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Flexural Characteristics of Roll-Wrapped GFRP Composite Hollow Square Tube

Kaleb Priyanto[1], Haniel[2], Martinus Heru Palmiyanto[3], Bambang Hari Priyambodo[4]
[1]Department of Mechanical Engineering Education, Universitas Negeri Semarang, Semarang 50229, Indonesia
[2]Doctoral Student of Mechanical Engineering, Faculty of Engineering, Universitas Diponegoro, Semarang 50275, Indonesia
[1]Department of Mechanical Engineering Education, Universitas Negeri Yogyakarta, Yogyakarta 55281, Indonesia
[1]Department of Mechanical Engineering, Vocational College, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia

E-mail: kalebpriyanto@mail.unnes.ac.id

Abstract-- *This research characterizes the bending behavior of hollow square tube glass fiber-reinforced polymer (GFRP) composites using the roll-wrapping method. CSM (Chopped Strand Mat) and WRM (Woven Roving Mat) glass fibers were chosen as reinforcing constituents with epoxy as the matrix. Glass fiber was chosen because it has strength, stiffness, lightness, corrosion resistance and high-temperature resistance. These properties can be utilized for frame and structural applications in various types of transportation equipment. The roll-wrapping technique was chosen for manufacturing GFRP composite hollow square tubes. The roll-wrapping technique is the simplest method and does not require a lot of money. The bending test using the Three Point Bending method is based on the ASTM D7264 test standard. In addition, macroscopic observations of the specimen's cross-section after experiencing a bending load are carried out to determine the product failure criteria. Bending tests were conducted on two types of GFRP composites, hollow square tube products produced from CSM and WRM fibers. The bending test results showed that the CSM fiber-reinforced composite has higher stress values (167.122 MPa) and strain (0.055%) compared to the WRM fiber-reinforced composite, which has stress values of 78.339 MPa and strain of 0.030%. The results of macro photo analysis show that random fiber composites dominate tensile failure while woven fiber composites dominate compressive failure. Failure analysis through macro photos is a critical process in determining the physical root cause of the problem.*

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1. INTRODUCTION

Composite products consist of reinforcement and a binder combined through a curing process, resulting in the bonding of each constituent. Glass Fiber Reinforced Polymer (GFRP) composites are among the most important engineering elements widely used to strengthen structures due to their advantageous material properties in various engineering applications [1][2]. Composite pipes play an important role in modern life thanks to their high strength, lightweight nature, and resistance to corrosion. They are widely used in industries like automotive and aerospace for fluid transport systems, as well as in construction and energy sectors for carrying water, gas, or oil. Their durability and low maintenance make them an innovative solution for improving efficiency and extending the lifespan of infrastructure [3]. Composite pipes play an important role in modern life thanks to their high strength, lightweight nature, and resistance to corrosion. They are widely used in industries like automotive and aerospace for fluid transport systems, as well as in construction and energy sectors for carrying water, gas, or oil. Their durability and low maintenance make them an innovative solution for improving efficiency and extending the lifespan of infrastructure. Composite pipes can be made from several layers of fibers or fabrics combined with resin to form a tubular shape.
There are four main processes for manufacturing composite pipes, including roll wrapping, pultrusion, and pullbraiding. Roll wrapping is a type of composite manufacturing process aimed at producing high-quality tubular structures [4]. Roll wrapping is efficient and low-cost because the materials used are already formed into woven or fiber sheet structures, which provide a more organized and consistent reinforcement.

In general, during the roll-wrapping process, prepreg (pre-impregnated layers) is placed around a mandrel using a winding machine. The prepreg must wrap tightly around the mandrel, as the outer diameter of the mandrel determines the inner diameter of the final tube. After the curing process, the mandrel is removed from the composite tube [4]. Roll wrapping is commonly carried out using prepreg products to ensure consistency. Prepreg is a composite material made of fabric or fiber that has been impregnated with epoxy resin, which is essential for bonding all the materials together. The prepreg is cut into several layers with different fiber orientations. These layers are then rolled onto a cylindrical rod known as a mandrel. The mandrel and prepreg are then wrapped in a plastic film to contain the epoxy resin, and pressure is applied to the layers during the curing process. Once the curing is complete, the mandrel is removed from the center of the finished tube. The roll-wrapping process provides maximum consistency in carbon fiber and fiberglass tubes. It also allows for greater customization in terms of fiber/mandrel configurations and production quantities. Roll wrapping is the preferred process for producing small-scale quantities.

The mechanical properties of composite products are influenced not only by the type of fiber material used as reinforcement but also by the shape and structure of the constituent fibers. Previous research on the flexural strength of GFRP showed extremely high flexural strength, with an absolute value of 153 MPa at a 0° fiber orientation. This value is 30 times higher than the predicted strength for composites with a 90° fiber orientation (5 MPa) and twice as high as the strength obtained for composites with an 11–45° fiber orientation (14 MPa) [5].

