Method to Estimate Mechanical Properties of Glulam on Flexure Testing Based on Its Laminae Characteristics and Position

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Abstract

Glulam strength is affected by its laminae characteristics and position. Modulus of Elasticity and Modulus of Rupture of layer system (including glulam) is usually estimated by Transformed cross section (TCS) method recently. But, TCS does not follow the principal due to its contrary assumption related with the reduction of material's plane area for laminae with lower E value and the extension of its plane area for laminae with higher E value. In fact the material properties are independent from its shape and size. Therefore, new calculation method is required. As the relevance, this paper discusses the formulation of a new method to determine the E and S_R for glulam based on its laminae properties and position. E and S_R calculated by TCS and new method give identical values. The new method confirms the independence of E and S_R which could not be fulfilled by TCS. According to this fact, TCS could be replaced by new method. The theoretical E value was higher than its corresponding empirical value, but it has high correlation ($R^2=68.53\%$). On the contrary, the theoretical S_R value was not significantly different from its corresponding empirical values, but they have poor correlation ($R^2=27.93\%$). This condition happened because of finger joint effect on the compression and tension side of the sample. Incorporating the finger joint effect into regression analysis, the equation provides very good prediction. The coefficients of determination were 99.58% and 97.19%, for E and S_R respectively.

Keywords: Glulam, Modulus of Elasticity, Modulus of Rupture, Transformed cross section

1. Introduction

Solid wood has dimensional limitation problems for construction purpose. Following the demand of large size of wood for construction purposes, then engineered wood products (EWP) are developed, among which glulam with I-shape (Glulam I-Joist). Glulam consists of laminae those are bundled together and glued. Characteristic and position of each laminae affects and determines the strength of the resulting glulam resisting the bending load, hence the glulam's strength could be expectedly predicted from its laminae characteristics and position. Modulus of Elasticity (E) and Modulus of Rupture (S_R) of EWP with layer system (e.g. glulam) were usually estimated by Transformed cross section (TCS) method recently. But, TCS does not follow the principal due to its assumption that the material properties depend on its shape and size. On TCS methods, laminae's width with lower E value must be reduced and laminae's width with higher E value must be elongated. In fact, E denotes material properties which is independent from the size and shape of material, therefore it will not be relevant to change the material's width based on E of laminae.

Based on above description, new method to calculate E and S_R value of glulam was required. This research aims to develop new method to calculate E and S_R of glulam based on mechanic and geometric

analysis. The new method must be applicable in more general case and could be implemented for glulam I-Joist besides ordinary (rectangular plane) glulam.

2. Material and Methods

This research utilized rubber wood (*Hevea brasiliensis*) as a raw material and phenol resorcinol formaldehyde (PRF) as adhesive. Rubber wood originated from non productive rubber farm located at West Java. Those woods were cut in rectangular shape to the sizes of 2 cm x 4 cm x 300 cm, 2 cm x 6 cm x 300 cm, and 2 cm x 8 cm x 300 cm, respectively. Both end sides of each laminae were cut to small specimen for bending test in accordance with the BS-373:1957¹⁾. The dimension for each small specimen is 2 cm x 2 cm x 30 cm.

Laminae were bundled and glued to become glulam I-joist, then bending test conducted with two-point loading configuration based on ASTM D-198²⁾. There are two types of glulam I-joist with different type of web arrangement. Type 1 set with web as vertically arranged laminae and type 2 set as horizontally arranged laminae (Figure 1). Some laminae must be assembled from two or three pieces of timber because of dimension limitation. On that case, finger joint is applied for end jointing. Average of E and S_R (weighted by its length ratio) is taken of the overall E and S_R for each laminae. Afterwards, E and

S_R glulam I-joist were calculated by theoretical method and verified by empirical testing.

Theoretical calculation method was done in two ways, comprising transformed cross section (TCS) and new developed method. Meanwhile, empirical values were gained from bending test result based on ASTM D-198, and were calculated using Equation 1 and Equation 2 respectively.

$$E = \frac{23}{108} \frac{PL^3}{\Delta bh^3} \quad (1)$$

$$S_R = \frac{P_{maks} L^3}{bh^2} \quad (2)$$

Meanwhile, E and S_R formula for TCS method employ Equation 3 and 4, respectively.

$$E = \frac{I_{xc(tcs)}}{I_{xc}} E_{(ref)} \quad (3)$$

$$S_R = b_{ref} c \frac{I_{tcs}}{I_{act}} \min \left| \frac{S_{Ri}}{b_{i(tcs)} y_i} \right| \quad (4)$$

Derivation of E and S_R formulaes for the new method was conducted through the mechanic and geometry analysis.

