Investigation of the Structural Performance of Pinus Sylvestris (Scots Pine) as Partial Replacement to Suspended Structural Beams

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Abstract

This study evaluates the structural performance of Pinus sylvestris (Scots Pine) when applied as a structural beam, which focuses on flexure and shear performances. Testing and mathematical evaluation were necessary to determine the properties of this material in order to investigate its performance as a structural beam. Following the prescribed sizes indicated in ASTM D905 and ASTM D198, specimens for shear and flexure were manufactured with the application of polyvinyl acetate adhesive between each lamina within each test sample. These specimens were tested using static bending and shear/delamination tests in accordance with the two standards, and results were analyzed quantitatively using the statistical methods and internationally accepted methods indicated in the Design Standard of Philippine Timber and the National Structural Code of the Philippines (NSCP). The analysis of results has shown that upon investigation of Pinus sylvestris glulam with Polyvinyl acetate (PVAc) adhesive manufactured using the available technology in the Philippines, it is not suitable for construction or any uses that involve load-bearing capabilities. Further investigation is recommended to be conducted in the future in relation to this study. The conclusions made in this study may be used for academic references pertaining to the use of this wood species.

Keywords: Glulam, Pinus Sylvestris, Scots Pine, Glue-laminated timber PVAc, Static bending, Shear, Delamination

I. Introduction

Timber is a material that has been harvested for many uses in different industries, such as medicine, furniture, and major construction. The usage of timber began way back during the prehistoric era when people gathered wood for crafting tools and weapons used for survival. Later, when people emerged from caves, wood became a material for building components of early nomadic houses and bridges as early as 10,000–15,000 B.C. (Malo., 2016). As tools evolved through time, people began to gather logs for construction, which were incorporated into the construction of early dwellings and large structures, such as temples, especially in the oriental Asian countries and early civilizations in Mesopotamia and Egypt. The use of timber for construction became prominent until the Industrial Revolution emerged which led to the invention of reinforced concrete due to the introduction and mass production of steel and concrete for construction of major building framing.

Since reinforced concrete became popular in the early part of the Industrial Revolution, it became the conventional construction material globally, especially in multi-story structures. Thus, the use of timber in major building construction became less popular due to the supply and mass production of concrete and steel. Reinforced concrete also became known to be advantageous in terms of its structural performance, as concrete has excellent performance in its compressive strength, and steel has exemplary performance in both tensile and flexural strength. Timber was then rarely used for major construction of building framing components, instead, it is mainly for finishing materials and furniture due to its elegance and aesthetic qualities even though it performs well in terms of its mechanical properties; it has its limitations, depending on the species of wood.

However, concrete and steel production has disadvantages in terms of environmental impact due to the gathering of raw materials from its natural resources, the energy required for manufacturing, and the amount of carbon footprint emission for processing the material. The energy requirements for beam manufacturing using reinforced concrete are five times the amount of energy required for softwood glulam beams, and the manufacturing and

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construction of steel beams are six times the amount of energy required for softwood glulam beams. Thus, timber is the most environmentally sustainable material among the three aforementioned materials used for the construction of major structural framing of buildings due to the amount of energy and carbon footprint emitted in the manufacturing process of the material.

Timber usage depends on the selection of species. The variations of wood species are classified mainly into two major categories: hardwood and softwood. Hardwood species are usually known to be used for the construction of major structural elements of a building, while softwood species are mainly used for light construction, furniture, medicines, paper production, and other applications that do not require extensive strength.

The major disadvantage of hardwood is the time required for the timber to be regrown and renewed, whereas softwood species could grow in a shorter period of time; however, the major disadvantage of softwood species is its limited dimension and strength. Hence, the invention of engineered timber, such as glued-laminated timber (glulam) and cross-laminated timber (XLT), is introduced to cater to both strength and sizing concerns in the timber industry.

Reinforced concrete and steel are highly thermally absorptive materials, unlike timber which has lower thermal absorption and conductivity due to its microscopic porous property. In the present day, the global temperature and heat index gradually and drastically increase, which reinforced concrete greatly contributes to the increase in the temperature of indoor and surrounding temperatures in buildings. Thus, the demand and trend of wood usage, particularly engineered wood, in construction emerges to address sustainability and thermal comfort in design, and at the same time, it contributes to the aesthetics of the building.

However, illegal logging became prominent in the Philippines which led to rapid deforestation in several provinces that affected many habitats, especially endangered species of both plants and animals. For this reason, the government under Benigno Aquino III proposed the implementation of a total log ban in 2013 (The Strait Times, 2011) under Executive Order 23 (2011) to address these environmental issues. Due to the log ban in the country, the Philippines became dependent on importing timber for almost a decade, while there are still plantations that exist within the country to cater for small construction.

Due to the continuous increase in the global temperature that is being experienced by people worldwide, the demand for timber in construction became a trend globally due to its property of having a low thermal absorption rate and carbon footprint emissions. However, due to the log ban in the Philippines, the country still depends on the use of imported species for the local timber industry. Upon selection of the species available during the formulation of this study, Pinus sylvestris (Scots pine) was selected as an imported species to be investigated in its structural performance as a structural beam to propose a possible alternative to concrete and steel. Recently, during the late period of the presidency of Rodrigo Duterte, the Department of Environment and Natural Resources (DENR) eased the requirements for the timber industry (Foundation for Economic Freedom, 2021) as the government agency helped boost the local lumber production of the country to somehow be less dependent on importing timber products (Teves, 2021), although the effectiveness of this is not quite applicable to the entire country as there are plenty of environmental concerns that are still being addressed in the Philippines. Though the DENR has eased the requirements in the Philippine timber industry, harvesting of timber is still selective in the country, and local hardwood species, which are the most preferable species for structural timber in the country, is still strictly prohibited for harvesting due to their growing cycle (Foundation for Economic Freedom, 2021). In order to address both economic and environmental concerns simultaneously through the enhancement of timber industry in the Philippines (Teves, 2021), only selected local softwood species are available to be harvested for construction and other essential uses (Foundation for Economic Freedom, 2021), since hardwood would take several decades to regrow, given that the country is still experiencing environmental recovery in the forestry products due to excessive logging in the past decades (Mayuga, 2017). Hence, the country still needs to depend on the importation of timber products.

As the advocacy for sustainability arises in the construction industry worldwide, wood is the most sustainable material as compared to concrete and steel due to its renewability and lower greenhouse gas emissions (Gambhir & Jamwal, 2011). Wood has been observed to perform well as structural framing materials to resist earthquakes due to its physical properties (Malo, 2016). One way to slow down the deforestation worldwide, especially in the Philippines, since hardwood is strictly currently banned for harvesting (Teves, 2021), is the use of engineered softwood species to promote sustainability in the construction industry in the country while addressing the environmental concerns. The Philippines also imports other species which are endemic or native in other countries for construction use, such as Scots pine *(Pinus sylvestris)*, to slow down the deforestation due to local harvesting and to give way for the environmental recovery of the country's forestry. Scots pine a species of least concern as categorized by the IUCN Standards and Petitions Subcommittee (2017), and it is still abundant in several countries in Europe. Scots pine, as a timber species that can be used for local construction, was investigated in this study, as details of its structural parameters are not provided in the country to evaluate its structural performance. As a softwood species, engineering procedures are required to be used as a major structural member, such as glue-lamination procedures (Ong, 2015).

