MARMARA UNIVERSITY
FACULTY OF ENGINEERING

RSR ORIGAMI ROBOT MANUFACTURING WITH COMPOSITE MATERIALS

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GRADUATION PROJECT REPORT

Department of Mechanical Engineering

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By

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OF

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Abstract

Origami-inspired engineering provides several advantages in the field of robotics. In our project, we aimed to produce and implement an origami robot with three degrees of freedom using composite materials. Our goal was to select the best composite material to achieve the required degree of freedom and mobility. Through detailed research on composite materials, we focused primarily on two main types: carbon fiber and aramid.

After conducting research on the properties, strength characteristics, manufacturing techniques, and other factors related to carbon fiber and aramid, we concluded that carbon fiber would be the most suitable choice for our project. Therefore, we proceeded to manufacture our robot with a carbon fiber body.

Carbon fiber offers exceptional strength-to-weight ratio, stiffness, and durability, making it an ideal material for lightweight yet robust robotic structures. Its superior mechanical properties ensure precise movement and reliable performance, essential for achieving the desired degrees of freedom in our origami robot. Additionally, carbon fiber's resistance to corrosion, fatigue, and environmental factors further enhances the longevity and reliability of our robot.
By selecting carbon fiber as the primary material for our origami-inspired robot, we aimed to optimize its performance, mobility, and overall functionality, ensuring that it meets the requirements of our project effectively.

However, due to expected and unexpected errors in the studies and manufacturing, we transitioned from carbon fiber to fiberglass and used Kapton film. We concluded that this change would help us achieve a more optimal result, especially concerning the thickness of the links and aesthetic appearance, as well as aligning with the analyses found in the literature.
Fiberglass provides us with the desired strength properties along with the advantage of flexibility. Compared to other composites on the market, it is slightly cheaper and more accessible. In the event of mass production, these factors will increase the sustainability, appeal, and functionality of the project more than other composite materials.

Symbols

V_f : Fiber Volume Fraction

W_f	: Fiber Areal Weight
ρ_r	: Density of Resin
ρ_f	: Density of Fiber
t	: Composite Thickness
JW	: Revolute Joint Length
V_c	: Volume of Composite per Unit Area
V_r	: Volume of Resin per Unit Area
W_r	: Volume of Resin to Weight
TCI	: Terephthaloyl chloride
PPD	: Para-phenylenedşamine
ICl	: Isophthaloyl Chloride
MPD	: Meta – phenylenediamine
GRP	: Glass-Reinforced Plastic
GFRP	: Glass-Fiber Reinforced Plastic
E-Glass	: Electrical Glass
S-Glass	: Structural Glass
C-Glass	: Chemical Glass
RTM	: Resine Transfer Molding

1. Introduction

The aim of this project is to learn, experience and use composite production techniques. We aimed to implement RSR robot production using composite materials (fiber glass was used in our project) in a way that would be suitable for mass production. We were expected to use the design called

'Waterbomb' in the spherical joint of the RSR robot and make the desired movements. An attempt was made to preserve the rigidity in the links without losing flexibility and mobility in the joints. Inspired by the closest examples of similar studies in the literature, it was aimed to contribute to robotics and production science by using Kapton film and fiberglass, as well as the best equivalents of the adhesive available in Turkey.

1.1 Literature Review

Manufacturing and Composite Applications, Origami-Inspired Robots, RSR Robots

The fields of composite materials, origami-inspired robots, and reconfigurable spherical robots (RSR) represent some of the most dynamic areas of research in modern engineering and materials science. This literature review synthesizes recent studies in these domains, highlighting key advancements, manufacturing processes, and applications.

Composite materials are engineered by combining two or more constituent materials with different physical or chemical properties, resulting in a material with characteristics distinct from the individual components. Recent research has focused on improving the manufacturing processes and expanding the applications of these materials.

Our most important and guide articles are [1]Ori-Pixel, a multi-DoFs origami pixel for modular reconfigurable surfaces (M. Salerno, J. Paik and S. Mintchev, 2020) and [2] A portable three-degrees-of-freedom force feedback origami robot for human–robot interactions (Stefano Mintchev, Marco Salerno, Alexandre Cherpillod, Simone Scaduto and Jamie Paik, 2019) , both are written by Salerno and Mintchey who worked about RSR origami inspired robots and on both articles they worked through composite applying to robots. Both of these are main guides for this project. In these articles authors used fiberglass for rigid bodies and Kapton for polyamide part. Brands of these are DuPont. Foldaway is a compact origami robot that provides three-DoF force feedback, crucial for immersive and natural interactions in virtual reality (VR) and teleoperation systems. Traditional haptic interfaces are often bulky or limited in tactile sensations, posing challenges for miniaturization and integration into portable devices. By utilizing origami design principles, Foldaway achieves a balance between rich haptic feedback and compactness, making it suitable for scalable manufacturing and practical applications.

[3]Advanced Robotics and Additive Manufacturing of Composites (Parmar, Khan, Tucci, Umer, & Carlone, 2022) explores the integration of advanced robotics and additive manufacturing in composite production. The study emphasizes Industry 4.0 technologies, which enhance efficiency and precision in manufacturing, enabling scalable and customizable composite products.

