Experimental Investigation of Galvanized Steel Sheet-Wrapped Structural Moso Bamboo as an Element of a Hybrid Beam

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Abstract: - One of the investigation's main objectives is to serve as a turning point for rediscovering the potential of bamboo in Philippine construction. The researchers opted to use steel sheets to reinforce bamboo. The study sought to evaluate the effects of steel sheet wrapping by welding on the flexural strength of bamboo as a structural element of beams. bamboo culms were harvested, cut, dried, treated, and wrapped in galvanized steel sheets in three methods. The research had three different wrapping methods as variables, namely whole vertical, horizontal strip, and vertical strip wrap, applied to the bamboo specimens. Eighteen produced steel sheet-wrapped structural bamboo samples and six treated unwrapped control samples were subjected to three-point bending tests and four-point bending tests. The results showed that the addition of steel sheet wrapping by welding significantly increased the flexural strength of bamboo. The SSWB samples were found to be 1.2 to 2.5 times stronger than the control samples. Furthermore, the study found that the vertical strip and whole vertical wrapping methods were the most efficient among the three methods, with the highest flexural strengths in both bending tests. In contrast, the horizontal strip wrap method was found to be the least efficient. It is also observed that samples with smaller inner diameters were more capable of withstanding flexural tendencies. In conclusion, steel sheet wrapping can significantly increase the flexural strength of bamboo, with the vertical strip and whole vertical wrapping methods being the most efficient. These findings will be able to contribute to developing stronger, more durable, and sustainable bamboo structures, particularly in areas where bamboo is a widely available and sustainable resource.

Key Words: — *Bamboo, Steel sheet, Wrapping, Flexural Investigation.*

I. Introduction

Concrete has been used for construction since the Roman Era and even much earlier but was not reinforced and had a very low tensile strength. French industrialist Francois Coignet introduced Iron on a widespread scale as a reinforcing element to concrete.

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In the late 1870s, Francois Hennebique of Paris also started to build reinforced concrete houses (Prasad, 2019).

Today, reinforced concrete is the typical type of foundation in the Philippines' construction industry (Berto, 2022). But according to Regal Industrial (2023), even before the use of reinforced concrete, Filipinos used bamboo, mud, clay, rocks, wood, bricks, and blocks to put up their shelters that provide safety in daily living. According to Datta & Mali (2020), the majority of housing and infrastructure projects being built today use conventional materials like steel and concrete, and this trend has grown over the last twenty years.

According to Pandit et al. (2020), to fulfill the demands of our expanding population, global demand for crude steel is projected to climb by 1.5 times by 2050, reaching 1,808.6 million tons in 2018. EPA (2022), also stated that the cement sector is the third largest industrial source of pollution, emitting more than 500,000 tons per year of sulfur dioxide, nitrogen oxide, and carbon monoxide.

However, aside from the environmental effects of steel and cement production, it has also economic impacts. As explained by International Trade Administration (2019), the Philippines is the 17th largest steel importer worldwide. The country imported 9.1 million metric tons of steel in 2018 which is an 11% increase from 8.1 million metric tons in 2017. The increasing demand for sustainable building materials has led to a growing interest in the use of bamboo as a structural element.

Bamboo is an organic material that belongs to the grass family. Several Bamboo species can be found in the tropical and subtropical regions, mainly Asia, Africa, and America. It is the fastest growing plant on Earth at a rate of 1.5 inches per hour and the plant just needs 3-5 years to maturity which means that the grass is a rapidly renewable resource. In addition to that, Bamboo absorbs twice as much as Carbon Dioxide trees. Bamboo forests or groves can help to absorb the greenhouse gases from air pollution making them Carbon sinks (Simply Organic Bamboo, 2021).

The microfiber structures of Bamboo are lignin and hemicellulose (lignin-carbohydrate complex (LCC)), which play a significant role in mechanophysical characteristics of bamboo in flexural strength that contribute to having greater strength than concrete and steel by weight. In addition to that, bamboo has a low density (1.4 g/cc), has high mechanical properties, and can show high tolerance against pressure and bending. In addition to that, because of its distinctive and unique traits, the demand for bamboo and the items made from it have very high tensile strength. Bamboo has 28,000 pounds psi which is significantly heavier than steel which has 23,000 psi. The topic under consideration is a description of bamboo's special properties and potential uses (Kaur, 2018).