The main concern in the timber industry in the Philippines is the availability of equipment for the manufacture of glulam beams. Although some equipment for glulam manufacture is available in the country, some materials and equipment are limited, especially the variation of adhesives and the machine for finger-jointing. Though Ong (2015) stated that finger-jointing is required for the end-to-end connection of laminae in glulam beams, the study by Dansoh, et al. (2004) states that there is little significant difference in the strength between butt-jointed ends of glulam laminae and finger-jointed ends. Therefore, glulam can be manufactured using the available materials and equipment in the Philippines but needs thorough investigation to determine if the strength of the glulam manufactured in the country would be the same as those manufactured abroad.

This study focuses on the investigation of the mechanical properties of Scots Pine glulam that are applicable to structural beams. Other mechanical properties are not included in this study, as other parameters would not be relevant to the subject of the study. The investigation of the performance of the glulam material for this research involved the manufacturing of samples and experimentation of specimens that were conducted based on the provisions of ASTM D198 (2015) and ASTM D905 (1998).

The main objective of this study is to determine the possibility of Scots pine glulam timber being an alternative to conventional materials. One of the objectives of this study is to establish structural parameters for this species with respect to the Philippine context based on the test results, since this timber species is an imported species, and there are no parameters provided for this species that correspond to the Philippine standard. This study also aims to compare the allowable shear and bending properties with other species indicated in the National Structural Code of the Philippines as additional reference in the design of timber structural beams to determine whether it is compatible being a structural beam based on the systematic investigation conducted in this study.

II. Materials and Methods

The timber of *Pinus sylvestris* (Scots Pine) used for this research was imported from Ukraine according to the supplier and manufacturer of samples that were used for this study. The warehouse and office of the manufacturer is in San Mateo, Rizal. The pinewood used for this study is stored and kiln dried, reaching and maintaining a moisture content of approximately 12% to 15%.

A. Physical Characteristics of Pinus Sylvestris

Pinus sylvestris is native to most parts of Europe and is widespread in the Siberian region. The size of trees varies, depending on the climate of their location. Scots pine trees located near the Mediterranean Sea tend to grow shorter and have a smaller diameter compared to locations with high altitudes and cooler temperatures; hence, trees of this species within Portugal have smaller dimensions compared to those within Eastern Europe and Northern Asia. The height of Scots pine trees ranges between twenty meters (20 m.) to thirty-five meters (35 m.) tall, and its trunk diameter varies between six hundred millimeters (600 mm.) to one meter (1 m.) wide. The lumber modulus of rupture of this species has an average of 83.3 MPa, and its modulus of elasticity reaches an average of 10.08 GPa. (The Wood Database, 2022).

The heartwood of Scots pine is light reddish brown. The grain of this timber is straight with a medium, even texture. IUCN (2017) states that this species is reported as being of least concern, which indicates that the plantations and forestry for this timber species are still abundant. Common uses of this wood are mostly utility poles, posts, boxes/crates, architectural finishing, paper, and construction lumber, which makes it suitable for building framing. (The Wood Database, 2022).

B. Composition of glulam samples

Two laboratory tests are conducted for this study: Static bending for flexure and delamination for glue line strength. Different samples are used for testing the flexural properties and glue line strength of the Scots pine glulam.

The samples for determining the flexural properties of the glulam are produced in accordance with the prescribed dimensions from ASTM D198 (2015). One hundred forty (140) laminae are produced, each having dimensions of 50 mm. thickness, 100 mm. breadth, and 500 mm. length. A total of thirty-five (35) glulam flexure samples are produced from these laminae, each having four (4) laminae glued together using Polyvinyl Acetate (PVAc) adhesive between them. Each assembled flexure specimen contains a dimension of 50 mm. breadth, 100 mm. depth, and 500 mm. length (see **Figure 1**).

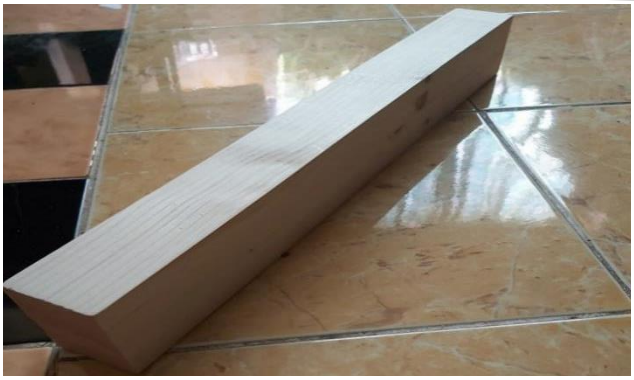

Figure 1. Actual image of flexure specimen.

The specimens for determining the glue line or adhesive strength of the glulam are manufactured in accordance with the dimensions indicated in ASTM D905 (1998). For this test, seventy-eight (78) laminae are made, each having dimensions of 50 mm. thickness, 20 mm. breadth, and 50 mm. length. Samples are assembled in accordance with the requirements of ASTM D905 (1998), where two (2) laminae are glued together using PVAc adhesive with an overlapping dimension of 5 mm. as shown in **Figure 2**. A total of thirty-nine (39) glulam shear specimens are produced from these laminae.

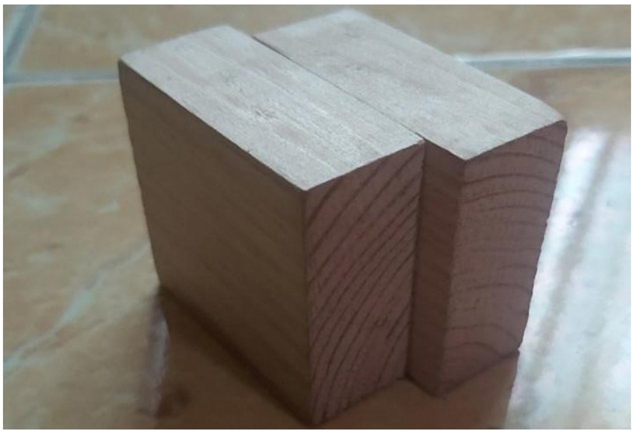

Figure 2. Prescribed dimension of shear and delamination specimen based on ASTM D905 (1998).