[4]Challenges of Natural Fiber Composites (Khan, Hameed Sultan, & Ariffin, 2018) reviews the use of natural fibers in composites, addressing material selection and manufacturing challenges. The study suggests surface treatments and hybridization with synthetic fibers to overcome issues such as variability and compatibility.

[5]Bio-based Composite Roof Structures (Dweib, Hu, Shenton III, & Wool, 2006) investigates the use of natural fibers and bio-resins in roofing materials. The study highlights the mechanical properties, durability, and environmental benefits of bio-based composites, while also identifying challenges in material uniformity and moisture resistance.

[6]Graphene-based Materials and Their Composites (Mohan, Lau, Hui, & Bhattacharyya, 2018) reviews the production and applications of graphene composites. Graphene's exceptional properties make it ideal for electronics, energy storage, and structural materials, though challenges in scalability and cost remain.

Origami-inspired robots leverage the principles of folding to create flexible, lightweight, and reconfigurable structures. These robots can change shape and function dynamically, offering significant advantages in various applications.

[7]Design, Fabrication, and Control of Origami-Inspired Robots (Rus & Tolley, 2015) explores the potential of soft robots inspired by origami for medical devices, space exploration, and search-and-rescue missions. The study emphasizes the use of flexible materials and folding techniques to achieve complex, reconfigurable structures.

[8]Self-Folding Robots: A Review of Recent Progress (Wood & Felton, 2014) reviews advancements in self-folding robots that transform from flat sheets into functional 3D structures. The article discusses materials and methods used in self-folding technologies, with applications in minimally invasive surgery and robotic swarms.

[9]Origami-Inspired Manufacturing of Soft Robots (Miyashita & Demaine, 2017) focuses on the manufacturing processes of soft robots using origami techniques. The study highlights the benefits of fabricating robots from a single sheet of material, reducing assembly complexity. Applications include deployable structures, medical devices, and wearable robotics.

[10]Design and Control of Reconfigurable Spherical Robots (Wang & Dai, 2016) presents the design and control strategies for RSR robots. The study highlights the kinematics and dynamics of these robots, emphasizing their adaptability to different terrains and tasks through modular components.

[11]Development of a Spherical Mobile Robot with Reconfigurable Mechanisms (Kondo & Tanaka, 2019) details the development of a spherical mobile robot with reconfigurable joints. The study focuses on the design and control algorithms enabling smooth transitions between configurations, with applications in environmental monitoring and surveillance.

[12] External Force/Torque Estimation on a Dexterous Parallel Robotic Surgical Instrument Wrist (Ugur Tumerdem & Nural Yılmaz & Merve Bazman 2018) shows the proposed method at the article and wrist mechanism provide a highly flexible system that can estimate force/torque in surgical applications. This system can be further miniaturized with versions with smaller inlet diameters and clutch mechanisms with force sensing capability can be added.

The advancements in composite materials, origami-inspired robots, and RSR robots demonstrate the interdisciplinary nature of modern engineering research. Composites are being enhanced through innovative manufacturing techniques and new material combinations, leading to applications across various industries. Origami-inspired robots offer flexible and reconfigurable designs suitable for medical, exploratory, and rescue missions. RSR robots provide versatile solutions for navigating complex environments, making them ideal for search and rescue and monitoring applications.

These fields highlight the importance of continued research and development to overcome existing challenges and fully realize the potential of these technologies. By leveraging advancements in materials science, robotics, and manufacturing, researchers can create more efficient, adaptable, and sustainable solutions for a wide range of applications.

2. Introduction to Parallel Mechanisms and Origami Inspired Robots

Origami robots and parallel mechanisms are two intriguing areas in the field of robotics and mechanical design, each offering unique advantages and solving different engineering challenges. While origami robots leverage the principles of folding and flexibility to achieve compact and versatile designs, parallel mechanisms excel in precision and rigidity through multiple interconnected arms. At the same time, robot-assisted minimally invasive surgery systems, on behalf of parallel mechanisms, are widely used in many surgical operations. One of the most important features of these systems is their ability to move with high flexibility and precision. However, the lack of force feedback is seen as a disadvantage of these systems.

Origami Robots

Origami robots take inspiration from the traditional Japanese art of paper folding, using flexible materials and innovative designs to create robots that can fold and unfold. These robots are particularly noted for their lightweight and portable nature, making them suitable for a variety of applications where space and weight constraints are critical.

1. **Foldable Design:**
    - Origami robots can transform from a compact form into a fully functional state through folding and unfolding mechanisms. This design makes them highly portable and easily deployable.
2. **Materials:**
    - Typically made from lightweight and flexible materials such as paper, plastic, or thin metal sheets, which allow the robot to achieve the necessary flexibility and strength.
3. **Movement Capabilities:**
    - Depending on their design, these robots can perform a range of movements including walking, swimming, flying, and other complex maneuvers.
4. **Cost-Effectiveness:**

- The use of inexpensive materials and straightforward manufacturing techniques makes origami robots economical to produce.