According to Nayak et al. (2013), bamboo that has undergone industrial treatment has demonstrated considerable potential for the development of composite materials and components that are affordable and may be used successfully for structural and non-structural applications in the building industry. New processing techniques are required to make bamboo more resilient and useful as a building material in light of innovation and engineering advancements and the limited supply of building materials. Experiments have shown that some species of bamboo have ultimate tensile strengths that are comparable to mild steel, ranging from 140 N/mm2 to 280 N/mm2.

About 2000 years ago, Bamboo Scaffolding was considered to have properties such as an increase in safety from the practical experience of workers, resistance to moisture, low cost, and high adaptability (Ding et al., 2020). Bamboo existed in Filipino culture way before the Spanish Colonial Era. It is the main material used for the traditional houses in the Philippines which are also called "Bahay Kubo". For other types of houses, it was used as a column, reinforcement, beam, joint, walls, and flooring in such ways as a whole culm or longitudinal cuts.

The use of domestic bamboo construction techniques is now somewhat limited, and bamboo construction is still in its early stages of development. Bricks and concrete are currently the main building materials used in rural areas (Xinping et al., 2018).

Despite Bamboo's popularity in Southeast Asia as a construction material, it is not widely accepted in the Philippines as an alternative to steel and concrete. Regardless of the geographical and cultural relevancy of bamboo in the country, the claim is based on the National Structural Code of the Philippines and the lack of related literature on Bamboo to suffice its effectiveness.

The researchers opted to use steel sheets to be wrapped around the bamboo which aimed to improve the flexural capacity and to rediscover the potential of bamboo. In addition to that method, the researchers identified processes to do to enhance the potential of bamboo in the Philippines' construction industry. Such processes were identified by the researchers as initial drying, termite, insect, and fungi resistance treatment, steel sheet wrapping for added flexural strength, and weather and fire resistance. The researchers conducted this study to investigate the flexural capacity of Steel Sheet-Wrapped Bamboo (SSWB) as an element of hybrid beams.

II. METHODOLOGY

The wrapping techniques on the bamboo samples were the variables in the study. The whole vertical wrap, vertical strip wrap, and horizontal strip wrap were the three different wrapping methods utilized to determine the most efficient wrapping method on the bamboo specimen. The bamboo species that was used in this study is the *Moso* bamboo with a length of 815 mm and diameters ranging from 90 mm to 118 mm. Galvanized steel sheet with a 1.0 mm thickness was used as the wrapping material. Before wrapping the bamboo samples, the specimens were initially dried for 30 days and then cold soaked for 14 days in the mixture of 6% borax, 4% of boric acid, and 90% of fresh water, and then sun-dried in a vertical stack for three days. The dried bamboo culms were wrapped using the galvanized steel sheet. The dimensions of the steel sheets were 4 ft by 8 ft by 1 mm thick. The steel sheet cuts for wrapping were 20 mm wider than the lateral area of the bamboo to allow for overlap to secure the weld. GPO 6013 welding rods were utilized as binding agents to secure the steel sheets to the bamboo culms. The welding rods were carefully placed to ensure maximum contact and adhesion between the steel sheet and the bamboo culm. After welding, the samples were inspected for any defects such as cracking or lack of fusion to secure the weld of the steel sheet.

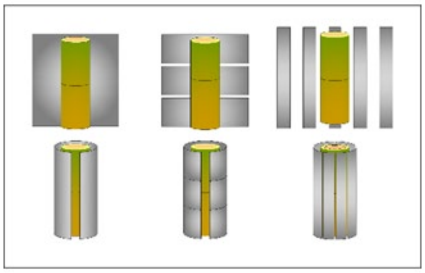

Fig.1. Three Different Wrapping Methods

Various tests were made in order to obtain the needed data for the study. The flexural test (also known as the bending test) is a mechanical test performed on a material to determine its flexural strength and modulus of elasticity. In this test, a specimen is supported on two points and subjected to a force applied at point/s located between the two supports, causing the specimen to bend. The three-point and four-point bending tests were used in this study. In the 3-point bending test, the load is applied at the center of the clear span of the beam, creating a region of tensile stress on the bottom of the sample and a region of compressive stress on the top. On the other hand, the Four-Point Bending Test is similar to the Three-Point Bending Test, but it applies load at two points on each side of the sample. Moreover, the standard code for testing bamboo that was used in the study is the ISO 22157.