C. Characterization of Pinus Sylvestris glulam

Shear tests were conducted through the glue line to determine its strength until delamination in accordance with ASTM D905 (1998) as shown in **Figure 3**. Static bending tests were performed in accordance with ASTM D198 (2015) using the same method derived from ASTM D143 (2000), which uses the three-point method, where the force is applied at the midpoint of each specimen as shown in **Figure 4**.

Statistical formulas for measures of central tendencies and dispersion were used to determine the average values and adjustments of the parameters required for this study, which are all based on the results from the tests conducted within the specimens. Since Scots pine wood is an imported species of timber, reference values for this species are not included within the tabulation provided by the National Structural Code of the Philippines (NSCP) (ASEP, 2016). Hence, the reference values applicable in the Philippine context are determined using the internationally accepted methods provided by Rocafort & Siopongco (1991), which is still practiced for determining the reference values of Philippine timber indicated in the table of references in NSCP (ASEP, 2016).

Figures 3. Shear test procedure in accordance with ASTM D905 (1998).

Using the methods of Rocafort & Siopongco (1991) for determining the working stresses of different timber species, the weighted averages are first determined using the statistical methods for central tendencies and dispersion. The values are grouped accordingly with respect to **Table 1**, where the stress grade of wood is based upon the calculation of the reference values of the working stress of timber. Recommended average variability factors shown in **Table 2** are then applied for the different properties or parameters with respect to the testing conducted. Another set of reduction factors indicated in **Table 3** is applied for the derivation of basic stresses to introduce a factor of safety, which is an important consideration in terms of material strength in long-term usage. Lastly, working stresses are computed under each of the stress grades with respect to the strength group, which is accomplished by multiplying the basic stresses by the grade factors of 80%, 63%, and 50% respectively. The factor to be used for this step can be determined using the figures in **Table 4**. Hence, based on the aforementioned procedures, the reference or allowable strength values for this study are computed using the formula shown in **Equation 1**.

The reference values of the flexural and shear parameters are further investigated for the categorization of strength with respect to the strength grouping according to Alipon & Bondand (2008). This way, the recommended usage for Scots pine glulam can be determined with respect to the strength group provided in the said study. Strength classification for determining the recommended uses is based on the figures shown in **Table 5**.

To further verify this conclusion, a deeper investigation was conducted quantitatively through calculations in accordance with the formulas provided in the NSCP (ASEP, 2016) with the use of the prescribed adjusted values with respect to the methods by Rocafort and Siopongco (1991).

Figures 4. Flexure test procedure in accordance with ASTM D198 (2015).

Table 1. Minimum Values for the Three Governing Strength Properties (Rocafort & Siopongco, 1991)

	Strength Group			
	I	II	III	IV
Modulus of rupture in bending, MPa	77.2	63.1	48.7	38.7
Compression parallel to grain, MPa	37.6	29.0	22.4	17.8
Shear parallel to grain, MPa	10.0	7.02	6.13	4.87

Table 2. Recommended Average Variability Factors (Rocafort & Siopongco, 1991)

Modulus of rupture in bending	0.74
Modulus of elasticity in bending	0.75
Compression parallel to grain	0.70
Compression perpendicular to grain	0.61
Shear parallel to grain	0.68

Table 3. Additional Reduction Factors (Rocafort & Siopongco, 1991)

Modulus of rupture in bending	1/2.25
Modulus of elasticity in bending	1/1.00
Compression parallel to grain	1/1.75
Compression perpendicular to grain	1/1.00
Shear parallel to grain	1/2.25

Table 4. Stress-Grade according to Strength Group (Rocafort & Siopongco, 1991)

Strength Group	Stress-Grade
I	50%
II	63%
III	80%
IV	80%

$$F = P(V)(R)(G) \tag{1}$$

Where:
F Allowable stress
P Strength Parameter (Compression, MoE, MoR, etc.)
V Recommended average variability factor with respect to **Table 2**
R Additional reduction factor with respect to **Table 3**
G Grade factors (0.80, 0.63, 0.50)

Table 5. Additional Reduction Factors (Alipon & Bondad, 2008)

Property		Class of Timber				
		C1	C2	C3	C4	C5
	Moisture Condition	High	Moderately High	Medium	Moderately Low	Low
<u>Static Bending</u>						
Modulus of Rupture (MPa)	Green	78.43	61.76	49.02	39.22	30.88
	12%	126	98	78.4	61.8	49.0
Modulus of Elasticity (GPa)	Green	12.74	9.80	7.55	5.88	4.57
	12%	15.7	11.8	9.31	7.16	5.49
<u>Compression Parallel to Grain</u>						
Maximum crushing strength (MPa)	Green	39.22	29.90	23.03	18.14	13.72
	12%	63.7	49.0	37.7	29.8	22.6
<u>Compression Perpendicular to Grain</u>						
Stress at proportional limit (MPa)	Green	8.82	5.49	3.48	2.21	1.37
	12%	13.2	8.82	5.69	3.68	2.40
<u>Shear Parallel to Grain (MPa)</u>	Green	9.80	7.84	6.18	4.90	3.92
	12%	13.7	10.8	8.33	6.37	4.90
<u>Relative Density</u>	Green	0.67	0.54	0.45	0.37	0.30
	12%	0.71	0.58	0.48	0.39	0.32

The load-carrying capacity of the Scots pine glulam was computed by applying adjustment factors provided in the NSCP (ASEP, 2016). Computations were conducted using the Allowable Stress Design (ASD) method. The adjusted allowable flexure stress and modulus of elasticity were computed to determine the maximum load that could be applied to the material.

The adjustment factors were determined to be multiplied by the reference values, which were obtained from the test results and applied with the given factors in accordance with Rocafort and Siopongco (1991) using Equation 1, in order to compute the more critical values of the material capacity. The procedures for determining the adjustment factors were based on the formulas given in the National Structural Code of the Philippines (NSCP) (ASEP, 2015). The methods for computing the adjusted allowable bending and shearing stress of the material are indicated in **Table 6**.

Table 6. Adjustment factors for allowable shear and bending stresses of glulam beams (ASEP, 2016)

	Load Reduction Factor	Wet Service Factor	Temperature Factor	Beam Stability Factor*	Volume Factor*	Shear Reduction Factor
$F_b' = F_b$ x	C_D	C_M	C_t	C_L	C_V	
$F_v' = F_v$ x	C_D	C_M	C_t			C_{vr}

After determining the adjusted allowable flexural and shear properties of the material, the maximum force couple and the maximum shear force and moment force couple that the material can carry were determined using the formulas shown in **Equations 2 and 3**. These formulas are based on the National Structural Code of the Philippines (NSCP) (ASEP, 2015).

$$f_b = \frac{6M_{max}}{bd^2} \tag{2}$$

Where:
f_b Actual bending stress, MPa
M_{max} Maximum force-couple, N-mm
b Breadth of beam, mm
d Depth of beam, mm

$$f_v = \frac{3V_{max}}{2bd} \tag{3}$$

Where:
f_v Actual shear stress, MPa
V_{max} Maximum shear force, N
b Breadth of the beam, mm
d Depth of beam, mm

Although the formulas given in **Equations 2 and 3** are intended for actual stresses, it is assumed that the adjusted allowable stress is equal to the actual stress in this situation. Hence, the adjusted allowable values were substituted for these variables in order to determine the maximum capacities and limitations of the material in terms of shear, moment, and applied load. These formulas are derived algebraically, since the maximum shear and moment stresses were already determined, and the maximum load is necessary to be determined.