Figure 1. Glulam I-joist shape.

3. Results and Discussions

3.1 Laminae characteristics

Many reseachers³⁻⁶⁾ reported that physical properties such as density and moisture content (MC) affected mechanical properties of wood. In glulam, physical properties of each laminae could affect those of its corresponding glulam. Therefore it is important to report the physical properties of each laminae sample. The physical properties of laminae and glulam which were used in this research are shown in Table 1. Density is calculated based on airdry condition, meanwhile specific gravity is based on ovendry condition.

Table 1. Average physical properties of laminae and glulam

Sample Code	MC (%)	Density (g/cm ³)	Specific Gravity
Laminae	Glulam	Laminae	Glulam
G11	12.99	11.72	0.70
G12	13.15	11.27	0.69
G13	12.85	11.92	0.66
G21	13.09	11.65	0.68
G22	12.84	11.66	0.68
G23	13.14	11.47	0.68
Mean	13.01	11.62	0.68

Prior to glulam assembling, each the laminae was cut into small specimen for bending test. Bending test of small specimen was conducted with center point loading configuration based on BS-373:1957. The test result reveals that average E and S_R values for small specimen are 8566 MPa, and 77 MPa, respectively. The summary of E and S_R for each laminae is shown in Table 2, while the related details are attached in Appendix 1. Based on its properties, rubber wood could be classified into grade III-II of wood strength classification according to Peraturan Konstruksi Kayu Indonesia (PKKI) NI-5 1961.

Table 2. E and S_R of laminae for glulam assembling

Glulam Code	Modulus of elasticity (E) (MPa)			Modulus of rupture (S _R) (MPa)		
	Min	Max	Mean	Min	Max	Mean
G11	3130	11800	9096	26.6	99.9	79.4
G12	5310	12200	8577	19.6	101.8	69.9
G13	4490	11040	8461	49.2	91.3	79.5
G21	4520	11630	8992	53.1	106.7	76.7
G22	2760	11360	7391	32.4	984.0	73.0
G23	1055	14188	8878	19.8	118.7	83.4
	Mean	8566		Mean	77.0	

3.2 Formulae derivation

3.2.1 Modulus elasticity (E) of vertical glulam

The web of glulam I-joist type 1 consisted of vertically arranged laminae (Figure 1). So it is necessary to develop formula to calculate the E and S_R of vertical glulam.

Basic formula for deflection is presented on Equation 5.

$$EI \frac{d^2 y}{dx^2} = M \quad (5)$$

For vertical glulam, each changes of laminae's shape due to bending moment parallel to laminae's face must be equal. Therefore, the bending moment deflection formula of each laminae is disclosed on Equation 6.

$$E_i I_i \frac{d^2 y}{dx^2} = M_i; i = 1, 2, 3, \dots, n \quad (6)$$

Bending moment (M) of vertical glulam distributes into each laminae (Equation 7).

$$M = \sum_{i=1}^n M_i \quad (7)$$

Substituting Equations 5 and 6 into Equation 7, it becomes:

$$EI = \sum_{i=1}^n E_i I_i \quad (8)$$

As seen on Figure 1, the laminae on the web has rectangular shape with similar height, so:

$$I_i = \frac{b_i h^3}{12} \quad (9)$$

Moment of inertia for vertical glulam could be expressed using Equation 10:

$$I = \frac{h^3}{12} \sum_{i=1}^n b_i \quad (10)$$

Substituting Equations 9 and 10 into Equation 8, Modulus of Elasticity (E) of parallel glulam could be calculated using Equation 11.

$$E = \frac{\sum_{i=1}^n E_i b_i}{\sum_{i=1}^n b_i} \quad (11)$$

Equation 11 is used to determine the E of web portion of glulam type 1 (Figure 1).