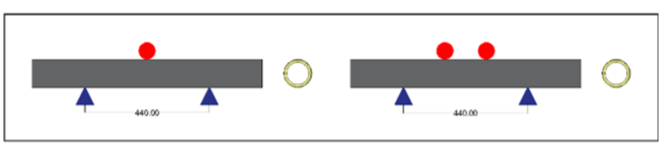

Fig.2. Three-Point Bending Test (left) and Four-Point Bending Test (right)

The figure below exhibits the procedure of how the researchers will execute the process of creating and evaluating the galvanized steel sheet-wrapped bamboo as a structural element.

Fig.3. Production Procedure

2.1 Three-Point Bending Test on Steel Sheet-Wrapped Bamboo

The three bamboo samples with three different methods of wrapping have undergone Three-Point Bending Tests to determine their durability and strength as an element of a hybrid beam.

1. Whole Vertical Steel Sheet-Wrapped Bamboo
2. Horizontal Strip Steel Sheet-Wrapped Bamboo
3. Vertical Strip Steel Sheet-Wrapped Bamboo

Table.1. Dimensions of SSWB for Three-Point Bending Test

WRAPPING/ NAME	DIMENSIONS (MM)				NO. OF SPECIMEN
	LENGTH	DIAMETER		THICKNESS	
		OUTER	INNER		
Whole Vertical Wrap	815	87.8 - 113.4	73.6 – 97.3	7.1 – 8.1	3
Horizontal Strip Wrap	815	105.7 – 126.3	87.8– 107.5	8.9 – 9.4	3
Vertical Strip Wrap	815	79.2 – 103.6	55.1 – 79.4	10.6 – 12.1	3

2.2 *Four-Point Bending Test on Steel Sheet-Wrapped Bamboo*

The three bamboo samples with three different methods of wrapping have undergone four-point bending tests to determine their durability and strength as an element of a hybrid beam.

1. Whole Vertical Steel Sheet-Wrapped Bamboo
2. Horizontal Strip Steel Sheet-Wrapped Bamboo
3. Vertical Strip Steel Sheet-Wrapped Bamboo

Table.2. Dimensions of SSWB for Four-Point Bending Test

WRAPPING/NAME	DIMENSIONS (MM)				NO. OF SPECIMEN
	LENGTH	DIAMETER		THICKNESS	
		Outer	Inner		
WHOLE VERTICAL WRAP	815	89.0 – 98.1	72.0 – 72.7	8.2 – 12.8	3
HORIZONTAL STRIP WRAP	815	102.7 – 111.3	83.3 – 97.4	6.9 – 13.4	3
VERTICAL STRIP WRAP	815	107.1 – 119.2	88.2 – 100.5	8.3 – 9.4	3

III. RESULTS AND CONCLUSION

3.1 *THREE-POINT BENDING TEST RESULTS*

Table.3. Three-Point Bending Test Results (Whole Vertical Strip Wrap)

SAMPLE CODE	MOMENT OF INERTIA *(mm⁴)*	CLEAR SPAN LENGTH *(mm)*	ACTUAL DIMENSIONS *(mm)*			MAX LOAD *(N)*	FLEXURAL STRENGTH σ_{ult} *(MPa)*
			DIAMETER		THICKNESS		
			OUTER	INNER			
W1	1473550.1	440	87.8	73.6	7.1	5640	18.48
W2	1865726	440	96.7	83.9	6.4	5020	14.31
W3	3725655.7	440	113.4	97.3	8.1	5920	9.91

Table 3 shows the results of the three-point bending test of the bamboo samples wrapped using the whole vertical wrapping method. The outcome of the test illustrates that the sample with the smallest inner diameter obtained the highest flexural strength, while the sample with the largest inner diameter acquired the lowest flexural strength value.