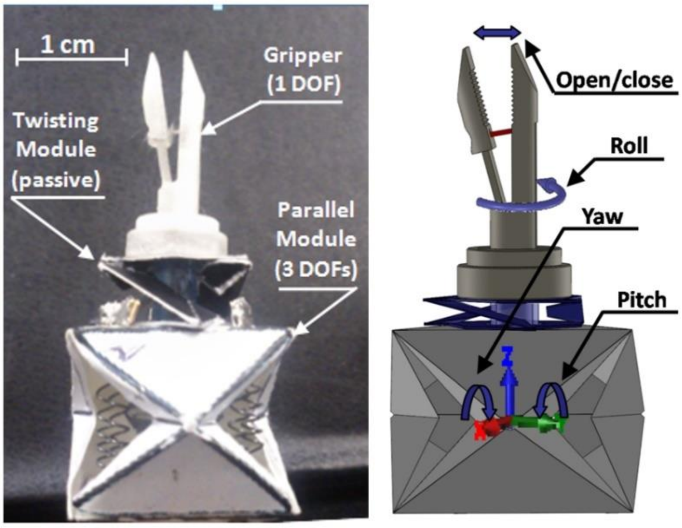

Figure 1 Origami Robot Wrist Modelling

Applications of Origami Robots

1. **Space Exploration:**
   - Due to their lightweight and compact nature, origami robots are ideal for space missions where every gram counts. They can be transported easily and deployed in space to perform tasks.
2. **Medical Field:**
   - Miniature origami robots can navigate within the human body for medical procedures, delivering treatments or conducting minimally invasive surgeries.
3. **Search and Rescue:**
   - Origami robots can reach confined spaces in disaster-stricken areas, assisting in search and rescue operations by navigating through rubble and debris.
4. **Education:**
   - They serve as excellent educational tools, helping students learn about robotics, engineering, and the principles of design and mechanics.

Kinematic Analysis of Origami Robots

Kinematic analysis of origami robots involves understanding how their folding patterns translate into movement. This analysis is crucial for designing robots that can perform specific tasks efficiently.

Forward Kinematics

Forward kinematic analysis determines the position and orientation of the robot's end-effector given the configuration of its joints or folding angles.

1. **Position Calculation:**
   - For a simple foldable structure, the position of a point on the robot can be expressed as:

$$P = P_0 + \sum_{i=1}^{n} R_i \times l_i$$

- Where:
  - P_0 is the initial position.
  - R_i is the rotation matrix for the i-th fold.
  - l_i is the length vector of the i-th segment.
  -

2. **Rotation Matrices:**
   - The rotation matrices can be calculated using the angles of the folds:

$$R_i = \begin{bmatrix} cos\theta_i & -sin\theta_i & 0 \\ sin\theta_i & cos\theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

   - Where θ_i is the angle of the i-th fold.

Inverse Kinematics

Inverse kinematic analysis determines the folding angles required to achieve a desired position and orientation of the end-effector.

1. **Angle Calculation:**
   - Given a desired end-effector position P_d, the folding angles θ_i can be determined by solving:

$$P_d = P_0 + \sum_{i=1}^{n} R_i(\theta_i) \times l_i$$

2. **Iterative Methods:**
   - Often, iterative numerical methods such as Newton-Raphson are used to solve the nonlinear equations involved in inverse kinematics.

Parallel Mechanisms

Parallel mechanisms consist of a fixed base and a movable platform connected by multiple independent arms. These mechanisms are known for their high precision and rigidity, making them suitable for applications that require exact movements and stability.

Key Features of Parallel Mechanisms

1. **Structural Design:**
   - Parallel mechanisms have a fixed base and a movable platform connected by several arms. These arms move in unison to control the platform's position and orientation.
2. **Degrees of Freedom:**
   - They offer multiple degrees of freedom, allowing complex movements in various directions.
3. **High Precision and Rigidity:**
   - The simultaneous movement of multiple arms provides high precision and rigidity, distributing forces evenly across the structure.

Applications of Parallel Mechanisms

1. **Robotic Arms:**
   - Used in industrial automation for tasks requiring high precision, such as assembly and pick-and-place operations.
2. **Flight Simulators:**
   - Employed in training pilots, providing realistic simulations of aircraft movements.
3. **Precision Machining:**
   - Utilized in CNC machines and other precision manufacturing tools where exact positioning is crucial.

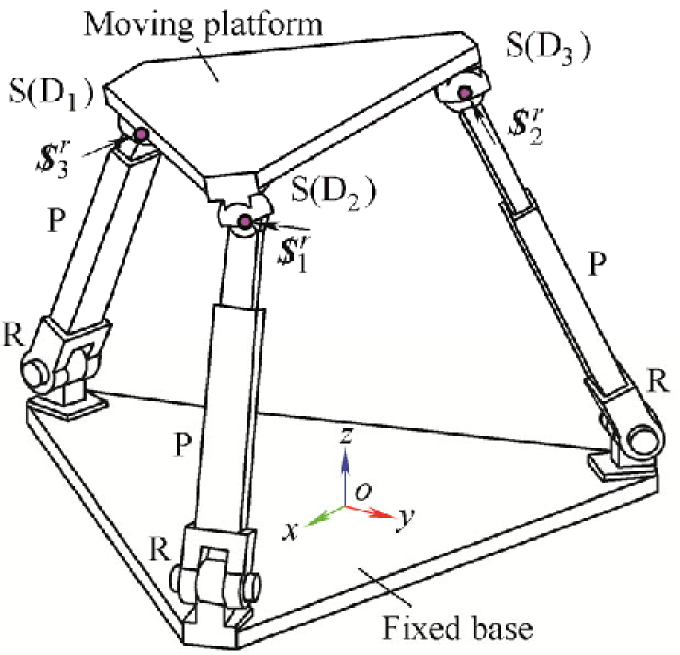

Figure 2 3-RPS Parallel Mechanism

Kinematic Analysis of Parallel Mechanisms

Kinematic analysis of parallel mechanisms involves solving forward and inverse kinematic equations to determine the positions and orientations of the moving platform based on the lengths and angles of the arms.