The development of two types of carbon/glass hybrid panels—namely, the random hybrid fiber (RH) mode and the core-shell hybrid (CH) mode—was reported in a previous study [6]. Continuous flexural loading and water immersion were conducted over 360 days to examine the effects of fiber hybrid mode and flexural loading on mechanical properties. The results showed that the synergistic effect between carbon and glass fibers could be fully expressed through the random hybrid fiber mode. Additionally, improper bearing behavior and stress concentration at the carbon/glass fiber/resin interface were eliminated mainly, contributing to improved mechanical properties. The retention of tensile and flexural strength reached 30–40% and 50–60%, respectively, after five years of use, providing durability guidelines based on hybrid fiber design for engineering applications.

A previous study [7] characterized the crushing response of capped composite tubes under quasi-static three-point bending and transverse compression conditions. A comparative study of energy absorption and cost efficiency was conducted for all samples. The study revealed that the failure mode varied depending on the ply angle during the quasi-static three-point bending test but remained consistent during the transverse compression test. Based on the previous research, the development of GFRP materials has primarily focused on material strength. However, further development in the application and modeling of GFRP materials is still necessary. There has been limited research on the fabrication of polymer matrix composite tubes reinforced with synthetic fibers using the roll wrapping technique. This makes it a promising area for further study, especially considering the potential benefits of improved structural consistency, cost efficiency, and production speed offered by roll wrapping. Therefore, the bending characteristics of hollow square GFRP composite tubes produced by the roll-wrapping process need to be investigated further.

2. METHODOLOGY

The materials used in this study include WRM glass fiber (woven roving mat) with a mass-to-area ratio of 2.52 g/cm² and CSM glass fiber (chopped strand mat) with a mass-to-area ratio of 1.25 g/cm². The CSM and WSM used are purchased from a supplier who includes that information as part of the material specifications used. The resin used as the matrix is SHCP Unsaturated Polyester Resin. Methyl Ethyl Ketone Peroxide was used as the catalyst, mixed with the resin at a 100:1 ratio. A thinner was added to maintain the viscosity of the matrix, making it more effective in binding all the gaps within the fibers. The roll wrapping technique was chosen to form the fiber-reinforced material using woven fiber.

The manufacturing process of the GFRP hollow square tube composites began with the preparation of the primary tool, namely the mandrel and its support. The cut glass fibers were coated with resin by hand through a lay-up process using a paintbrush before the roll-wrapping process was carried out. Each composite produced had a distinct material composition. The WRM glass fiber-reinforced composite consisted of 15 fiber layers with a length of 17 cm, resulting in a product mass of 199 grams. On the other hand, the CSM glass fiber-reinforced composite consisted of 8 fiber layers with a length of 27 cm, with an ideal product mass of 215 grams. The number of layers and fiber lengths differ because WRM has a higher mass-to-area ratio than CSM, making it denser and heavier per unit area. Therefore, WRM requires more layers but shorter fiber lengths to achieve the desired composite strength and performance compared to CSM. The specifications of the resulting products are presented in Table 1.

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Table 1. Specifications of Hollow Square GFRP Tube Composites

Type of Fiber	*Fiber Length (cm)*	*Fiber Width (cm)*	*Fiber Mass (g)*	*SCHP Mass (g)*	*Total Composite Mass (g)*
Random (CSM)	*105*	27	*118*	*97*	*215*
Woven (WRM)	*198*	17	*117*	*82*	*199*

The fibers being wound on the mandrel are coated with resin while rolling. The curing of polymer resin composites takes time because it involves a chemical reaction that gradually transforms the resin from a liquid to a solid state. The number of mandrel rotations is adjusted based on the type of fiber and the intended number of layers to be made. The process of applying resin to the fibers is shown in Figure 1.

Figure 1. The process of applying resin to the fibers

After all the fibers are wound on the mandrel, it is necessary to cull the composite before the resin hardens and becomes dry. The curing process is depicted in Figure 2 after wrapping the rolls.

Figure 2. Curing process

The comparison data of resin and fiber are obtained by weighing the composite mass and the mass of the fibers used. The difference between the composite mass and the fiber mass represents the amount of resin used. The percentage calculation data for resin and fiber are as follows:

a. Woven fiber-reinforced composite:
   Fiber: $\frac{117}{119}\, x\ 100\% = 59\%$
   Resin: $\frac{82}{119}\, x\ 100\% = 41\%$
b. Random fiber-reinforced composite:
   Fiber: $\frac{118}{215}\, x\ 100\% = 55\%$
   Resin: $\frac{97}{215}\, x\ 100\% = 45\%$

The specimen sampling for the hollow square tube GFRP composite products is carried out by cutting one side of the composite cross-section. The specimen dimensions are cut according to the ASTM D7264 testing standard. Each variable is represented by three specimens for flexural testing using the three-point bending method. The specimen dimensions used in the ASTM D7264 testing standard are shown in Figure 3.