Table.4. Three-Point Bending Test (Horizontal Strip Wrap)

SAMPLE CODE	MOMENT OF INERTIA *(mm⁴)*	CLEAR SPAN LENGTH (mm)	ACTUAL DIMENSIONS *(mm)*			MAX LOAD *(N)*	FLEXURAL STRENGTH σult *(MPa)*
			DIAMETER		THICKNESS		
			OUTER	INNER			
H1	5917802.6	440	126.3	107.5	9.4	6510	7.64
H2	5228390.2	440	121.0	101.9	9.5	5230	6.66
H3	3194252.2	440	105.7	87.9	8.9	6160	11.21

The table 4 above exhibits the outcomes of the three-point bending test of the bamboo samples wrapped using the horizontal strip wrapping method. From this table, it is observed that the sample with the smallest inner diameter garnered the highest flexural strength.

Table.5. Three-Point Bending Test (Vertical Strip Wrap)

SAMPLE CODE	MOMENT OF INERTIA *(mm⁴)*	CLEAR SPAN LENGTH (mm)	ACTUAL DIMENSIONS *(mm)*			MAX LOAD *(N)*	FLEXURAL STRENGTH σult *(MPa)*
			DIAMETER		THICKNESS		
			OUTER	INNER			
V1	1473735.7	440	79.2	55.1	12.0	6630	19.58
V2	1944017.1	440	87.8	66.7	10.6	6990	17.36
V3	3705680.6	440	103.6	79.4	12.1	6060	9.32

Table 5 displays the outturns of the three-point bending test of the bamboo samples wrapped using the vertical strip wrapping method. Based on the data above, the highest flexural strength procured is the specimen with the smallest inner diameter. The specimen with the largest inner diameter attained the least flexural strength.

Table.6. Average Flexural Strength Comparison

Wrapping Method	Sample Code	Flexural Strength *MPa*	Average Flexural Strength per Wrapping Method *MPa*
Whole Vertical Wrap	W1	18.48	14.23
	W2	14.31	
	W3	9.91	
Horizontal Strip Wrap	H1	7.64	8.50
	H2	6.66	
	H3	11.21	
Vertical Strip Wrap	V1	19.58	15.43
	V2	17.36	
	V3	9.32	

Table 6 portrays the average flexural strength comparison of the three-point bending tests of the three wrapping methods with three samples of each wrapping method. The vertical strip wrap gained the highest average flexural strength. On the other hand, the lowest average flexural strength is the horizontal strip wrap.

Table.7. Three-Point Bending Test (Treated Unwrapped Bamboo)

Sample code	Moment Of inertia *(mm⁴)*	Clear Span Length *(mm)*	Actual dimensions *(mm)*			Max Load *(N)*	Flexural Strength σ_{ult} *(MPa)*	Highest Flexural Strength Of Wrapped Bamboo Culms *(MPa)*
			Diameter		Thic kness			
			Outer	Inner				
T1	4324703.3	440	115.0	96.6	9.2	4220	4.22	15.43

Table 7 above data that appears in the table refers to the three-point bending test of unwrapped bamboo. The value of the highest average flexural capacity is 15.43 MPa. Comparing this with the treated unwrapped bamboo that garnered an average flexural stress of 6.17 MPa, the wrapped bamboo is 2.5 times stronger than the unwrapped.

3.2 SSWB and Timber Comparison

Apart from bamboo, timber is also one of the organic materials used in the Philippine Construction Industry. The use of the two materials in the field is almost similar, from sturdy old furniture to structural components such as beams and trusses. To further identify the potential of the SSWB, an investigation of timber and *Glulam* conducted by Ezeagu et al. (2015) was also assessed and compared to the study. The study aimed to find out the effects of glue laminating on the flexural strength of the timber. The research revealed that the glue lamination significantly reduced the ability of the timber samples to withstand flexure which may be due to irregularities in the glued potions of the beam. Six locally accessible species, three of which were hardwoods, and the other three were softwoods. The results obtained after three-point flexural tests of the following 900mm-hardwood solid timber specimens are as follows:

Table.8. Three-Point Flexural Test Results of Three Hardwood Solid Timber Beam

SAMPLE CODE	TIMBER STANDARD NAME	CROSS-SECTION DIMENSIONS *(mm x mm)*	MAXIMUM LOAD CAPACITY *(kN)*	FLEXURAL STRENGTH *(MPa)*
Beam A	Berlina	100 x 100	108	10.80
Beam B	Danta	100 x 100	85	8.50
Beam C	Alstonia	100 x 100	66	6.60

Table 8 above represents the results of the three hardwood solid timber beams upon conducting a three-point bending test. The timber Berlina obtained the highest flexural strength at 10.80 MPa while the Alstonia garnered the least flexural strength at 6.60 MPa.