Forward Kinematic Analysis

Forward kinematic analysis calculates the position and orientation of the moving platform given the joint lengths or angles.

Stewart Platform Example

1. **Leg Lengths and Connection Points:**
   - P_i: Connection points on the fixed base (i = 1, 2, ..., 6)
   - Q_i: Connection points on the moving platform
   - P_i and Q_i : Coordinates of the fixed and moving connection points
   -
2. **Leg Lengths:**

$$\boldsymbol{l_i} = \sqrt{(\boldsymbol{P_{ix}} - \boldsymbol{Q_{ix}})^2 + (\boldsymbol{P_{iy}} - \boldsymbol{Q_{iy}})^2 + (\boldsymbol{P_{iz}} - \boldsymbol{Q_{iz}})^2}$$

3. **Position and Orientation of the Moving Platform:**

$$Q_i = T + R \times \ Q_i^0$$

Where:

- T : Center of the moving platform (output position)
- R : Rotation matrix
- Q_i^0 : Initial connection points of the moving platform

4. **Full Equations:**

$$= \sqrt{\left(\boldsymbol{P_{ix}} - \left(\left(T_x + R_{xx}Q_{ix}^0 + R_{xy}Q_{iy}^0 + R_{xx}Q_{iz}^0\right)\right)\right)^{\mathbf{2}} + \left(\boldsymbol{P_{iy}} - \left(\left(T_y + R_{yx}Q_{ix}^0 + R_{yy}Q_{iy}^0 + R_{yz}Q_{iz}^0\right)\right)\right)^{\mathbf{2}} + \left(\boldsymbol{P_{iz}} - \left(\left(T_z + R_{zx}Q_{ix}^0 + R_{zy}Q_{iy}^0 + R_{zz}Q_{iz}^0\right)\right)\right)^{\mathbf{2}}}$$

Inverse Kinematic Analysis

Inverse kinematic analysis determines the joint positions or angles required to achieve a desired position and orientation of the moving platform.

1. **Given Position and Orientation:**
   - T : Desired center position of the moving platform
   - R : Desired orientation of the moving platform
2. **Connection Points on the Moving Platform:**

$$Q_i = T + R \times Q_i^0$$

3. **Calculation of Leg Lengths:**

$$l_i = \ \|P_i - Q_i\|$$

$$= \sqrt{\left(\mathbf{P_{ix}} - \left(\left(\mathbf{T_x} + \mathbf{R_{xx}Q_{ix}^0} + \mathbf{R_{xy}Q_{iy}^0} + \mathbf{R_{xx}Q_{iz}^0}\right)\right)\right)^{\mathbf{2}} + \left(\mathbf{P_{iy}} - \left(\left(\mathbf{T_y} + \mathbf{R_{yx}Q_{ix}^0} + \mathbf{R_{yy}Q_{iy}^0} + \mathbf{R_{yz}Q_{iz}^0}\right)\right)\right)^{\mathbf{2}} + \left(\mathbf{P_{iz}} - \left(\left(\mathbf{T_z} + \mathbf{R_{zx}Q_{ix}^0} + \mathbf{R_{zy}Q_{iy}^0} + \mathbf{R_{zz}Q_{iz}^0}\right)\right)\right)^{\mathbf{2}}}$$

3. Introduction to Composites

Composite materials are created by combining two or more different materials that retain their own properties while working together to create a material with superior performance characteristics. They are widely used in modern engineering and industrial applications due to their lightweight, high strength, corrosion resistance, and design flexibility. This paper will discuss the general production methods, manufacturing processes, possible applications, and usage areas of composite materials. Later, it will focus specifically on fiberglass, detailing its production processes, manufacturing techniques, curing methods, and workability.

3.1 General Production Methods of Composite Materials

Composite materials typically consist of two main components: the matrix and the reinforcement. The matrix serves as the primary component that surrounds the reinforcement material, which enhances the mechanical properties of the composite. Common production methods for composite materials include:

3.1.1 Hand Lay-Up:

This is the simplest and most common method. The reinforcement material (e.g., glass fiber) is placed on a mold, and resin is applied over it. Layers are added to achieve the desired thickness. This method is suitable for low-cost and small-scale productions.
Hand lay-up is a traditional and widely used method for manufacturing composite materials. It is known for its simplicity and flexibility, making it suitable for producing a variety of composite parts.

Preparation:
-Material Preparation: Composite materials such as fiber reinforcements (e.g., fiberglass, carbon fiber) and resin are prepared. The resin is typically mixed with a hardener to initiate the curing process.
-Mold Preparation: The mold, which defines the shape of the final product, is cleaned thoroughly. A release agent is applied to the mold surface to ensure easy removal of the cured composite part.

