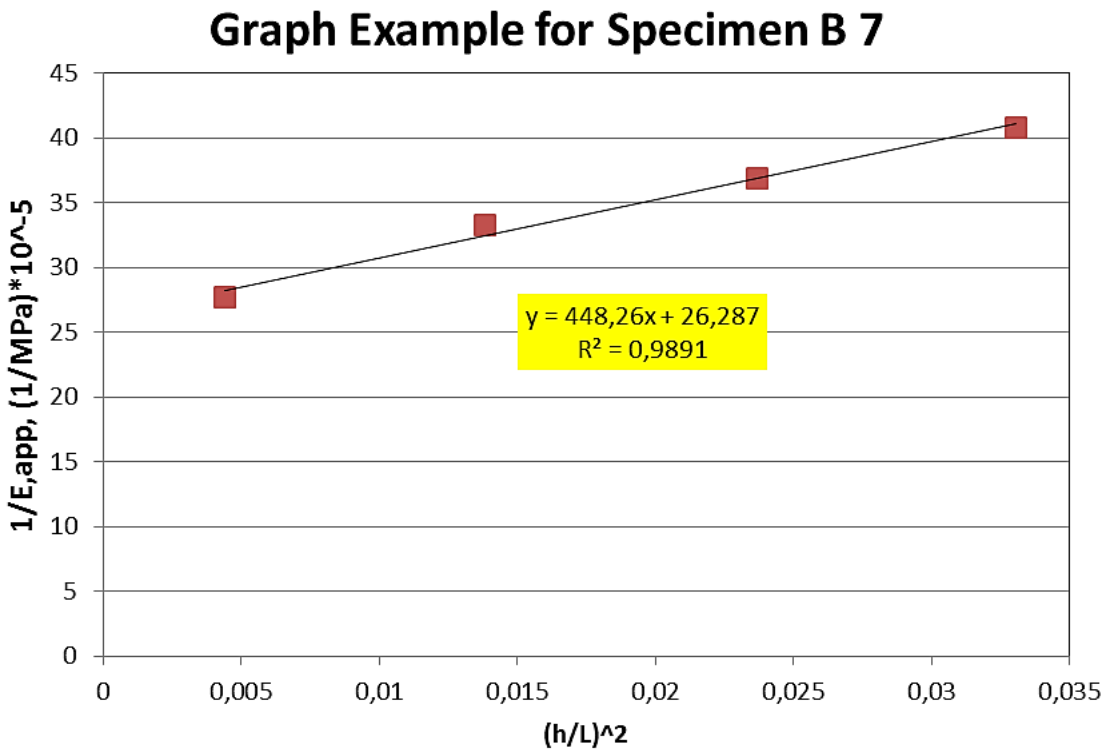
(h/L)^2	0.0025	0.0149	0.0262	0.0373



Specimen B; 3-ply -105

	E,app (MPa)				E,app^-1 (1/MPa)x10^-5				Slope (1/Mpa) 10^-5	R^2	G (Mpa)	E,true (Mpa)
	hx15	hx8.5	hx6.5	hx5.5	hx15	hx8.5	hx6.5	hx5.5				
B1	3903.61	3412.24	3021.37	2598.80	25.62	29.31	33.10	38.48	442.25	0.99	**271.29**	4228.43
B2	3609.15	3184.42	2797.89	2606.15	27.71	31.40	35.74	38.37	379.49	0.99	**316.14**	3837.32
B3	3965.28	3700.61	3459.27	3050.30	25.22	27.02	28.91	32.78	256.34	0.96	**467.95**	4148.93
B4	3637.10	3328.35	2855.62	2618.85	27.49	30.04	35.02	38.18	387.25	0.99	**309.93**	3879.19
B5	3320.82	2880.95	2675.52	2402.85	30.11	34.71	37.38	41.62	388.12	1.00	**309.37**	3521.56
B6	2964.39	2755.97	2532.81	2413.76	33.73	36.28	39.48	41.43	274.81	0.99	**436.95**	3074.47
B7	3607.10	3003.50	2709.65	2448.89	27.72	33.29	36.91	40.83	448.31	0.99	**267.7**	3882.48
B8	4233.09	3701.88	3025.87	2661.15	23.62	27.01	33.05	37.58	500.73	0.99	**239.76**	4666.99
B9	2825.34	2487.96	2142.10	1955.12	35.39	40.19	46.68	51.15	561.80	1.00	**213.67**	3038.82
B10	3173.93	2912.38	2635.83	2401.48	31.51	34.34	37.94	41.64	354.96	1.00	**337.91**	3341.44