3.3 FOUR-POINT BENDING TEST RESULTS

Table.9. Four-Point Bending Test (Whole Vertical Wrap)

SAMPLE CODE	MOMENT OF INERTIA *(mm⁴)*	CLEAR SPAN LENGTH *(mm)*	ACTUAL DIMENSIONS *(mm)*			MAX LOAD *(N)*	FLEXURAL STRENGTH σ_{ult} *(MPa)*
			DIAMETER		THICKNESS		
			OUTER	INNER			
W1	1709891.1	440	89.0	72.7	8.2	7640	14.58
W2	3186663.2	440	98.1	72.5	12.8	7670	8.65
W3	2297953.9	440	92.7	72.0	10.3	7710	11.40

Table 9 above shows the outcomes of the four-point bending test of the whole vertical-wrapped structural bamboo. The highest flexural strength is the specimen with the largest diameter.

Table.10. Four-Point Bending Test Results (Horizontal Strip Wrap)

SAMPLE CODE	MOMENT OF INERTIA *(mm⁴)*	CLEAR SPAN LENGTH *(mm)*	ACTUAL DIMENSIONS *(mm)*			MAX LOAD *(N)*	FLEXURAL STRENGTH σ_{ult} *(MPa)*
			DIAMETER		THICKNESS		
			OUTER	INNER			
H1	6293717.9	440	119.0	92.1	13.4	8720	6.04
H2	3101528.2	440	102.7	83.3	9.7	5650	6.86
H3	3109488.4	440	111.3	97.4	6.9	6310	8.28

Table 10 describes the results of the four-point bending test of the horizontal strip-wrapped structural bamboo. The specimen with the largest diameter acquired the highest flexural strength among the samples.

Table.11. Four-Point Bending Test (Vertical Strip Wrap)

SAMPLE CODE	MOMENT OF INERTIA *(mm⁴)*	CLEAR SPAN LENGTH *(mm)*	ACTUAL DIMENSIONS *(mm)*			MAX LOAD *(N)*	FLEXURAL STRENGTH σ_{ult} *(MPa)*
			DIAMETER		THICKNESS		
			OUTER	INNER			
V1	3480323.6	440	107.1	88.2	9.4	7440	8.39
V2	4913014.5	440	119.2	100.5	9.4	8550	7.61
V3	3279384.0	440	108.4	91.9	8.3	5170	6.27

Table 11 pertains to the outcomes of the four-point bending test of the vertical strip-wrapped structural bamboo. The results show that the bamboo specimen with the smallest inner diameter obtained the highest flexural strength and the sample with the middle size diameter garnered the lowest flexural strength.

Table.12. Average Flexural Strength Comparison

WRAPPING METHOD	SAMPLE CODE	FLEXURAL STRENGTH *(MPa)*	AVERAGE FLEXURAL STRENGTH PER WRAPPING METHOD *(MPa)*
Whole Vertical Wrap	W1	14.58	11.54
	W2	8.65	
	W3	11.40	
Horizontal Strip Wrap	H1	6.04	7.06
	H2	6.86	
	H3	8.28	
Vertical Strip Wrap	V1	8.39	7.42
	V2	7.61	
	V3	6.27	

Table 12 above reports the average flexural strength comparison gained from the four-point bending test per wrapping method. The lowest average flexural strength is the. On the other hand, the whole vertical wrap has the highest average flexural strength.