The maximum applicable combined load for this material was computed through the algebraical derivation of formulas shown in **Equations 4 and 5**, using the obtained values of shear force and moment couple that were determined using **Equations 2 and 3**. The formulas used in **Equations 4 and 5** correspond to the setup of the sample testing conducted for this study, which comprises a simply supported beam applied with a center. The determined maximum applicable combined load is also converted into units of mass to determine the maximum weight capacity of the glulam beam.

$$V_{max} = R = \frac{P}{2} \tag{4}$$

Where:
V_{max} Maximum shear force, N
R Reaction force, N
P Total combined load, N

$$M_{max} = \frac{PL}{4} \tag{5}$$

Where:
M_{max} Maximum force couple, N-mm
P Total combined load, N
l Length of beam, mm

D. Data Analysis

The experiments were conducted with respect to ASTM D905 (1989) and ASTM D198 (2015), with each sample tested in a random sequence. Thirty-five (35) and thirty-nine (39) samples were provided for the flexural and shear test respectively, and results for each specimen are determined upon emergence of movement or breakage of the sample (see **Figures 5 and 6**). The graphical illustration of the test results for both tests is provided by the testing facility, which are shown in **Figures 7 and 8.**

Flexure samples often resulted in tensile cracks at the bottom laminae or part of the specimen, and some resulted in shear cracks that are mostly evident near the glue lines. Delamination samples often resulted in shear cracks near the glue lines, though the separation of laminae is rarely seen. Thus, the experiment concludes that the (Polyvinyl Acetate (PVAc) adhesive is greatly compatible with the bonding of Scots pine.

Figure 5. Aftermath of Shear and Delamination Test in Accordance with ASTM D905 (1998).

Figure 6. Aftermath of Static Bending Test in Accordance with ASTM D198 (2015).

The mechanical strength parameters for this study were selected with respect to the relevance to the performance of structural beams. The test results provided the values of the modulus of rupture (MoR), modulus of elasticity (MoE), and stress at the proportional limit (SPL) for flexure specimens with respect to ASTM D198 (2015). Maximum shear parallel to the grain of beam samples was calculated using the equation prescribed by ASTM D198 (2015) with respect to the maximum force applied to the samples before material failure emerges. On the other hand, the values for maximum parallel load applied and shearing strength of glue lines were provided in the test results for the shear specimens with respect to ASTM D905 (1989). The average values for each parameter were calculated using statistical formulas for the measures of central tendencies and measures of dispersion.

The raw data provided by DOST-FPRDI (**Figures 7 and 8**) were necessary to determine measures of dispersion for each parameter. The mean value of each parameter is shown in **Table 7**. The standard deviation is necessary for indicating errors and adjustments in relation to the mean values of each parameter, which is also shown in **Table 7**.

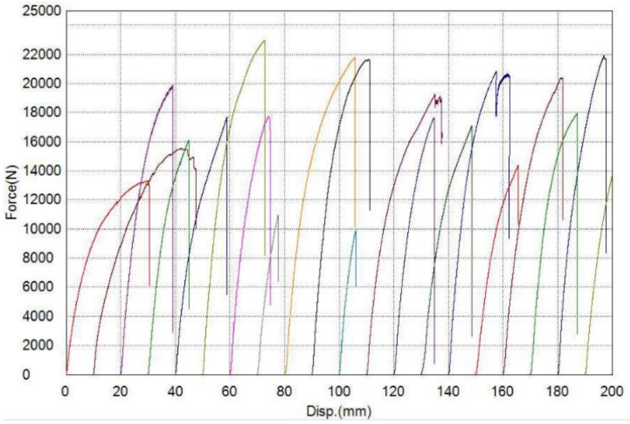

Figure 7. Graphical Results of the Shear Test in Accordance with ASTM D905 (1998).

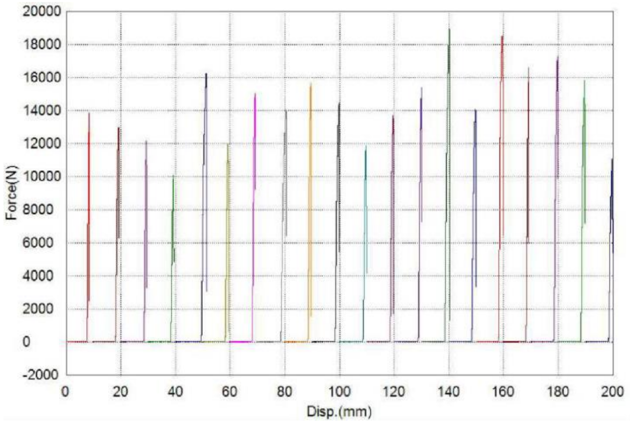

Figure 8. Graphical results of Static Bending test in accordance with ASTM D198 (2015).

Measures of central tendencies are shown in **Table 7**, which indicates the frequency of each class and distribution for each parameter. These are illustrated in **Figures 9 to 12**. The distribution of frequencies in the parameters in the shear test represents a normal distribution as shown in **Figure 9**, where the largest frequencies are distributed at the middle classes of variables, while the distribution of frequencies in the parameters within the static bending test is skewed on the left as shown in **Figures 10 and 12**, which indicates that the average of the variables represented by the majority of the samples are classified above the middle class.

The capacity of Scots pine glulam timber was determined after calculating the average values of each parameter, which were obtained from the test results and its statistical analysis. The objective of this method of analysis is to determine the maximum load that Scots pine glulam timber can carry. The reference values for shear and bending can be obtained by calculating the shear and bending capacity of the material indicated in **Equation 1**, which was based on the methods provided by Rocafort & Siopongco (1991). According to the methods provided, the application of adjustment factors is necessary so that the reference value could consider the most stringent situation in the long run.