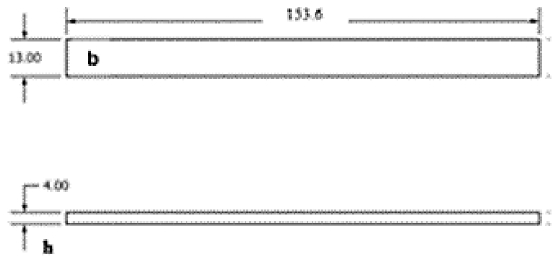

Figure 3. Flexural test specimen dimensions

For:
Ps = specimen length
b = specimen width
h = specimen thickness

The maximum stress value produced from the flexural test is calculated using Equation (1) as follows:

$$\sigma = \frac{3PL}{2bh_2} \quad (1)$$

For:
σ = stress (MPa)
L = support span distance (mm)
P = load or force (N)
b = specimen width (mm)
h = specimen thickness (mm)

Strain is the change in size or shape of a material from its original length as a result of the applied force. Strain is linear in the elastic region and ends at the yield point, and when it enters the plastic region, the behavior becomes non-linear. The magnitude of linear strain is the elongation of the material divided by the original length. Equation (2) is used to determine the maximum strain value of the specimen.

$$\varepsilon = \frac{6\delta h}{L^2} \quad (2)$$

For:
ε = maximum strain at the surface (mm/mm)
δ = mid-span deflection (mm)

The elastic properties of the specimen are determined by the value of the material's longitudinal elasticity constant, commonly referred to as the modulus of elasticity, using Equation (3) as follows:

$$Y = \frac{\sigma}{\varepsilon} \quad (3)$$

For:
Y = Young's modulus (N/mm^2)

Besides performing calculations according to the formulas in the ASTM D7264 test standard, the research also conducted observations on the fracture surface of the specimen using macro photos after testing. This was done to ensure the accuracy of the research results and to draw conclusions from the findings.

3. RESULTS AND DISCUSSION

The resin curing duration of the woven and random fiber-reinforced composite specimens was made using the same manufacturing technique. The manufacturing technique used combines filament winding and hand lay-up techniques. The purpose of this technique combination is to bond the fibers to the mold/rolling mandrel while performing the lay-up process using a brush. The mold/rolling mandrel is rotated, pulling the fibers, which have been impregnated with resin, to form a square hollow pattern.

Composite manufacturing techniques such as hand lay-up, spray-up, and filament winding are considered open mold processes. The use of open molding processes offers advantages in manufacturing costs and facilitates the molding of various mold/rolling mandrel patterns.

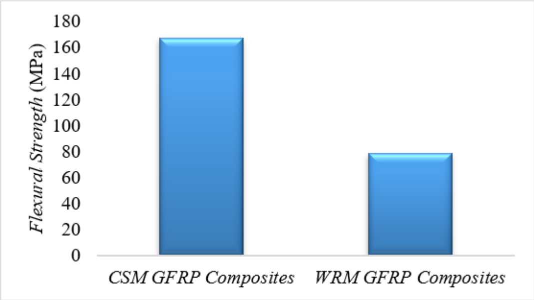

Figure 4. Comparison diagram of composite flexural strength

Figure 4 shows that the random fiber composite demonstrates higher stress and elastic modulus in withstanding bending loads compared to the woven fiber composite due to the stronger bond between the fibers and resin [8]. Since resin functions as the binder for the fibers in the composite, the resin content in the random fiber composite is higher than in the woven fiber composite. This is the reason why the random fiber composite is more substantial in withstanding bending loads.

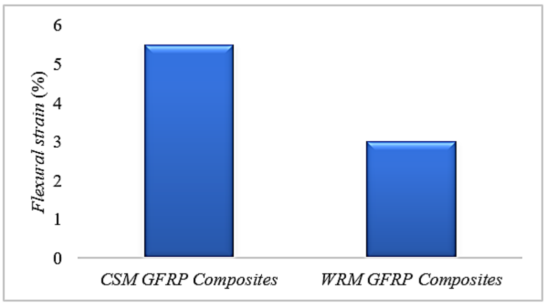

Figure 5. Comparison diagram of composite flexural strain.