3.2.2 Modulus of rupture (S_R) of vertical glulam

Modulus of rupture (S_R) of vertical glulam is formulated as follow. If Equation 6 is divided by Equation 5, the result is:

$$M_i = M \frac{E_i I_i}{EI}; i = 1, 2, 3, \dots, n \quad (12)$$

Normal stress occurred on each laminae could be expressed using Equation 13.

$$\sigma_i = \frac{M_i y_i}{I_i}; i = 1, 2, 3, \dots, n \quad (13)$$

Substituting Equation 12 into Equation 13, it becomes:

$$\sigma_i = \frac{M y_i}{I} \frac{E_i}{E}; i = 1, 2, 3, \dots, n \quad (14)$$

Maximum normal stress for each laminae occurred on its upper and lower portion fiber, which could be expressed as a half height of vertical glulam (Equation 15).

$$y_{i(max)} = \frac{h}{2} \quad (15)$$

Hence, maximum normal stress was calculated by substituting Equations 10 and 15 into Equation 14.

$$\sigma_{i(max)} = \frac{6M}{h^2} \frac{E_i}{\sum_{i=1}^n b_i} \quad (16)$$

Damage that occurred when maximum normal stress of each lamina is lower than its bending strength parallel to grain ($\sigma_{i(max)} \leq S_{Ri}$). Therefore, the biggest moment which may be resisted by glulam is the minimum moment value of each laminae (M_{min}):

$$M_{min} = \min \left(\frac{S_{Ri}}{E_i} \right) \left(\frac{E h^2}{6} \sum_{i=1}^n b_i \right); i = 1, 2, 3, \dots, n \quad (17)$$

Modulus of rupture (S_R) of vertical glulam is calculated by substituting Equation 17 into 16:

$$S_R = \min(S_{Ri}) \quad (18)$$

Equation 18 concludes that the S_R of vertical glulam is similar to the weakest laminae, which has lowest S_R . It is consistent with the weakest link theory, whereby the sequence of events or objects is dependent

on the support of the whole, and the whole is only as reliable as the weakest member or link^{7,8}.

3.2.3 Modulus of Elasticity (E) of Horizontal Glulam

As seen on Figure 1, most laminae were arranged perpendicular to the moment which made up horizontal glulam. The bending equation for this condition is formulated as follows. Figure 2 shows glulam deflection as a result of bending moment. If R is deflection radius, and x_0 is initial of glulam length, thus on above neutral line shortening may occur and under neutral line will occur prolongation. If fiber distance (y) under neutral line marked with positive sign ($+y_i$) and above neutral line marked with negative sign ($-y_i$), based on geometric analysis, the condition could be formulated by Equation 19 (Figure 2).

$$\begin{aligned} \frac{R}{x_0} &= \frac{R + y_1}{x_1} \\ &= \frac{R + y_2}{x_2} = \dots = \frac{R + (-y_5)}{x_5} = \frac{R + y_i}{x_i} \end{aligned} \quad (19)$$

Figure 2. Deflection on horizontal glulam

Equation 19 could be modified to calculate the strain of each laminae (ϵ_i):

$$\epsilon_i = \frac{\Delta x_i}{x_0} = \frac{x_i - x_0}{x_0} = \frac{y_i}{R} \quad (20)$$

Substituting Hooke's law into Equation 20:

$$\sigma_i = E_i \epsilon_i = E_i \frac{y_i}{R} \quad (21)$$

Internal moment for each of the laminae could be expressed by Equation 22.

$$M_i = y_i \sigma_i dA_i; i = 1, 2, 3, \dots, n \quad (22)$$

Therefore, total moment of each laminae:

$$M_{i(total)} = \int y_i \sigma_i dA_i; i = 1, 2, 3, \dots, n \quad (23)$$

and total value for internal moment exerted at all cross-sectioned plane:

$$M_{(total)} = \sum_{i=1}^n \left(\int y_i \sigma_i dA_i \right) \quad (24)$$

Substituting equation 21 into equation 24:

$$M_{(total)} = \sum_{i=1}^n \left(\frac{E_i}{R} \int y_i^2 dA_i \right) \quad (25)$$