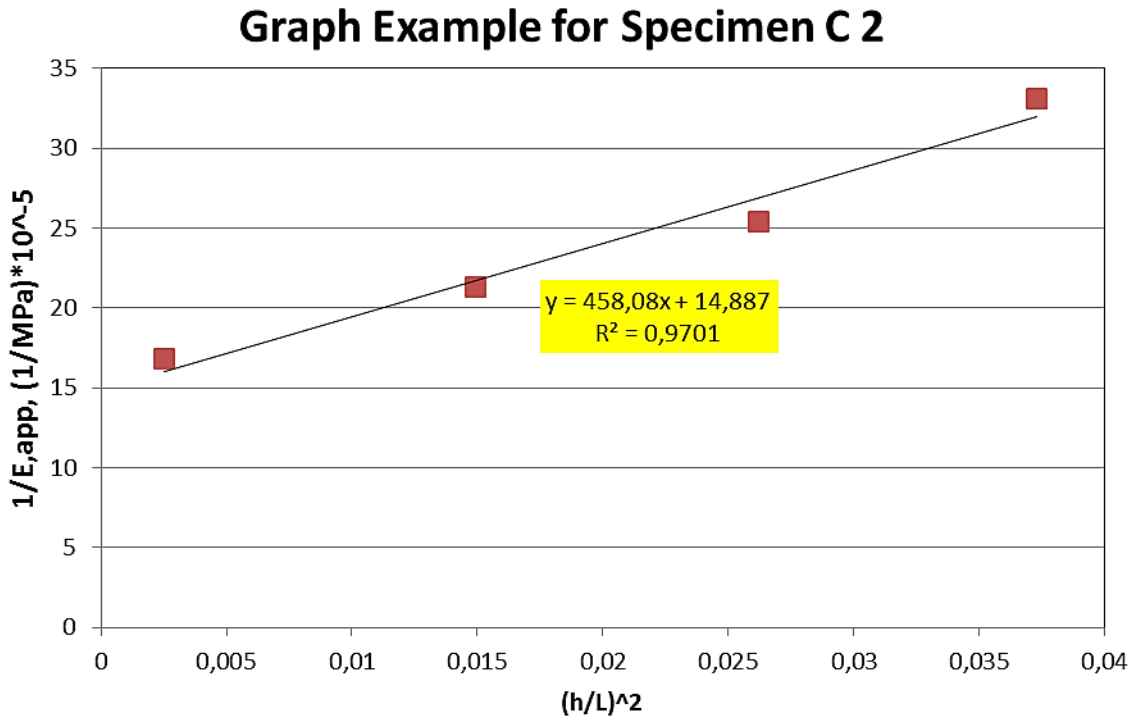
(h/L)^2	0.0044	0.0138	0.0237	0.0331



Specimen C; 5-ply -175

	E,app (MPa)				E,app^-1 (1/MPa)x10^-5				Slope (1/Mpa)	R^2	G	E,true (Mpa)
	hx19.9	hx8.2	hx6.2	hx5.2	hx19.9	hx8.2	hx6.2	hx5.2	10^-5		(Mpa)	
C1	6404.81	5359.67	4289.65	3372.71	15.61	18.66	23.31	29.65	403.13	0.97	**297.71**	7361.07
C2	5955.52	4692.92	3938.50	3018.97	16.79	21.31	25.39	33.12	458.00	0.97	**261.96**	6751.76
C3	6219.67	4998.23	3988.85	3015.76	16.08	20.01	25.07	33.16	485.31	0.96	**247.24**	7323.86
C4	6339.40	5024.67	3997.64	3218.04	15.77	19.90	25.01	31.07	440.49	0.99	**272.40**	7142.84
C5	6218.88	4678.56	3761.28	3048.31	16.08	21.37	26.59	32.81	479.15	1.00	**250.54**	6890.55
C6	5922.67	4714.27	3860.05	3006.03	16.88	21.21	25.91	33.27	464.87	0.98	**258.28**	6730.52
C7	6744.58	5155.44	4151.91	3172.12	14.83	19.40	24.09	31.52	472.68	0.98	**253.77**	7795.85
C8	6887.13	5073.49	4063.60	2837.59	14.52	19.71	24.61	35.24	578.11	0.95	**207.57**	8638.83
C9	7213.45	5197.63	4248.03	3381.40	13.86	19.24	23.54	29.57	444.98	1.00	**269.66**	7977.19
C10	7030.66	5404.17	4271.24	3384.64	14.22	18.50	23.41	29.55	439.62	0.99	**273.10**	7997.00