Table 7. Mean, Standard Deviation, and CoV from Test Results

	Mean (± Standard Deviation)	Coefficient of Variance
Maximum Flexural Stress, MPa	64.66 ± 10.43	0.16
Modulus of Elasticity, GPa	5.31 ± 0.76	0.14
Maximum Shear Parallel to Grain, MPa	3.63 ± 0.47	0.13
Maximum Shear along Glue Line	7.79 ± 1.12	0.14

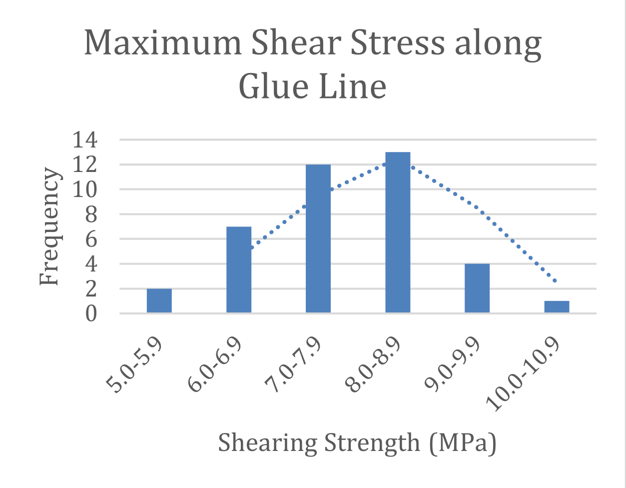

Figure 9. Statistical Distribution of Max Shear Stress along Glue Line on Test Results

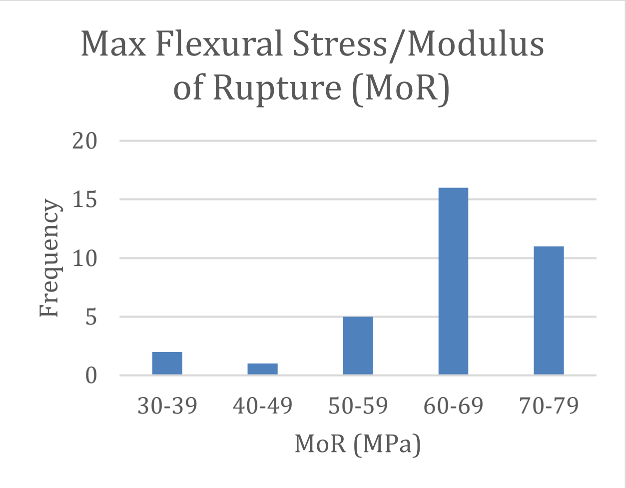

Figure 10. Statistical Distribution of Max Flexural Stress/Modulus of Rupture Based on Test Results

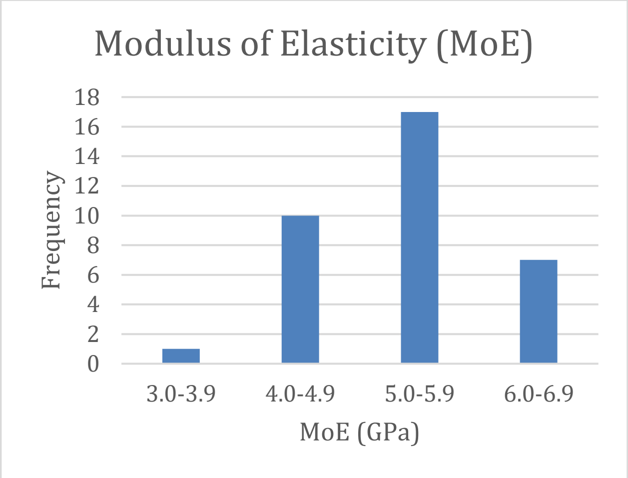

Figure 11. Statistical Distribution of Modulus of Elasticity Based on Test Results

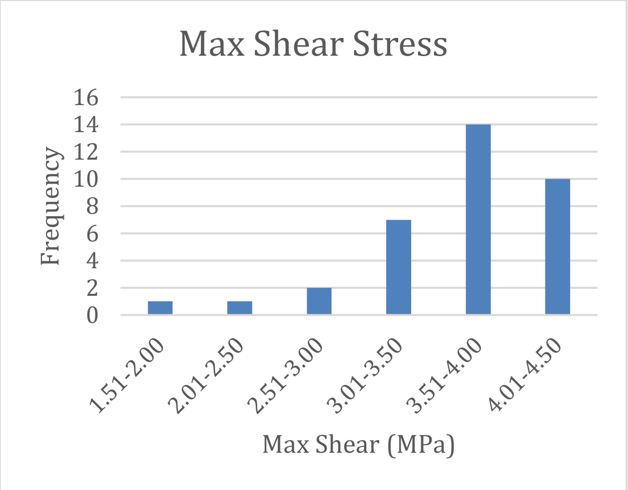

Figure 12. Statistical Distribution of Max. Shear Parallel to Grain Based on Test Results

The graphs in **Figures 13 to 15** illustrate the linear regression of the flexural properties of the Scots pine glulam beams, showing the relationship between the Scots pine glulam beam parameters and the size of the component. These parameters are usually affected by the proportion of the length of the beam with its cross-sectional area, especially its depth. However, since the length of all the beam samples is the same and the cross-sectional areas of each sample vary, the parameters therefore shown in the linear regression graphs in **Figures 13 to 15** relate the beam parameters to the cross-sectional area.

The coefficients of correlation, R, and determination, R^2, were also determined to have an in-depth interpretation of the linear regression graphs using the data obtained from the test results. The coefficient of correlation corresponds to the direction of the trendline of the linear regression, as well as the intensity of the relationship between the two factors. The coefficient of determination, on the other hand, shows how the dependent variable is accounted for by the independent variable.

The coefficient of correlation was calculated using the two related factors as both variables for this equation. The coefficient of determination (R^2) was determined by squaring the value of the coefficient of correlation (R). In this study, the physical dimensions of the beam samples were used as the independent variable for this equation, and the structural parameters were used as the dependent variables. The coefficients of correlation and determination explain the relationship between the dimensions of the beam and its strength.

Figure 13 indicates the relationship between the cross-sectional area of the beam and its modulus of elasticity. The graph explains that the modulus of elasticity of the beam decreases when its cross-sectional area increases. This is probably due to the thickness of the laminae or the amount of adhesives applied to the glulam beam as explained in the article by Kilincarslan and Turker (2019). It can be explained mathematically by analyzing the formula for deflection, shown in **Equation 6**; if the formula is derived algebraically, the cross-sectional area is inversely proportional to the modulus of elasticity of the beam, which explains the increase of the modulus of elasticity as the cross-sectional area decreases.