By definition, moment inertia (I) is formulated as follow:

$$I_i = \int y_i^2 dA_i \quad (26)$$

R could be calculated by substituting Equation 26 into Equation 25:

$$R = \frac{\sum_{i=1}^n E_i I_i}{M_{(total)}} \quad (27)$$

R value for glulam and its laminae is similar, hence R for glulam:

$$R = \frac{EI}{M_{(total)}} \quad (28)$$

R could be eliminated by substituting Equation 27 into Equation 28, so Modulus of elasticity (E) for horizontal glulam could be calculated by Equation 29:

$$E = \frac{\sum_{i=1}^n E_i I_i}{I} \quad (29)$$

3.2.4 Modulus of rupture (S_R) of horizontal glulam

Modulus of rupture (S_R) equation for glulam with horizontally arranged laminae is formulated through the following discussion. The stress on each laminae could be calculated by substituting Equation 28 into Equation 21:

$$\sigma_i = \frac{E_i}{E} \frac{M_{(total)} y_i}{I} \quad (30)$$

In order to avoid the damage, laminae's normal stress shall be lower than bending strength of each laminae ($\sigma_i \leq S_{Ri}$). Therefore, the bending strength formula becomes:

$$\frac{E_i}{E} \frac{M_{(total)} y_i}{I} \leq S_{Ri}; i = 1, 2, 3, \dots, n \quad (31)$$

The highest total moment that can be resisted by glulam depends upon the minimum moment which appears on each laminae (M_{min}):

$$M_{(min)} = \min \left[\frac{S_{Ri}}{E_i y_i} \right] (EI); i = 1, 2, 3, \dots, n \quad (32)$$

Modulus of rupture (S_R) of glulam is defined as stress which occurs on outer fiber of glulam assembly. If the distance of outer fiber from neutral axis is denoted by " y ", so the S_R of glulam could be expressed by Equation 33:

$$S_R = \frac{M_{(min)} y}{I} \quad (33)$$

Substituting Equation 32 into 33:

$$S_R = E y \left(\min \left[\frac{S_{Ri}}{E_i y_i} \right] \right) \quad (34)$$

Based on Equation 34, the value of " y_i and y " variables have been still undefined. In order to define the " y_i and y " variables, the neutral line shall be identified. If the compressive stress denotes by positive value and tensile stress denotes by negative value, resultant stress on cross sectional plane area must be equal to 0 (zero) because of the equilibrium

condition. The total of tensile stress shall be equal with compression stress, therefore:

$$\int \sigma_i dA = \frac{M_{total} y}{EI} \sum_{i=1}^n \left(E_i \int y_i dA_i \right) = 0 \quad (35)$$

For I-plane with different width on each lamina, the formula becomes:

$$\frac{M_{total} y}{EI} \sum_{i=1}^n \left(E_i b_i \int_{\sum_{i=1}^{n-1} h_i}^{\sum_{i=1}^n h_i} y_i dy \right) = 0 \quad (36)$$

Since all variables outside the sigma sign are not equal to 0, then:

$$\sum_{i=1}^n \left(E_i b_i \int_{\sum_{i=1}^{n-1} h_i}^{\sum_{i=1}^n h_i} y_i dy \right) = 0 \quad (37)$$

An assisting line is needed to solve Equation 37. The assisting line is located at the bottom side of back laminae. Integrating Equation 37, we get Equation 38. Notation c denotes neutral axis position, measured from the assisting line (bottom line).

$$\sum_{i=1}^n E_i b_i \left(\left(\sum_{i=1}^n h_i - c \right)^2 - \left(\sum_{i=1}^{n-1} h_i - c \right)^2 \right) = 0 \quad (38)$$

Equation 38 is a quadratic function, which could be solved and become:

$$c = \frac{\sum_{i=1}^n E_i b_i \left(\left(\sum_{i=1}^n h_i \right)^2 - \left(\sum_{i=1}^{n-1} h_i \right)^2 \right)}{2 \left(\sum_{i=1}^n E_i h_i b_i \right)} \quad (39)$$

As mentioned above, " y " variable is the distance of outer fiber to neutral line and " y_i " is distance of i -th fiber to neutral line. If the assisting line is bottom line, then " y " variable has similar value with neutral line (c). Finally Modulus of rupture (S_R) of horizontal glulam could be calculated by Equation 40. Equation 40 is then formulated by replacing y on Equation 34 with c :

$$S_R = E c \left(\min \left[\frac{S_{Ri}}{E_i y_i} \right] \right) \quad (40)$$

3.3 Application of TCS method

Transformed cross section (TCS) method needs a reference laminae as a standard width while the width of another laminae would be shortened or elongated based on its E . The width of laminae which has lower E than that of the reference laminae would be shortened, and laminae width which has higher E would be elongated.