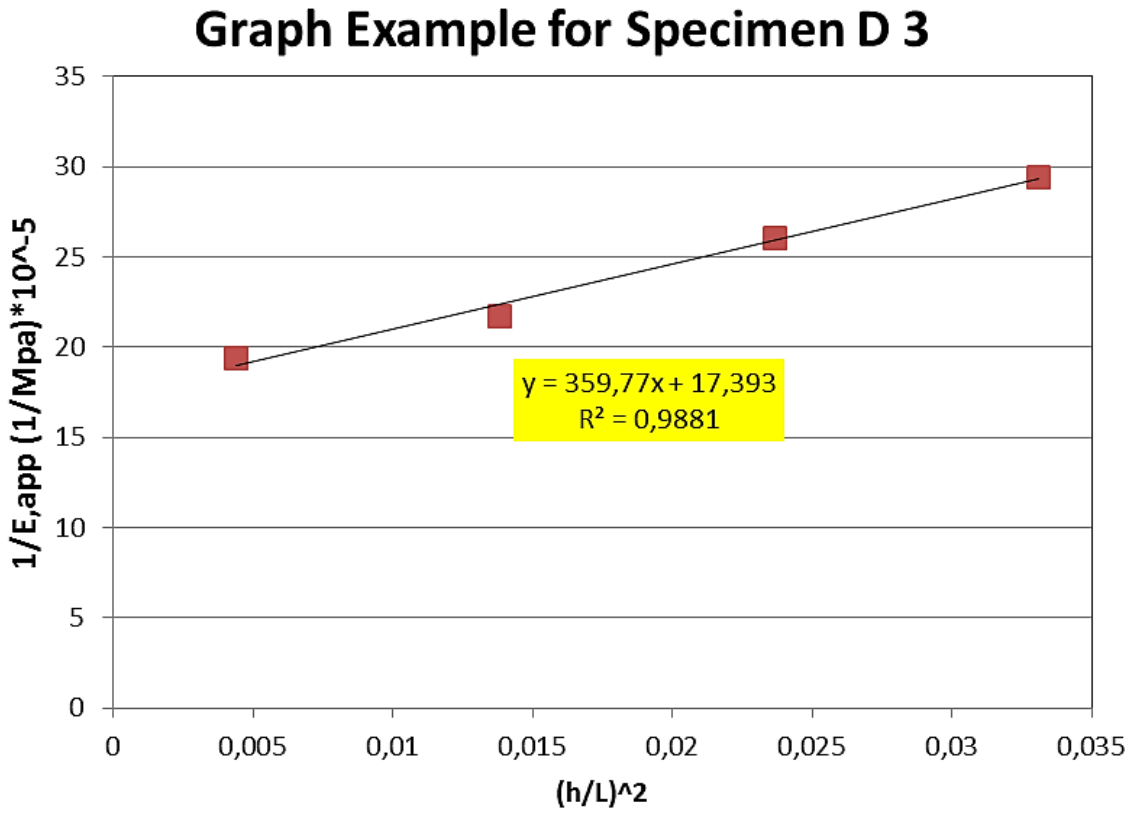
(h/L)^2	0.0025	0.0149	0.0262	0.0373



Specimen D; 5-ply - 175L

	E,app (MPa)				E,app^-1 (1/MPa)x10^-5				Slope (1/Mpa) 10^-5	R^2	G (Mpa)	E,true (Mpa)
	hx15	hx8.5	hx6.5	hx5.5	hx15	hx8.5	hx6.5	hx5.5				
D1	4485.30	3874.61	3292.97	3056.73	22.30	25.81	30.37	32.71	374.04	0.99	**320.58**	4815.05
D2	4233.84	3724.79	3150.21	2777.21	23.62	26.85	31.74	36.01	439.37	1.00	**273.11**	4692.40
D3	5152.58	4615.00	3839.58	3398.40	19.41	21.67	26.04	29.43	359.77	0.99	**333.55**	5753.61
D4	4045.56	3513.20	3098.64	2530.98	24.72	28.46	32.27	39.51	502.71	0.97	**238.69**	4592.25
D5	4446.94	3815.93	3101.77	2682.76	22.49	26.21	32.24	37.28	526.54	0.99	**227.92**	5084.08
D6	3954.66	3708.38	3149.04	2512.29	25.29	26.97	31.76	39.80	504.40	0.92	**237.79**	4679.04
D7	5087.85	4419.73	3778.36	3313.09	19.65	22.63	26.47	30.18	370.03	1.00	**324.33**	5619.43
D8	4936.96	4234.82	3810.50	3082.06	20.26	23.61	26.24	32.45	408.87	0.96	**293.49**	5576.84
D9	4001.86	3474.65	2822.52	2580.35	24.99	28.78	35.43	38.75	501.05	0.99	**239.41**	4429.48
D10	4273.08	3894.08	3307.17	2768.17	23.40	25.68	30.24	36.13	446.40	0.97	**268.97**	4888.37