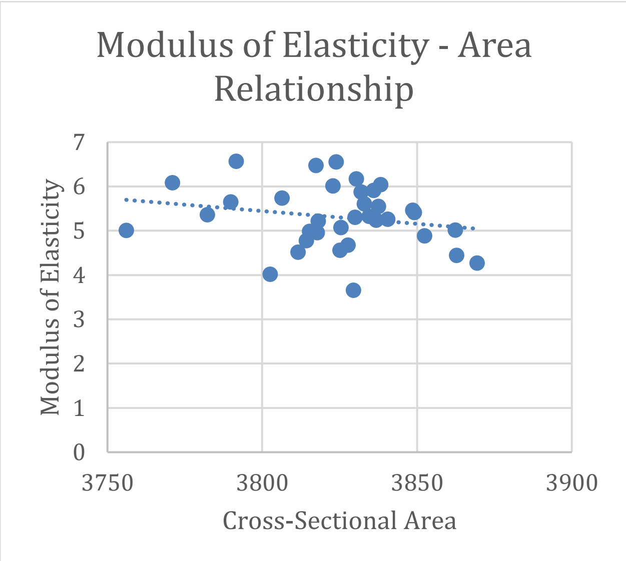

Figure 13. Linear Regression for MOE and Cross-sectional Area Relationship

$$\delta = \frac{PL}{AE} \quad (6)$$

Where:

δ	Deflection, mm
P	Max Force, N
L	Beam Length, mm
A	Cross-Sectional Area, mm^2
E	Modulus of Elasticity, GPa

The independent variable for the linear regression in **Figure 13** is the cross-sectional area, and its dependent variable in this graph is the modulus of elasticity. With the use of Equation 3, the coefficient of correlation resulted in -0.20, in which the negative value of this coefficient justifies the downward direction of the regression line. However, the absolute value of the coefficient of correlation shows a weak relationship between the cross-sectional dimension and the modulus of elasticity. The coefficient determination for **Figure 13** states that the cross-sectional dimension accounts for only 4.15% of the beam's modulus of elasticity

The graph shown in **Figure 14** indicates the relationship between the cross-sectional area of the beam and its flexural stress capacity. The graph shows an upward trendline, in which the flexural capacity of the beam can be increased by also increasing its cross-sectional area, which is also the general principle of determining stresses. However, Kilincarslan and Turker (2019) mentioned in their article that the beam may still be affected by the amount of adhesive applied to the glulam beam as well as the type of adhesive used for the lamination process as indicated in the articles of Segundinho, et al. (2015) and Mirski, et al. (2020). The formula in **Equation 7** may be used as a basis to mathematically explain the relationship between the bending capacity and the cross-sectional dimensions of the beam, although **Equation 7** provides the formula for actual bending stress. **Equation 7** is the formula for determining the modulus of rupture according to ASTM D198 (2015), which also has the same formula for the actual bending stress provided in the National Structural Code of the Philippines (NSCP) (ASEP, 2016). **Equation 7** shows that the actual stress acting in the beam is inversely proportional to the cross-sectional area, especially the depth, of the beam, which explains that the actual stress can be reduced by increasing the cross-sectional dimensions of the beam, especially its depth. Logically, since the actual bending stress is decreased by increasing the cross-sectional dimensions of the beam due to the actual stress being inversely proportional to the allowable stress, the allowable bending capacity of the beam would be directly proportional to the cross-sectional area of the beam, thus explains the relationship shown in the graph in **Figure 14**.

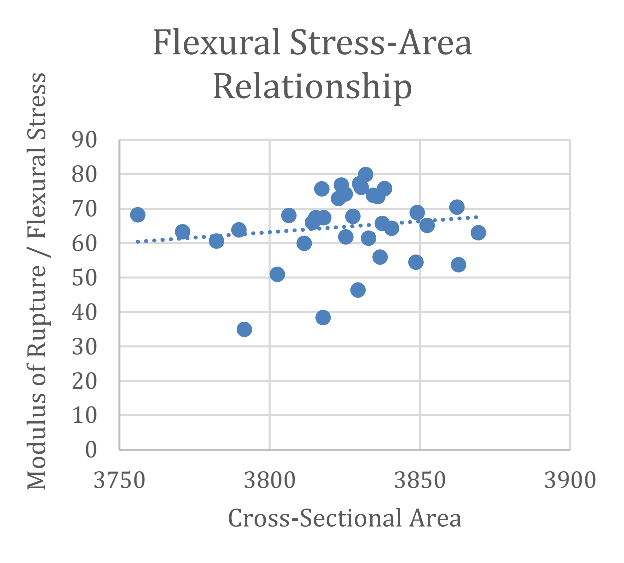

Figure 14. Linear Regression for MOR and Cross-sectional Area Relationship

$$f_b = S_R = \frac{Mc}{I} = \frac{6M_{max}}{bd^2} \quad (7)$$

Where:

f_b	Actual bending stress, MPa
M_{max}	Maximum moment couple, N-mm
b	Breadth of beam, mm
d	Depth of beam, mm

.

The independent variable for the linear regression in **Figure 14** is the cross-sectional area, and its dependent variable in this graph is the modulus of rupture or bending strength. With the use of Equation 3, the coefficient of correlation resulted in a positive value of 0.15, in which the positive value of this coefficient justifies the upward direction of the regression line shown in the graph. However, the value of the coefficient of correlation also shows a weak relationship between the cross-sectional dimension and the modulus of rupture. The coefficient determination for **Figure 14** states that the cross-sectional dimension accounts for only 2.18% of the beam's bending strength.

Figure 15 indicates the relationship between the cross-sectional area of the glulam beam and its shear stress capacity. The graph also shows an upward trendline, in which the shearing capacity of the beam can be increased by also increasing its cross-sectional dimensions. Shear in glulam beams may occur in either the glue lines or the wood grain, which is why a delamination test in accordance with ASTM D905 (2003) is necessary for this study. The choice of adhesive may also be a factor in the shearing capacity of the beam, which is also indicated in the experimentation of Segundinho, et al. (2015). However, the shearing stress parallel to the direction of wood grain and glue lines in this graph is caused by forces perpendicular to their directions, in which such delamination and shear are caused by bending stresses. The relationship between the shear capacity and the cross-sectional size of the beam may be mathematically validated by analyzing the formula for determining the beam shear shown in **Equation 8**, which is provided in ASTM D198 (2015) for determining the shear capacity based on the force applied to the samples and their respective cross-sectional dimensions. **Equation 8** provides the amount of actual shear based on the applied forces, in which the actual shear is inversely proportional to the cross-sectional area of the glulam beam. Therefore, the actual shear stress may be reduced by increasing the cross-sectional area, which explains the direct relationship between the allowable shear capacity of the beam and the cross-sectional area as illustrated in the graph in **Figure 15.**