Layer Placement:
-Gel Coat Application: For parts requiring a smooth surface finish, a gel coat is first applied to the mold. This coat is allowed to partially cure before the reinforcement layers are added.
-Fiber Placement: Fiber reinforcement layers are placed on the mold. These layers can be cut to specific shapes and sizes to fit the mold properly.

Resin Application:
-Manual Impregnation: Resin is applied manually to the fiber layers using brushes, rollers, or spray guns. The resin must fully saturate the fibers to ensure proper bonding and eliminate air pockets.
-Consolidation: The resin and fiber layers are consolidated using hand rollers to ensure even distribution of resin and removal of trapped air bubbles.

Building Up Layers:
-Multiple Layers: The process of placing fiber layers and applying resin is repeated until the desired thickness and strength are achieved. Each layer must be carefully applied to maintain uniformity and avoid defects.

Curing:
-Ambient Curing: In many cases, the composite part is allowed to cure at room temperature. This can take several hours to days, depending on the resin system used.
-Accelerated Curing: For faster curing, the part can be placed in a heated environment, such as an oven, to speed up the process.

Removal from Mold:
-Demolding: Once the part has fully cured, it is carefully removed from the mold. The application of the release agent helps in this process.
-Finishing: The cured part may require trimming, sanding, or other finishing processes to achieve the desired final shape and surface quality.

Advantages and Disadvantages:
-Low Cost: Hand lay-up is a cost-effective method, especially for low-volume production and

prototyping.
-Flexibility: This process is highly adaptable and can be used to produce a wide range of shapes and sizes.
-Simplicity: The method is straightforward and does not require complex machinery or equipment.
-Labor-Intensive: The process requires significant manual labor, making it less suitable for large-scale production.
-Variable Quality: The quality of the final product can vary depending on the skill and experience of the operator.
-Long Curing Time: Ambient curing can take a long time, which may not be suitable for high-speed production environments.

Hand lay-up is a versatile and widely used method for manufacturing composite materials, particularly suited for applications where customization and low production costs are essential.

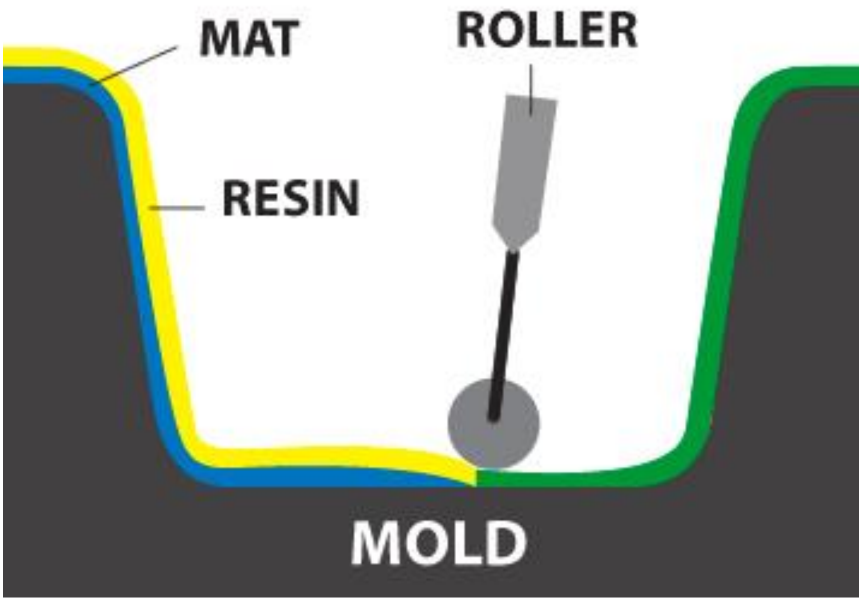

Figure 3 Hand Lay-Up Method

3.1.2 Vacuum Bagging:

Similar to the hand lay-up method, but the composite material on the mold is covered with a vacuum bag, and vacuum is applied to remove excess resin and air bubbles. This method ensures higher quality and uniformity. Vacuum bagging is an advanced composite manufacturing technique that enhances the hand lay-up process by using vacuum pressure to remove air bubbles and excess resin. This results in higher quality, stronger, and lighter composite parts.

Preparation:
-Material Preparation: Composite materials such as fiber reinforcements (e.g., fiberglass, carbon fiber) and resin are prepared. The resin is typically mixed with a hardener to initiate the curing process.
-Mold Preparation: The mold, which defines the shape of the final product, is cleaned thoroughly. A release agent is applied to the mold surface to ensure easy removal of the cured composite part.

Layer Placement:
-Gel Coat Application: For parts requiring a smooth surface finish, a gel coat is first applied to the mold. This coat is allowed to partially cure before the reinforcement layers are added.
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Resin Application:

-Manual Impregnation: Resin is applied manually to the fiber layers using brushes, rollers, or spray guns. The resin must fully saturate the fibers to ensure proper bonding and eliminate air pockets.
-Consolidation: The resin and fiber layers are consolidated using hand rollers to ensure even distribution of resin and removal of trapped air bubbles.