On TCS methods, there are 6 (six) steps to calculate the E and S_R of glulam, namely:

1. Identifying the actual size and E of each laminae.
2. Transforming the width of each laminae based on its E -ratio.

3. Calculating neutral axis and moment inertia of transformed glulam cross-sectional plane.
4. Calculating neutral axis and moment inertia of glulam for empirical testing based on actual glulam cross-sectional plane.
5. Calculating E of glulam by Equation 3.
6. Calculating S_R of glulam by Equation 4.

In this research, TCS applied twice: (1) face laminae choosen as reference, and (2) back laminae chosen as reference. TCS give identical result when face or back is taken as reference laminae. The result is reported in Table 3. This condition proves Bodig and Jayne (1993) and other reseacher⁹⁻¹⁰⁾ statement that TCS method will give identical result about E and S_R of layer system no matter which reference laminae was chosen. On the contrary, another reseacher reported different E of glulam if the back or face laminae was choosen as reference, therefore a piece of glulam will have different E value coresponding to the number of its laminae. It is confusing very much if a piece of material has many E value.

Table 3. Theoretical E and S_R of Glulam calculated by TCS and New Method

Type	Glulam Code	E (MPa)		S_R (MPa)	
		TCS	New Method	TCS	New Method
1	G11	7982	7982	84	84
	G12	10222	10222	103	103
	G13	7363	7363	77	77
	Average	8522	8522	88.0	88.0
2	G21	7406	7406	79	79
	G22	7403	7403	79	79
	G23	7406	7406	94	94
	Average	7330	7330	83.8	83.8

3.4. Application of new method

Although TCS is well known already as a standard method to calculate E and S_R of layer system, it has a fatal weakness because of its inconsistency with basic science. E and S_R are material properties which are independent from its shape and size. This condition could not be fulfilled by TCS because the method changes the size (width) of cross-sectional plane of laminae depend on its E. That's why it is important to develop a new method which is more consistent with basic science. The formulae derivation of a new method to calculate the E and S_R of glulam has been describe above. Equations 11 and 18 are suitable to calculate E and S_R of vertical glulam, respectively, while Equations 29 and 40 are suitable for horizontal glulam. More complex layer system could be solved by the combination of those equations.

On the new methods, there are 6 (six) steps to calculate the E of glulam, namely:

1. Identifying the actual size and E of each laminae.
2. Calculating the theoretical neutral axis of glulam by Equation 39.

3. Calculating moment inertia (I_{xc}) of each laminae based on glulam theoretical neutral axis, using parallel axis theory.
4. Calculating neutral axis and moment inertia of glulam for empirical testing based on actual glulam cross-sectional plane.
5. Calculating E of glulam by Equation 11 for vertical glulam, and Equation 29 for horizontal glulam.
6. Calculating S_R of glulam by Equation 18 for vertical glulam and Equation 40 for horizontal glulam.

The detail steps examples for aplication of the new method is shown in Appendix 2 and 3, for glulam type 1 and 2, respectively. And the result is shown in Table 3.

As seen on Table 3, the new method gives identical results with those of TCS. Theoretical E and S_R calculated by TCS or new method give identical result. It means, the new method could replace TCS method to calculate E of layer system because they bring out identical value, and all of its steps confirm the independence of material properties from its size and shape.