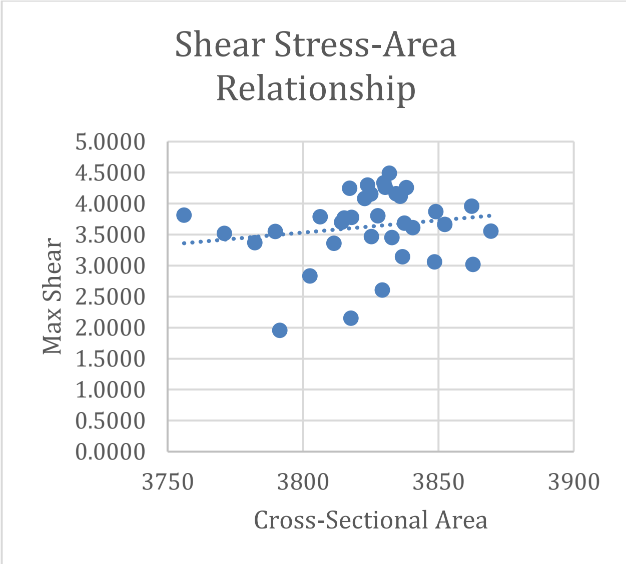

Figure 15. Linear regression for Maximum Shear and Cross-sectional Area Relationship

$$f_v = \frac{3P_{max}}{4bd} \quad (8)$$

Where:

f_v	Shear stress, MPa
P_{max}	Maximum applied force, N
b	Breadth of beam, mm
d	Depth of beam, mm

The independent variable for the linear regression in **Figure 15** is the cross-sectional area, and its dependent variable in this graph is the maximum shear capacity of the beam. With the use of Equation 3, the coefficient of correlation resulted in a positive value of 0.16, in which the positive value of this coefficient justifies the upward direction of the regression line shown in the graph in **Figure 15**. However, the value of the coefficient of correlation still shows a weak relationship between the cross-sectional dimension and the maximum shear capacity of the beam. The coefficient determination for **Figure 15** states that the cross-sectional dimension accounts for only 2.70% of the beam's shear strength.

In conclusion to the linear regression, the cross-sectional dimension affects the structural performance of the beam, but in the design of timber structural beams, it only accounts for a small percentage of the beam's performance.

The great contributor to the beam's strength is most likely the selected wood and its adhesive (Kilincarslan & Turker, 2019). The beam strength may be affected by other factors, such as additional reinforcement that may be provided between laminations (Ramage, et al., 2017).

III. Results and Discussion

A. Physical Properties of Wood

The wood and laminae used for the production of test specimens contain a moisture content (MC) of 12-15%, which it is still within the desired range of moisture content for lumber. Comparing some of the physical properties and characteristics of Scots pine (*Pinus sylvestris*) with other selected Philippine timber species as shown in **Table 8**, the timber itself has higher characteristics in terms of flexure (Konofalska, et al., 2020) and Modulus of Elasticity (MoE) (The Wood Database, 2022) compared to the Philippine pine species, Gmelina, and Sasalit, the hardest wood species available in the country according to the National Structural Code of the Philippines (NSCP) (ASEP, 2016).

Categorizing the mechanical properties of the Scots pine sawn lumber with respect to the classification of timber by Alipon & Bondand (2008), Scots pine (Pinus sylvestris) will only fall under C5 (Low) class timber, which is suitable only for light construction where strength, hardness, and durability are not critical requirements. Due to the limited dimensions of this species, it may be used as moldings, doors, window sashes, drywall framing, and other lightweight construction.

B. Flexural Properties of Scots Pine Glulam

According to ASTM D198 (2015), the modulus of rupture is congruent to the value of flexural stress of a beam. **Table 7** shows that the average modulus of rupture for Scots pine glulam with cross-sectional dimensions of 50 millimeters and 100 millimeters and a length of 500 millimeters is 64.66 MPa, which is therefore the value of the average flexural stress of the material.

Using the formula in **Equation 1** with respect to the methods by Rocafort & Siopongco (1991), the reference flexural stress for Scots pine glulam of this size, reference modulus of elasticity, and reference shear stress parallel to grain were determined. Categorizing this material based on this result with respect to the Classification of Timber by Alipon & Bondad (2008) shown in **Table 5**, this material falls beyond the low class, which concludes that Scots pine glulam timber of this proportion would not be suitable to carry loads as a structural beam.

Table 8. Consolidated Measures of Dispersion from Both Shear and Flexure Test Results

	Pinus Sylvestris (Scots Pine)	**Pinus spp.**	**Gmelina arborea (Yemane)**	**Sasalit (Tejimanniodendron ahemianum)**
	80% Stress Grade			
Max Shear Parallel to Grain (F_v), MPa	**0.88**	1.56 (-43.59%)	1.96 (-55.10%)	3.38 (-73.96%)
Max Flexural Stress (F_b), MPa	17.01	14.7 (+15.71%)	12.6 (+35.00%)	31.3 (-46.65%)
Modulus of Elasticity (E), GPa	3.19	6.66 (-52.10%)	4.09 (-22.00%)	9.72 (-67.18%)
	63% Stress Grade			
Max Shear Parallel to Grain (F_v), MPa	0.69	1.23 (-43.90%)	1.55 (-55.48%)	2.67 (-74.16%)
Max Flexural Stress (F_b), MPa	**13.40**	11.6 (+15.52%)	9.90 (+35.35%)	24.7 (-45.75%)
Modulus of Elasticity (E), GPa	**2.51**	5.24 (-52.10%)	3.32 (-24.40%)	7.65 (-67.19%)
	50% Stress Grade			
Max Shear Parallel to Grain (F_v), MPa	0.55	0.98 (-43.88%)	1.23 (-55.28%)	2.12 (-74.06%)
Max Flexural Stress (F_b), MPa	10.63	9.19 (+15.67%)	7.86 (+35.24%)	19.6 (-45.77%)
Modulus of Elasticity (E), GPa	1.99	4.16 (-52.16%)	2.55 (-21.96%)	6.08 (-67.27%)

According to the reference design values shown in **Table 8**, Scots pine has shown lower reference elasticity compared to the Philippine pine species by around 52%, Gmelina by 22-24%, and Sasalit by 67%. The magnitude of the reference shear parallel to grain within the Scots pine is weaker than the Philippine pinewood species by 44%, Gmelina by 55%, and Sasalit by 74%. Both shear and elastic parameters shown in Table 17 imply that Scots pine glulam is significantly weaker than the other species in terms of shear parallel to the direction of grain and flexure, even though the material is a glulam component. However, the comparison in Table 17 shows that Scots pine is relatively stronger than the Philippine pinewood species by 16% and Gmelina in terms of flexural capacity by 35%; its reference bending stress capacity is significantly weaker than Sasalit by 46%.

Table 9 indicates that the bending stress of the Scots pine glulam beam in this study is higher than the result in the analysis of Mirski, et al. (2020) by 45%, but the modulus of elasticity in this study is lower than the results in their study by 62%. Comparing the characteristics and properties of the beams from both studies, the major factor for these results is the adhesives applied in the lamination of the glulam beams. The glulam beams applied with Polyvinyl Acetate

(PVAc) adhesives contain stronger flexural capacity, but melamine-urea formaldehyde adhesives with hardeners contribute to a higher modulus of elasticity of the glulam beams. However, both beams do not reach the minimum strength required to be categorized under Class V according to the strength categorization by Alipon and Bondad (2008), which is shown in **Table 5**; hence, the beams from both studies are not recommended for being incorporated as a structural beam, unless advanced innovations in strengthening the glulam members through additional reinforcement are applied as mentioned in the articles of Malo (2016) and Ramage, et al. (2017).