Vacuum Bagging Setup:

-Peel Ply: A peel ply is placed on top of the last layer of resin-impregnated fiber. This layer helps in the removal of the bagging materials and provides a textured surface for secondary bonding.
-Breather/Bleeder Cloth: A breather or bleeder cloth is placed over the peel ply. This material allows air and excess resin to flow through and be absorbed, ensuring uniform vacuum pressure distribution.
-Vacuum Bag: A vacuum bag is placed over the entire assembly and sealed around the edges of the mold. The bag must be airtight to maintain the vacuum pressure.

Vacuum Application:

-Vacuum Pump: A vacuum pump is connected to the vacuum bag through a valve. The pump removes air from the bag, creating a vacuum that applies pressure evenly across the composite lay-up.
-Vacuum Level Control: The vacuum level is continuously monitored and adjusted to ensure optimal pressure is maintained throughout the curing process.

Curing:

-Ambient Curing: The composite part is allowed to cure at room temperature. The vacuum pressure helps remove air bubbles and excess resin, resulting in a denser and stronger part.
-Accelerated Curing: For faster curing, the part can be placed in a heated environment, such as an oven, to speed up the process.

Removal from Mold:

-Demolding: Once the part has fully cured, the vacuum bag, breather cloth, and peel ply are removed. The composite part is then carefully taken out of the mold.
-Finishing: The cured part may require trimming, sanding, or other finishing processes to achieve the desired final shape and surface quality.

Advantages and Disadvantages:

-Improved Quality: Vacuum bagging produces higher quality parts with fewer air bubbles and voids, resulting in stronger and more durable composites.
-Better Resin Distribution: The vacuum pressure ensures even resin distribution, reducing excess resin and making the part lighter.
Consistency: This method provides more consistent results compared to hand lay-up alone.
-Higher Cost: The vacuum bagging process requires additional materials and equipment, such as vacuum pumps and bags, increasing the overall cost.
-Complexity: This method is more complex and time-consuming than hand lay-up, requiring careful setup and monitoring.
-Skill Requirement: Proper execution of vacuum bagging requires skilled technicians to ensure optimal results.

Vacuum bagging is a valuable technique for producing high-quality composite parts, particularly for applications that demand precision, strength, and lightweight properties.

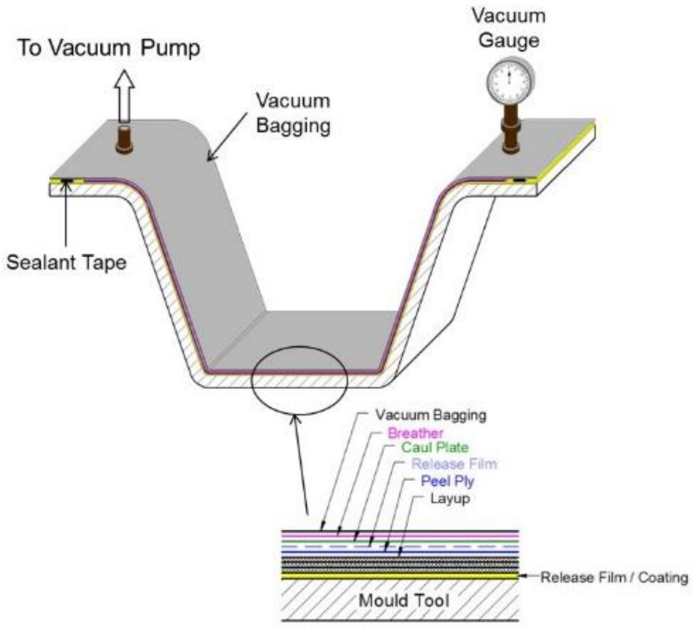


Figure 4 Vacuum Bagging Method

3.1.3 Resin Transfer Molding (RTM):

In this method, the reinforcement material is placed in a mold, and the mold is closed. Resin is injected into the mold at low pressure, thoroughly wetting the reinforcement material. RTM is suitable for high-volume and complex-shaped parts. Resin Transfer Molding (RTM) is a closed-mold process used to produce high-quality composite parts with complex shapes. It is known for its ability to produce parts with a high degree of precision and excellent surface finish.

Preparation:
-Material Preparation: Fiber reinforcements (e.g., fiberglass, carbon fiber) are prepared. These can be in the form of fabrics, mats, or preforms.
-Mold Preparation: The mold, which defines the shape of the final product, is cleaned thoroughly. A release agent is applied to the mold surface to ensure easy removal of the cured composite part.

Preform Placement:
-Preform Assembly: The fiber reinforcements are assembled into the desired shape and placed in the mold. These preforms are often stitched or bonded to maintain their shape.
-Mold Closing: The mold is then closed and sealed. RTM typically uses a two-part mold (a top and bottom half) that can be clamped together to ensure a tight seal.

Resin Injection:
-Injection System Setup: An injection system is connected to the mold. This system includes a resin reservoir, pumps, and injection lines.
-Resin Mixing: The resin is mixed with a hardener or catalyst to initiate the curing process. This mixture is then prepared for injection.
-Resin Injection: The mixed resin is injected into the mold under pressure. The resin flows through the mold, impregnating the fiber reinforcements and filling the entire cavity. The pressure ensures that the resin reaches all areas of the mold and displaces any trapped air.