3.5 Empirical verification

Verifying the theoretical value by empirical testing was conducted on this research, and the result is shown in Table 4. As seen on Table 4, the empirical value of E is about 30% lower in average than the theoretical value. Paired t-test value confirm the significant different between those values ($p=0.0276$), but they have high correlation ($r=82.78\%$). Figure 5a confirms that the theoretical E value could predict the empirical E value with 68.53% coefficient of determination. On the contrary, the theoretical value of S_R had no significant different from the empirical value, which was proven by paired t-test ($p=0.2998$). However the Pearson's correlation is low ($r=52.85\%$) and the coefficient of determination is 27.93%, so the linier regression was not a good fit enough to determine the empirical S_R value based on its theoretical value only (Figure 5b). This condition occurs because of the joint effects which influence the mechanical properties of glulam. On this research, joint effects were defined as number of joints multiplied by the vertical distance of outer surface of each laminae and divided by its length (Equation 41).

$$J = \frac{n_i y_i}{L_i} \times 100\% \quad (41)$$

Where J joint effect (%), n_i amount of joint on each laminae, y_i distance of outer laminae from theoretical neutral axis (cm), L_i laminae length (cm). J value bellow neutral axis is called finger joint effect under tension and above neutral axis is called finger joint effect under compression. The both value is shown in Table 4.

Table 4. Empirical verification of Modulus of elasticity (E) and Modulus of rupture (S_R) of the glulam

Sample Code	J (%)		E (MPa)		S_R (MPa)	
	Com- pression	Ten- sion	Theo- retic	Empiric	Theo- retic	Empiric
G11	3.65	3.71	7982	7174	83.67	81.98
G12	2.21	3.18	10222	9584	103.42	89.28
G13	3.40	2.47	7363	3186	76.90	72.10
Mean	3.09	3.12	8522	6648	88.00	81.12
G21	3.94	4.11	7406	6728	78.91	89.8
G22	2.04	2.85	7181	2426	78.91	42.82
G23	3.28	3.20	7403	4157	93.56	93.73
Mean	3.09	3.39	7330	4437	83.79	75.45

Incorporating finger joint effect under tension and compression into regression analysis, this bring out Equation 42. It is a very good fit regression equation because it could predict the empirical E with 99.58% coefficient of determination (Figure 6a). Further analysis shows that Finger joint effect on compression didn't give significant effect to empirical E (Table 6). Empirical E value depends on its theoretical value and its finger joint effect on tension.

$$E = -20092 + 2.14 E' + 1890.05 F_t + 810.82 F_c ;$$

$$(R^2 = 99.58) \quad (42)$$

Similar analysis was conducted on empirical S_R value, and this results in Equation 43. The regression equation is a very good fit because it can predict the empirical S_R value with high coefficient of determination ($R^2=97.19\%$) (Figure 6b). On this case, finger joint under tension doesn't give significant effect to empirical S_R , but theoretical S_R value and finger joint under compression give significant effect (Table 6)

$$S_R = -129.97 + 1.62 S'_R + 0.14 F_t + 22.15 F_c ;$$

$$(R^2 = 97.19) \quad (43)$$

Figure 5. Linier Regression between Theoretical and Empirical Value of Glulam I-Joist (a. Modulus of Elasticity (E); b. Modulus of Rupture (S_R))

Table 5. Anova of empirical verification for Modulus of elasticity of the glulam

	df	SS	MS	F	Sig. F
Regression	3	37433371	12477790	159 ^{**}	0.006
Theoretical E Value	1	25759367	25759367	329 ^{**}	0.003
Finger Joint on Tension	1	10661455	10661455	136 ^{**}	0.007
Finger Joint on Compression	1	1012550	1012550	13 ^{ns}	0.069
Residual	2	156504	78252		
Total	5	37589875			

Note : ^{**}) = Highly significant; ns) = not significant

Table 6. Anova of empirical verification for Modulus of rupture of the glulam

	df	SS	MS	F	Sig. F
Regression	3	1751	584	23 [*]	0.042
Theoretical E Value	1	503	503	20 [*]	0.047
Finger Joint on Tension	1	451	451	18 ^{ns}	0.052
Finger Joint on Compression	1	796	796	31 [*]	0.030
Residual	2	51	25		
Total	5	1802			

Note : ^{*}) = significant; ns) = not significant

Figure 6. Linier Regression between Corrected Theoretical and Empirical Value of Glulam I-Joist (a. Modulus of Elasticity (E); b. Modulus of Rupture (S_R))

4. Conclusion

This research comes up with a new method to calculate the Modulus of elasticity (E) and Modulus of rupture (S_R) for layer system in order to substitute for the transformed cross section (TCS) method. Both methods provides identical results. The new method is proven by mechanic and geometric analysis and consistent with independence of material properties, which could not be fulfilled by TCS method.