Figure 5 shows the comparison diagram of bending strain in random fiber and woven fiber composites. The diagram indicates that the random fiber composite is stronger in withstanding bending loads than the woven fiber composite. This is because the resin content in the random fiber composite is higher than in the woven fiber composite, leading to a more effective bond and making the random fiber composite stronger in withstanding bending loads. This is also emphasized in previous research [9], which states that the more resin present, the higher the bending strength. The increase in strength and elastic modulus occurs due to a stronger bond between the fibers and resin as the resin fraction increases [10].

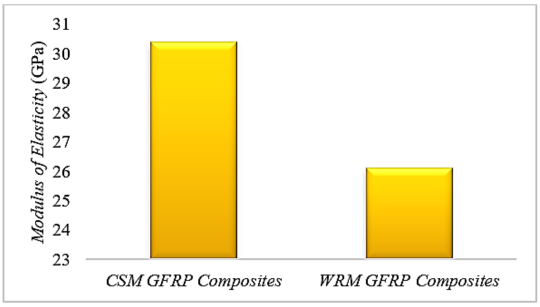

Figure 6. Comparison diagram of composite flexural modulus.

Figure 6 shows the comparison diagram of the composite bending modulus. The diagram indicates that the average modulus value for the random fiber composite specimen is 3044.804 N/mm², while the average modulus value for the woven fiber composite specimen is 2565.7 N/mm². The average value for the random fiber composite specimen is higher than that of the woven fiber composite.

Failure analysis is a critical process in determining the physical root cause of the problem [11]. Generally, the failure resulting from bending tests is a tensile and compressive failure. In addition, damage to the matrix also becomes one of the causes of bending failure in composite materials.

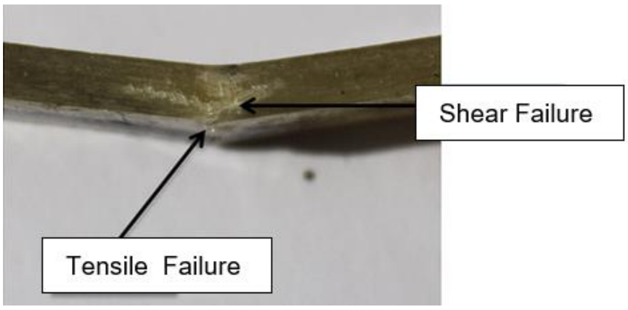

Figure 7. Flexural failure model of CSM/GFRP (random fiber composite)

Random fiber composites are predominantly characterized by tensile and shear failure. This is shown in Figure 7. The composite has an average stress value of 167.122 MPa and a resin-to-fiber mass ratio of 55% to 45%. Generally, the failure pattern begins with an initial crack that starts the failure process on the underside of the specimen. Subsequently, the specimen, unable to withstand the maximum load, experiences tensile failure. The composite, initially subjected to tensile load, eventually undergoes shear failure as the load continues. Imperfections in the specimen could cause this. These imperfections include small bubbles (voids) within the specimen [12]. The same was observed in previous research [13].

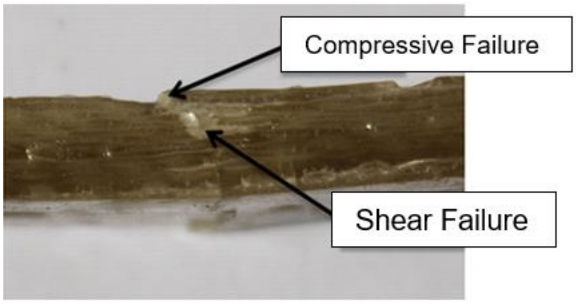

Figure 8. Flexural failure model of WRM GFRP (woven fiber composite)

Random fiber composites are predominantly characterized by compressive and shear failure, with an average stress value of 78.339 MPa and a resin-to-fiber mass ratio of 41% to 59%. Figure 8 clearly shows compressive failure on the upper surface of the composite. In line with previous research [14], the failure in woven fibers is the opposite of that in random fibers, which experience tensile failure. The fracture mechanism occurs due to damage in the woven fiber composite from bending loads, starting with an initial crack on the upper side of the specimen. Then, the specimen, unable to withstand the maximum load, experiences compressive failure [15], and from compressive failure, it propagates into shear failure as the load continues to be applied.

4. CONCLUSION

The composite manufacturing process carried out using the roll wrapping method resulted in comparison data of the resin-to-fiber mass fraction of 45:55 for the CSM GFRP composite and 41:59 for the WRM GFRP composite. Meanwhile, the bending strength of the CSM GFRP composite is 167.122 MPa, and the bending strength of the WRM GFRP composite is 78.339 MPa. The bending failure experienced by the WRM GFRP composite is dominated by damage due to loading on the compressive side and the occurrence of shear stress on the transverse plane of the specimen. Seeing how a specimen looks after impact testing helps us understand where and how the material started to break, like cracks or layers coming apart. This gives us insight into how well the composite can handle sudden hits in real-life situations.

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