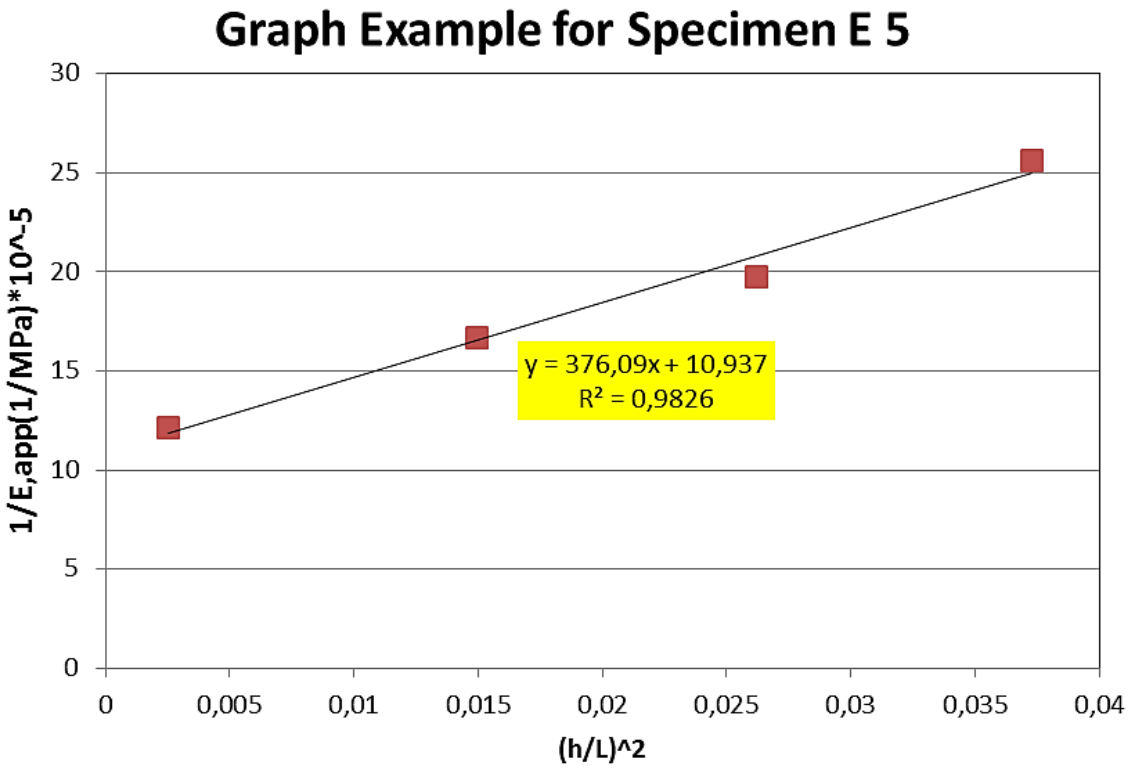
(h/L)^2	0.0044	0.0138	0.0237	0.0331



Specimen E; 3-ply -78

	E,app (MPa)				E,app^-1 (1/MPa)x10^-5				Slope (1/Mpa)	R^2	G	E,true (Mpa)
	hx19.9	hx8.2	hx6.2	hx5.2	hx19.9	hx8.2	hx6.2	hx5.2	10^-5		(Mpa)	
E1	8544.59	6409.85	5278.76	4428.24	11.70	15.60	18.94	22.58	311.58	1.00	**385.14**	9172.27
E2	8138.23	6328.67	5265.97	4317.52	12.29	15.80	18.99	23.16	309.59	1.00	**387.49**	8861.75
E3	8143.91	6390.87	5454.88	4358.66	12.28	15.65	18.33	22.94	299.54	0.98	**400.43**	8916.84
E4	7785.05	6554.74	5426.34	4250.22	12.85	15.26	18.43	23.53	303.47	0.96	**395.30**	8836.75
E5	8234.49	5993.32	5070.39	3901.57	12.14	16.69	19.72	25.63	376.12	0.98	**319.07**	9172.83