Empirical test verified the theoretical E value which is higher than the empirical value, however they have high correlation ($R^2=68.53\%$). On the contrary, the theoretical S_R value is not significantly different from its empirical value, but it has poor correlation ($R^2=27.93\%$). This condition is happened because of

finger joint effect under the compression and tension side of the sample.

Incorporating finger joint effect into regression analysis, the equation results in a very good prediction. The coefficient of determination is 99.58% and 97.19%, for E and S_R respectively. The theoretical values of E and S_R afford significant effect on its empirical value. Meanwhile, the finger joint effect under tension provides significant effect on empirical E value only, and finger joint effect under compression offers significant effect to empirical S_R value only.

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Table 7. Bending test result of small specimens related with its place on Glulam I-joist Type 1 (G11, G12, G13) and Type 2 (G21, G22, G23) **Table 8.** Example Detail of TCS Methods to calculate the E of type 2 Glulam.

1. Actual	Figure	b_i (cm)	h_i (cm)	E_i (kg/cm ²)
	1	7.5	2.0	5490
	2	7.5	2.0	5294
	3	3.3	1.7	10754
	4	3.3	1.7	7850
	5	3.3	1.7	10478
	6	7.5	2.0	8914
	7	7.5	2.0	10665
2. Transformed cross section: - Choosing 1 st laminae as reference - Transforming each laminae's width by equation: $b_{i(tcs)} = \frac{E_i}{E_{ref}} b_{ref}$	Figure	$b_{i(tcs)}$ (cm)	h_i (cm)	$E_{(tcs)}$ (kg/cm ²)
	1	7.50	2.0	5490
	2	7.23	2.0	
	3	6.46	1.7	
	4	4.72	1.7	
	5	6.30	1.7	
	6	12.18	2.0	
	7	14.57	2.0	

Table 8. Continued

<p>3. Calculating neutral axis (c) of Transformed Cross Section (TCS) :</p> $c_{(tcs)} = \frac{\sum_{i=1}^n A_{i(tcs)} y_i}{\sum_{i=1}^n A_{i(tcs)}}$ <p>Note: y_i = distance from assist line</p>	<p>Figure</p>	$A_{i(tcs)}$	y_i	$\sum A_{i(tcs)} y_i$	$c_{(tcs)}$
<p>4. Calculating Moment Inertia (I_{xc}) of TCS :</p> $I_{xc(tcs)} = \sum_{i=1}^n (I_{xci(tcs)} + y_i^2 A_i)$ <p>Note: y_i = distance from neutral axis of TCS</p>	<p>Figure</p>	A_i	y_i	$\sum A_{i(tcs)} y_i$	c
<p>5. Calculating neutral axis (c) for Empirical Testing</p> $c = \frac{\sum_{i=1}^n A_i y_i}{\sum_{i=1}^n A_i}$ <p>Note: y_i = distance from assist line</p>	<p>Figure</p>	A_i	y_i	$\sum A_{i(tcs)} y_i$	c
<p>6. Calculating Moment Inertia (I_{xc}) for Empirical Testing :</p> $I_{xc} = \sum_{i=1}^n (I_{xci} + y_i^2 A_i)$ <p>Note: y_i = distance from neutral axis (empirical)</p>	<p>Figure</p>	A_i	y_i	$\sum A_{i(tcs)} y_i$	c
<p>7. Calculating E of Glulam I-joist:</p> $E = \frac{I_{xc(tcs)}}{I_{xc}} E_{(tcs)}$	<p>Figure</p>	A_i	y_i	$\sum A_{i(tcs)} y_i$	c
<p>8. Calculating S_R of Glulam I-joist:</p> $S_R = b_{ref} c \frac{I_{tcs}}{I_{act}} MIN \left \frac{S_{Ri}}{b_{i(tcs)} y_i} \right $ <p>Note: y_i = distance from neutral axis (c_{tcs}) of TCS</p>	<p>Figure</p>	A_i	y_i	$\sum A_{i(tcs)} y_i$	c

Table 9. Example Detail of New Method to calculate the E of type 2 Glulam.