Curing:
-Curing Process: The injected resin is allowed to cure inside the mold. The curing time can vary depending on the type of resin and the part's thickness. During this process, the resin hardens and

bonds with the fiber reinforcements, creating a solid composite part.
-Temperature Control: In some cases, the mold may be heated to accelerate the curing process and improve the resin's flow characteristics.

Demolding:

-Mold Opening: Once the resin has fully cured, the mold is opened, and the composite part is carefully removed.
-Post-Curing (if necessary): In some cases, the part may require additional curing in an oven to achieve the desired mechanical properties.

Finishing:

-Trimming and Sanding: The cured part may require trimming to remove excess material and achieve the final desired dimensions.
-Surface Finish: Additional surface finishing processes, such as sanding or coating, may be applied to achieve the desired surface quality.

Advantages and Disadvantages:

-High Quality: RTM produces parts with excellent surface finish and high dimensional accuracy.
Complex Shapes: This process is suitable for manufacturing complex shapes and intricate designs.
-Consistent Properties: The closed-mold process ensures consistent resin distribution and mechanical properties across the part.
-Reduced Waste: The closed mold minimizes resin waste and reduces emissions of volatile organic compounds (VOCs).
-High Initial Cost: The tooling and equipment costs for RTM are higher compared to open-mold processes.
-Longer Cycle Times: The curing process can be longer, depending on the resin system and part thickness.
-Complexity: The process setup and control require skilled technicians to ensure optimal results.

Resin Transfer Molding is a highly effective method for producing high-quality composite parts, particularly for applications requiring precision, strength, and complex geometries. It is widely used in industries such as aerospace, automotive, marine, and wind energy.

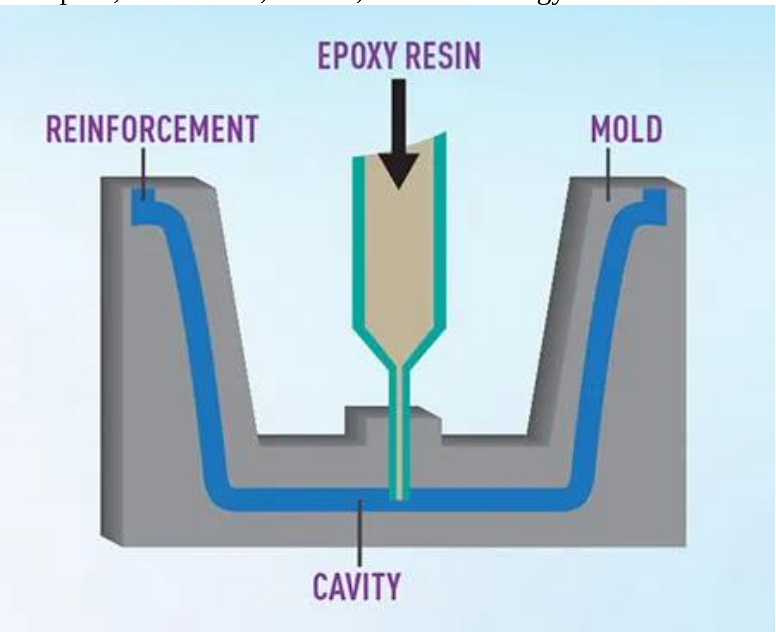


Figure 5 Resin Transfer Method

3.1.4 Autoclave Molding:

Autoclave molding is a process used in the production of composite materials, particularly for applications requiring high performance and superior mechanical properties.

Preparation:

-Material Preparation: Firstly, composite material layers (usually carbon fiber or glass fiber) and resin are prepared. These layers are placed into a mold to take the desired shape.
-Mold Preparation: The mold is where the composite material is placed to achieve the desired shape. The mold surface is cleaned, and a release agent is applied if necessary.

Placement:

-Layer Placement: Composite material layers are placed into the mold in a specific order and orientation. These layers are usually placed manually or with automated machines.
-Vacuum Bag: A vacuum bag is placed over the composite layers. This bag is sealed at the edges to create an airtight seal.

Vacuum Application:

-Vacuum System: The air inside the vacuum bag is removed using a vacuum pump. This process removes air bubbles and excess resin between the composite layers.
-Vacuum Control: The vacuum level is continuously monitored and adjusted.

Curing in the Autoclave:

-Autoclave: The mold prepared with the vacuum bag is placed in an autoclave, a specialized chamber that applies pressure and heat.
-Pressure and Heat Application: The autoclave is operated according to a specific pressure and temperature program. High pressure ensures that the composite layers bond tightly and increase material density. Heat ensures the resin cures (polymerizes).
-Curing Time: The autoclave applies pressure and heat for a specified period (depending on the type and thickness of the material).

Cooling and Removal:

-Cooling: After the curing process is complete, the autoclave is slowly cooled down.
Removing from the Mold: Once cooling is complete, the vacuum bag is removed, and the composite part is carefully taken out of the mold.