Table 9. Comparison Between Acquired Stress Value of Scots Pine with PVAc Adhesive and Results by Mirski, et al. al. (2020) Using MUF Adhesive with Hardener.

	Average Unadjusted Values from Test Result	
	Acquired Test Results	Mirski, et. al. (2020)
Max Flexural Stress (F_b), MPa	64.66	44.6 (+44.98%)
Modulus of Elasticity (E), GPa	5.31	14.08 (-62.29%)

C. Structural Performance of Scots Pine Glulam

The most stringent reference design stress values for each parameter based on the strength grouping by Rocafort and Siopongco (1991) which were calculated from **Equation 1,** shown in **Table 8**, are multiplied to the necessary adjustment factors given in the National Structural Code of the Philippines (NSCP) (ASEP, 2016) and ASTM D3737 (2003) shown in **Table 6** in order to determine the adjusted allowable stress for the Scots pine glulam beam. The formulas in **Equations 2 to 5** were then derived algebraically to determine the maximum shear force, moment force couple, and allowable combined load using these adjusted allowable stress values in order to determine the weight that the Scots pine glulam beam can carry.

Upon obtaining the maximum shear, moment, and load capacities of the Scots pine glulam beam, which were derived from the adjusted allowable shear and bending stresses using the reference stress values in Table 8 applied with the necessary adjustment factors in Table 6, the analysis of the material's capacity resulted in a stringent combined applicable load of 2,551.94 Newtons, which is equivalent to a converted value of mass of 260.14 kilograms. The obtained maximum weight of the Scots pine glulam beam is analogously equivalent to four times (4x) the average weight of persons, which defines that it could not really carry much load to be incorporated into a structural beam. Thus, this quantitatively justifies the classification of strength by Alipon and Bondad (2008), which indicates that Scots pine glulam beams with Polyvinyl acetate (PVAc) adhesive are categorized below Class V timber strength unless otherwise reinforcements will be applied between the laminations to increase its strength, but this method requires another set of testing and investigation.

IV. Conclusion and Recommendations

The structural parameters for the flexure and shear, particularly modulus of elasticity, bending stress, and shear parallel to grain, of Scots pine glulam timber structural beam with polyvinyl acetate adhesives (PVAc) were established in this study. The test results indicated that Scots pine with PVAc adhesive contains a glue strength of 7.79±1.12 MPa, bending strength of 64.66±10.43 MPa, maximum shear parallel to grain of 3.63±0.47 MPa, and MOE of 5.31±0.76 GPa, which were gathered from the testing of specimens in accordance with ASTM D905 (2003) for shear capacities of the glue line and ASTM D198 (2015) for flexure capacities of the beam. After a thorough investigation with the aid of quantitative validation using the formulas and equations provided in the Design Standards by Rocafort & Siopongco (1989) and the National Structural Code of the Philippines (NSCP) (ASEP, 2016), the result of the analysis shows that the modulus of elasticity, bending stress capacity, and shear stress capacity parallel to the grain of the Scots pine glulam timber with polyvinyl acetate (PVAc) adhesive contain values of 2.51 GPa, 13.40 MPa, and 0.88 MPa respectively, which were significantly lower compared to the sawn lumber of the same species (Konofalska, et. al, 2020 and The Wood Database, 2022).

The adjusted reference shear stress parallel to the grain of Scots pine glulam beam with PVAc adhesive is lower than the Philippine pine species by 44%, Gmelina by 55%, and Sasalit by 74%. Its adjusted reference bending stress is higher than the Philippine pine species by 16% and Gmelina by 35% but lower than Sasalit by 46%. Lastly, its adjusted reference modulus of elasticity is lower than the Philippine pine species by 52%, Gmelina by 24%, and Sasalit by 67%. Overall, despite being a glulam beam, it is weaker and from the several selected species probably due to the plasticity of adhesives that are applied between each lamina. The reference values of the Scots pine glulam timber specimens were categorized in accordance with the classification of timber by Alipon & Bondad (2008), and the results show that the glulam is beyond the Class V (Low) category, which is not suitable for structural beams.

Another study was conducted by Mirski, et al. (2020), which also investigated Scots pine glulam beam, but melamine-urea formaldehyde (MUF) with hardener was applied for the lamination process. Though a full-scale beam was conducted in their study, the results were compared to the obtained value in this study. The results in both studies show that Scots pine glulam with PVAc adhesive is stronger than those with MUF in terms of bending strength by 45% but weaker in terms of elasticity by 62%. Both obtained values of glulam strength did not meet the minimum required strength by Alipon and Bondad (2008) to be classified as Class V (Low), which is not suitable for construction use.

Upon further investigation, the adjusted allowable stresses were determined by the application of necessary adjustment factors to the reference stress values that were derived through the methods of Rocafort and Siopongco (1991). The allowable stresses were computed using the adjustment factors with respect to allowable stress design (ASD) methods. The mathematical validation showed that Scots pine glulam beam with PVAc adhesive could only carry a load of 2.55 kilonewtons, which is equivalent to 260.14 kilograms of mass. This result validates the strength classification of the material with respect to Alipon and Bondad (2008), which concludes that Scots pine glulam with PVAc adhesive is not suitable for partial replacement to suspended structural beams.

Therefore, not all glue-laminated members are stronger than the sawn lumber, as it depends on the adhesive used, as well as the number of layers within the glulam members. However, flexure tests as well as delamination tests are enough to assess the strength of the glulam beams, in which no other tests are necessary to evaluate the structural performance of glulam beams. In addition, the number of layers of lamination in glulam beams is one factor that affects the strength of the beam, which is proven in the comparative analysis between the result of this study and the results from Mirski, et al. (2020).

This study recommends further investigation of the material, and applying other available adhesives other than PVAc and MUF. This study also recommends conducting testing of beams with various layers of lamination to determine the effect of the number of laminations on the structural parameters of beams. It is also recommended to investigate Scots pine glulam applying reinforcements between laminations.

This study may be used as an initial basis for further studies towards an in-depth investigation of the structural properties of Scots pine glulam beams. Upon validation of the aforementioned results through quantitative methods, this study also suggests that the parameters for the structural design of Scots pine, which is not indicated in the National Structural Code of the Philippines due to being an imported species, particularly glued-laminated timber, can be used as a basis for academic reference and further studies of this species relevant to the Philippine context. Further analysis and quantitative validations are worth looking into for other parametric investigations for succeeding research and studies.

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