1. Actual	<div>Figure</div>		b (cm)	h (cm)	E (kg/cm ²)	
			7.5	2.0	5490	
			7.5	2.0	5294	
			3.3	1.7	10754	
			3.3	1.7	7850	
			3.3	1.7	10478	
			7.5	2.0	8914	
			7.5	2.0	10665	
2. Calculating actual neutral axis (c) of glulam $c = \frac{\sum_{i=1}^n E_i b_i \left(\left(\sum_{i=1}^n h_i \right)^2 - \left(\sum_{i=1}^{n-1} h_i \right)^2 \right)}{2 \left(\sum_{i=1}^n E_i h_i b_i \right)}$	$E_i b_i$	$\left(\sum_{i=1}^n h_i \right)^2 - \left(\sum_{i=1}^{n-1} h_i \right)^2$	$E_i b_i \left(\left(\sum_{i=1}^n h_i \right)^2 - \left(\sum_{i=1}^{n-1} h_i \right)^2 \right)$	$2 E_i h_i b_i$	c	
	15.00	48.40	1992870	164700	5.55	
	14.46	40.40	1604006	158812		
	10.99	28.05	995421	120657		
	8.02	22.27	576904	88077		
	10.71	16.49	570154	117558		
	24.35	12.00	802238	267413		
	29.14	4.00	319950	319950		
	Sum		6861543	1237167		
	3. Calculating Moment Inertia (I _{xc}) of each laminae on glulam neutral axis $I_{xi} = I_{xci} + y_i^2 A_i$ Note: y _i =distance from centroid	$I_{xci} = \frac{b_i h_i^3}{12}$	$(y_i - c)^2 A_i$		$I_{xi} = I_{xci} + y_i^2 A_i$	
5.00		644.29		649.29		
5.00		311.06		316.06		
1.35		41.01		42.36		
1.35		5.65		7.00		
1.35		2.72		4.07		
5.00		97.25		102.25		
5.00		310.02		315.02		
4. Calculating neutral axis (c) for empirical testing $c = \frac{\sum_{i=1}^n A_i y_i}{\sum_{i=1}^n A_i}$ Note: y _i =distance from assist line	<div>Figure</div>		A_i	y_i	$\sum A_i (y_{ics}) y_i$	c
			15	12.10	181.50	6.55
			15	10.10	151.50	
			5.61	8.25	46.28	
			5.61	6.55	36.75	
			5.61	4.85	27.21	
			15	3.00	45.00	
			15	1.00	15.00	
	Sum		76.83		503.24	
5. Calculating Moment Inertia (I _{xc}) for empirical testing : $I_{xc} = \sum_{i=1}^n (I_{xci} + y_i^2 A_i)$ Note: y _i =distance from centroid (empiric)	$I_{xci} = \frac{b_i h_i^3}{12}$	$y_i^2 A_i$		$I_{xci} + y_i^2 A_i$		I_{xc}
	5.0	462.0		467.0		1358.6
	5.0	189.0		194.0		
	1.4	16.2		17.6		
	1.4	0.0		1.4		
	1.4	16.2		17.6		
	5.0	189.0		194.0		
	5.0	462.0		467.0		
	Sum				1358.6	
	6. Calculating E of Glulam I-joist: $E = \frac{\sum_{i=1}^n E_i I_{xi}}{I_{xc}}$	$E_i I_{xi}$	I_{xc}		E	
3564598		1358.6		7406		
1673141.5						
455571						
54981.943						
42643.619						
911387.59						
3359642						
Sum = 10061966						

Table 9. Continued

7. Calculating SR by Equation:	S_{Ri}	y_i	$\left \frac{S_{Ri}}{E_i y_i} \right $	$MIN \left \frac{S_{Ri}}{E_i y_i} \right $	Ec	S_R
$S_R = Ec \left(MIN \left \frac{S_{Ri}}{E_i y_i} \right \right)$ Note: y_i = distance from actual centroid	73.2	6.55	0.00203	0.00195	41074.8	80.08
	63.0	4.55	0.00261			
	101.7	2.70	0.00350			
	63.1	1.00	0.00801			
	69.7	-0.70	0.00956			
	67.9	-2.55	0.00299			
	94.5	-4.55	0.00195			