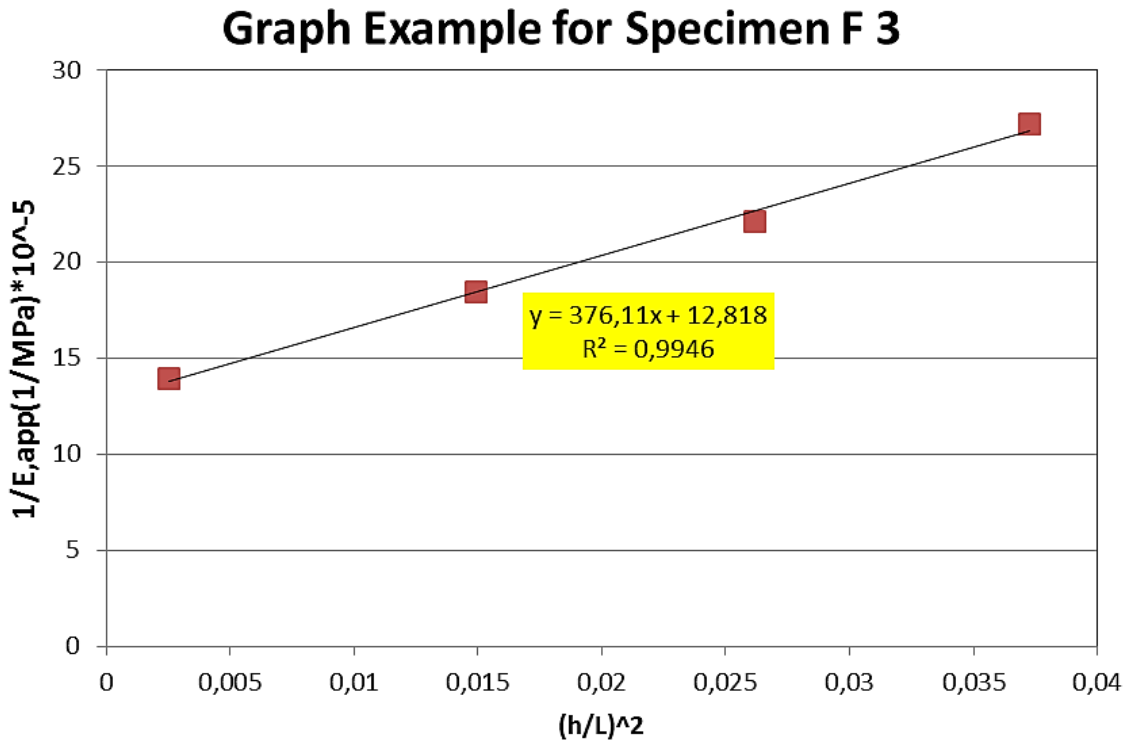
(h/L)^2	0.0025	0.0149	0.0262	0.0373



Specimen F; 5-ply -131

	E,app (MPa)				E,app^-1 (1/MPa)x10^-5				Slope (1/Mpa) 10^-5	R^2	G (Mpa)	E,true (Mpa)
	hx19.9	hx8.2	hx6.2	hx5.2	hx19.9	hx8.2	hx6.2	hx5.2				
F1	7567.6	5943.47	4948.38	3858.01	13.21	16.83	20.21	25.92	358.39	0.98	**334.91**	8704.28
F2	7104.62	5695.24	4744.30	3774.51	14.08	17.56	21.08	26.49	351.84	0.98	**340.86**	7625.53
F3	7171.39	5419.98	4526.52	3673.52	13.94	18.45	22.09	27.22	376.16	1.00	**319.06**	7733.60
F4	6984.88	5654.82	4671.97	3562.80	14.32	17.68	21.40	28.07	387.73	0.96	**309.46**	8148.66
F5	7337.30	5886.76	4871.90	3522.36	13.63	16.99	20.53	28.39	411.92	0.94	**291.31**	9086.25