Table.13. Four-Point Bending Test Results (Treated Unwrapped Bamboo)

SAMPLE CODE	MOMENT OF INERTIA *(mm^4)*	CLEAR SPAN LENGTH *(mm)*	ACTUAL DIMENSIONS *(mm)*			MAX LOAD *(N)*	FLEXURAL STRENGTH σ_{ult} *(MPa)*	AVERAGE FLEXURAL STRENGTH σ_{ult} *(MPa)*
			Outer diameter	Inner diameter				
T1	3822483.8	440	112.9	95.8	8.5	5450	5.90	11.45

From Table 13, the most efficient wrapped bamboo gave the highest average flexural capacity of 11.54 MPa. Differentiating it with the treated unwrapped bamboo that gained an average flexural stress of 5.90 MPa, the wrapped bamboo is 1.95 times stronger than the unwrapped.

IV. CONCLUSIONS

The accelerating global warming drove the interest of researchers to opt for the concept of renewable building materials. Aside from timber, the Philippines has also its own organic material which is bamboo which belongs to the grass family. As a tropical country, this plant has always been a part of the Filipino culture. One of the main objectives of this study was to provide a turning point for the Philippine Construction Industry to rediscover the potential of bamboo.

Steel sheet wrapping was used to reinforce the bamboo samples. The sheets were wrapped around the bamboo and fastened by welding. Therefore, the investigation sought to determine the contribution of steel sheets to the flexural capacity of bamboo as an element of a hybrid structural beam. The variables considered by the researchers were in the form of various methods for bamboo wrapping; whole vertical, horizontal strip, and vertical strip wrap.

The study aimed to know the most efficient wrapping method among whole vertical, horizontal strip wrap, and vertical strip wrap. In the three-point bending test, the highest average flexural strength obtained among the wrapping is 15.43 MPa which is the vertical strip wrapped bamboo. On the other hand, the highest average flexural strength in the four-point bending test is whole vertical wrapped bamboo at 11.54 MPa. The most efficient wrapping methods are vertical strip wrapping and whole vertical wrapping. The least efficient in both tests conducted was the horizontal strip wrap method.

The incorporation of Steel Sheets into bamboo culms by wrapping and welding contributes to the strength of the bamboo. Under the three-point flexural test, it was observed that the vertical strip-wrapped samples are 2.5 times, the whole vertically wrapped culms are 2.1 times, and the horizontal strip-wrapped bamboos are 1.3 times stronger than the control sample. On the other hand, the four-point bending test revealed that the whole vertical wrapping obtained almost double, the vertical strip wrapping has 1.3 times, and the horizontal strip wrapping acquired 1.2 times more flexural capacity than the treated unwrapped culms. To sum these up, the steel sheet-wrapped bamboo can withstand bending without permanent deformation 1.2-2.5 times more than the conventional unwrapped bamboo.

During the observation in testing and the analysis of data, the researchers discovered that the flexural test results for steel sheet-wrapped bamboo generated a general pattern that the smallest diameters have the largest amount of flexural strength.

V. RECOMMENDATIONS

The research has proved that adding galvanized steel sheets to structural Moso bamboo using the welding method significantly increases its flexural capacity. Future studies can explore other variables such as the initial drying factor, other bamboo species, the use of different types of steel sheets with varying specifications and thicknesses, other reinforcing materials, and wrap-securing methods other than welding to further improve the flexural strength of bamboo. It is also recommended to conduct further research on the utilization of other preservation methods for bamboo for SSWB, economic benefit, long-term durability, and sustainability of SSWB as a building material. Steel sheet wrapping can also contribute –but need to be tested– to the following: 1.) environmental effects; 2.) termite, fungal, and insect resistance; and 3.) fire, weather/moisture resistance of the product. Structural integrity is the priority of the study with the given limited time and budget, but other studies can also consider the aesthetics side of the product. Aside from flexural tests, it is also suggested to perform other tests to further identify the structural integrity of the composite material.

The study proposes that future producers, manufacturers, and researchers should use vertical strip-wrapping and whole vertical sheet-wrapping since these are the most efficient methods based on the findings of this study.

Based on the conclusion from the trend of the results, it is prescribed to use smaller diameter bamboo culms on the base part of the plant as it possesses the most consistent dimensions of the whole culm. The flexural capacity of steel sheet-wrapped bamboo can also be improved by bundling these samples with smaller diameters.

Moreover, future researchers can consider the season during the selection and collection of the bamboo samples as it has an effect on the material's structural integrity; they may also test bamboo for its other mechanical properties such as its fiber content in order to maximize the potential of the material during the sample collection and flexural testing.

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