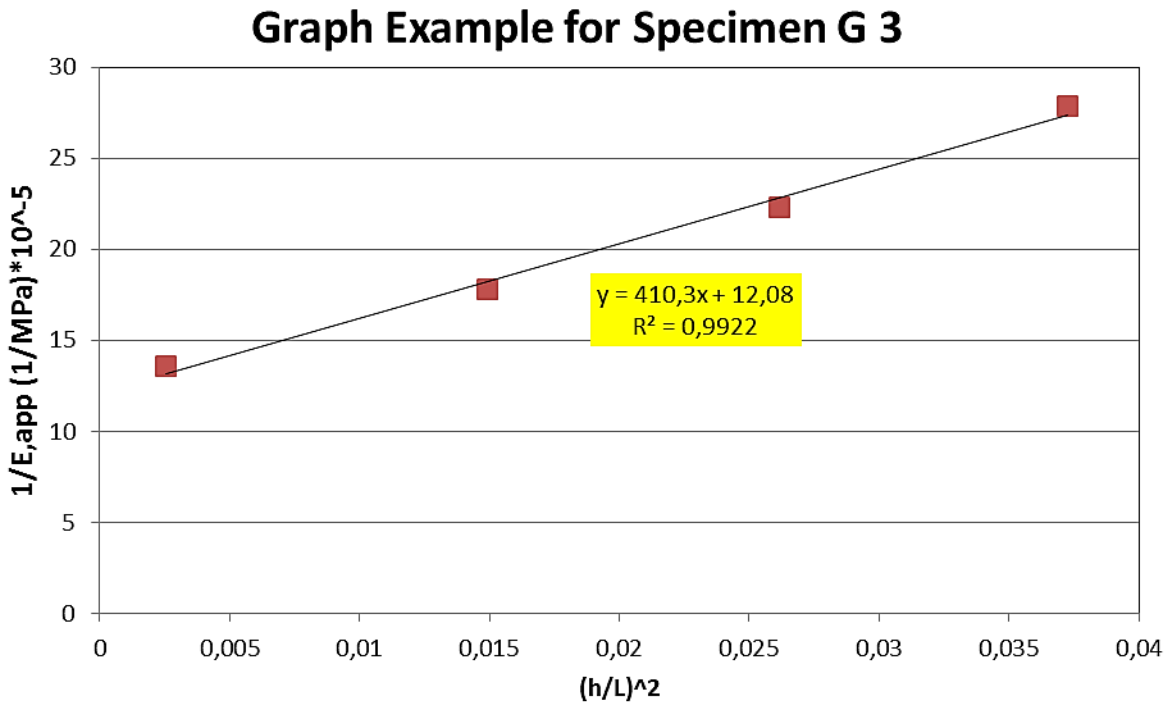
(h/L)^2	0.0025	0.0149	0.0262	0.0373



Specimen G; 7-ply -244 I

	E,app (MPa)				E,app^-1 (1/MPa)x10^-5				Slope (1/MPa)	R^2	G	E,true (Mpa)
	hx19.9	hx8.2	hx6.2	hx5.2	hx19.9	hx8.2	hx6.2	hx5.2	10^-5		(Mpa)	
G1	7235.82	5739.46	4483.14	3406.36	13.82	17.42	22.31	29.36	444.13	0.97	**270.28**	8576.76
G2	7448.07	5639.40	4484.09	3566.76	13.43	17.73	22.30	28.04	418.22	0.99	**286.93**	8409.23
G3	7380.52	5618.66	4484.10	3587.50	13.55	17.80	22.30	27.87	410.14	0.99	**292.47**	8289.51
G4	7110.16	5244.39	4159.06	3279.87	14.06	19.07	24.04	30.49	468.98	0.99	**255.92**	8059.60
G5	7729.44	5784.64	4392.46	3537.13	12.94	17.29	22.77	28.27	444.78	0.99	**269.74**	8853.55
G6	7466.62	5675.38	4438.82	3439.85	13.39	17.62	22.53	29.07	448.51	0.98	**267.59**	8669.20
G7	7434.51	5684.03	4490.80	3285.04	13.45	17.59	22.27	30.44	479.83	0.96	**250.11**	9007.46
G8	7719.27	5678.22	4286.60	3507.40	12.95	17.61	23.33	28.51	453.10	1.00	**264.91**	8751.22
G9	7892.01	5998.73	4654.52	3556.87	12.67	16.67	21.48	28.11	441.26	0.98	**271.87**	9306.86
G10	7312.29	5523.57	4243.95	3330.40	13.68	18.10	23.56	30.03	470.72	0.99	**254.92**	8488.27

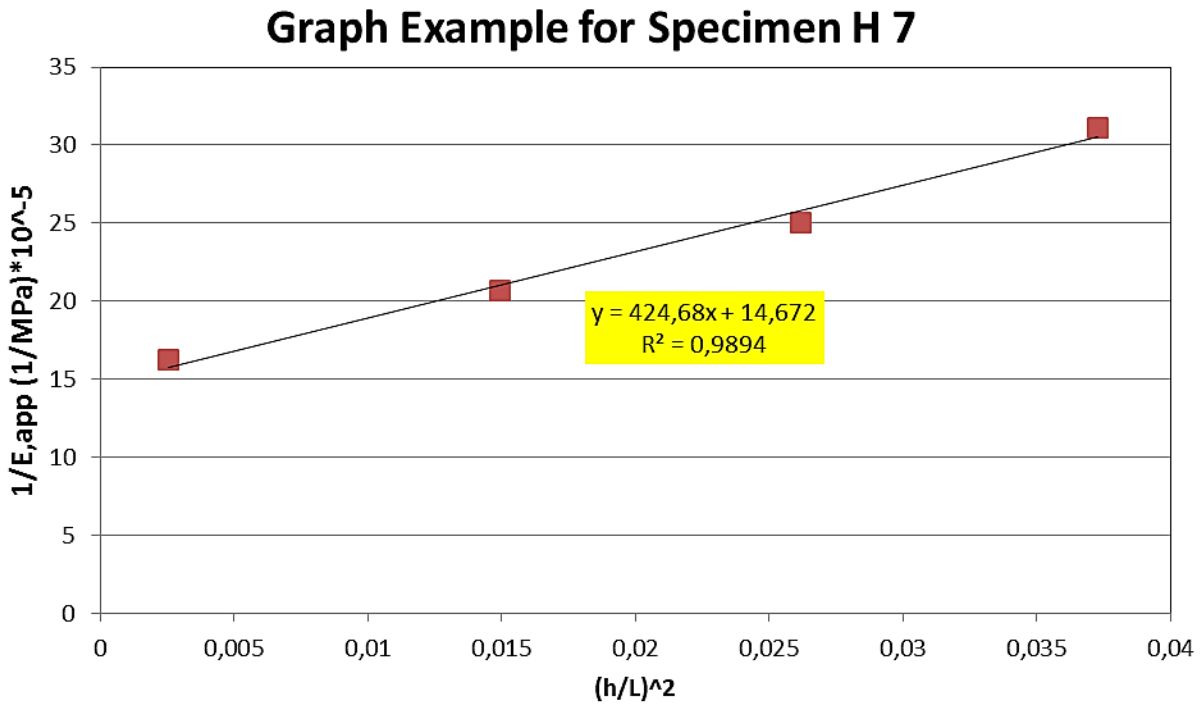
(h/L)^2	0.0025	0.0149	0.0262	0.0373



Specimen H; 7-ply -244 S

	E,app (MPa)				E,app^-1 (1/MPa)x10^-5				Slope	R^2	G	E,true (Mpa)
	hx19.9	hx8.2	hx6.2	hx5.2	hx19.9	hx8.2	hx6.2	hx5.2	(1/Mpa) 10^-5		(Mpa)	
H1	5856.35	4581.98	3730.16	2958.86	17.08	21.82	26.81	33.80	476.30	0.99	**251.95**	6575.68
H2	6024.64	4607.22	3820.87	3034.07	16.60	21.71	26.17	32.96	462.74	0.99	**259.28**	6680.27
H3	6294.78	5056.12	4085.28	3218.61	15.89	19.78	24.48	31.07	433.53	0.98	**276.75**	7152.24
H4	6502.41	4819.41	3809.10	3058.41	15.38	20.75	26.25	32.70	496.80	1.00	**241.56**	7294.85
H5	6480.17	4967.66	3981.42	3111.64	15.43	20.13	25.12	32.14	476.00	0.99	**252.18**	7388.89
H6	6388.74	4981.77	3910.89	3089.14	15.65	20.07	25.57	32.37	480.53	0.99	**249.76**	7322.52
H7	6170.27	4837.46	3993.08	3212.04	16.21	20.67	25.04	31.13	424.51	0.99	**282.56**	6825.40
H8	6161.53	4761.42	3991.04	3092.14	16.23	21.00	25.06	32.34	452.45	0.98	**265.25**	6919.32
H9	6510.63	4960.08	3945.96	3078.11	15.36	20.16	25.34	32.49	488.52	0.99	**245.66**	7454.40
H10	6497.83	5026.74	3947.03	2978.69	15.39	19.89	25.34	33.57	517.45	0.97	**231.91**	7701.59

(h/L)^2	0.0025	0.0149	0.0262	0.0373



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