Advantages and Disadvantages:

-High Strength and Durability: Autoclave molding ensures composite materials have excellent mechanical properties.
-Homogeneous Structure: The vacuum and pressure applications minimize air bubbles and voids within the material, resulting in a more uniform structure.
-High Quality: This method is preferred in industries requiring high performance, such as aerospace, automotive, and sports equipment.
-High Cost: Autoclave equipment and processes are quite expensive.
-Long Production Time: The curing time and preparation processes can be longer compared to other manufacturing methods.

Autoclave molding is a manufacturing process that ensures composite materials have superior properties but comes with higher costs and longer production times. Therefore, it is commonly used in industries that require high performance and precision.

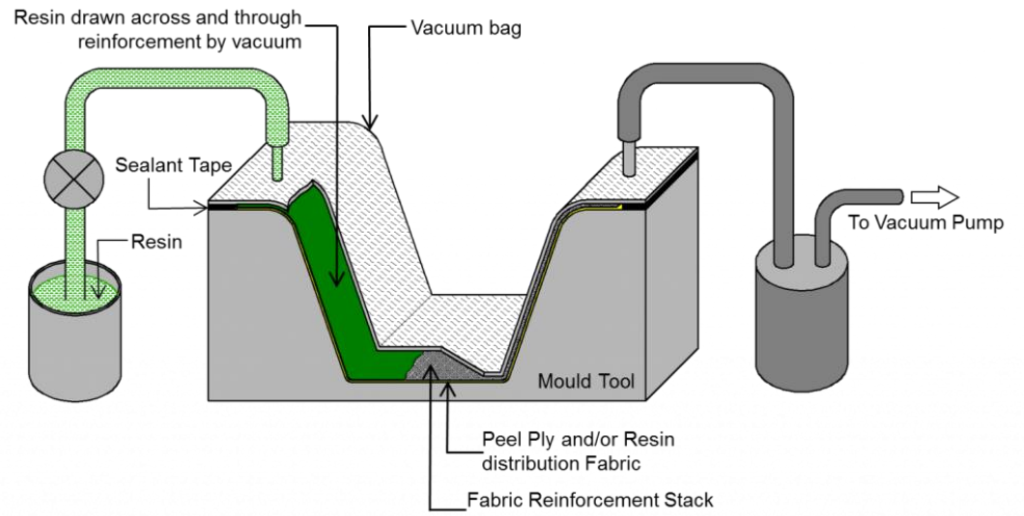


Figure 6 Autoclave Molding Method

3.1.5 Pultrusion:

Pultrusion is a continuous manufacturing process used to create high-strength, lightweight composite materials with a constant cross-sectional shape. It is commonly used to produce structural profiles such as beams, rods, and tubes.

Material Preparation:

-Fiber Reinforcements: Continuous fiber reinforcements, such as fiberglass, carbon fiber, or aramid fibers, are prepared. These fibers are typically supplied on spools.
-Resin System: A liquid resin system, usually consisting of a resin and a hardener, is prepared. The resin can be polyester, vinyl ester, epoxy, or another thermosetting resin.

Fiber Impregnation:

-Fiber Guidance: The fibers are guided from the spools through a series of guides and tensioning devices to ensure they are aligned and properly tensioned.
-Resin Impregnation: The aligned fibers are pulled through a resin bath or impregnator where they are thoroughly saturated with the resin. The resin must fully impregnate the fibers to ensure proper bonding and structural integrity.

Preforming:

-Preforming System: After impregnation, the wet fibers are guided through a preforming system. This system shapes the fibers into the approximate final cross-sectional shape and removes excess resin.

Pultrusion Die:

-Heated Die: The preformed, resin-impregnated fibers are pulled through a heated die. The die is precisely machined to the desired cross-sectional shape of the final product.
-Curing: As the fibers pass through the heated die, the resin cures and hardens, bonding the fibers together and forming a rigid composite profile. The heat and pressure applied in the die ensure proper curing and consolidation of the composite material.

Pulling Mechanism:

-Continuous Pulling: A continuous pulling mechanism, typically using hydraulic or mechanical grippers, pulls the cured composite profile through the die. The pulling speed and force are carefully controlled to ensure consistent quality.

Cutting and Finishing:

-Continuous Cutting: The continuous composite profile is cut to the desired length using a cutting saw

or other cutting devices. This is usually done automatically to maintain production efficiency.
-Finishing: The cut profiles may undergo additional finishing processes such as sanding, drilling, or coating to meet specific application requirements.

Advantages and Disadvantages:

-High Strength and Lightweight: Pultruded composites have a high strength-to-weight ratio, making them ideal for structural applications.
-Consistent Quality: The continuous nature of the process ensures uniform material properties and consistent cross-sectional dimensions.
-Efficient Production: Pultrusion is a highly efficient process that can produce large volumes of composite profiles with minimal waste.
-Corrosion Resistance: Pultruded composites are resistant to corrosion, making them suitable for harsh environments.
-Limited Shapes: Pultrusion is limited to producing profiles with constant cross-sectional shapes.
-Initial Setup Cost: The tooling and equipment for pultrusion can be expensive, making it less suitable for low-volume production.
-Complexity in Process Control: Maintaining consistent quality requires precise control of the process parameters, which can be complex.

Pultrusion is a versatile and efficient manufacturing process that produces high-quality composite materials with excellent mechanical properties and corrosion resistance, making it widely used in various industries.

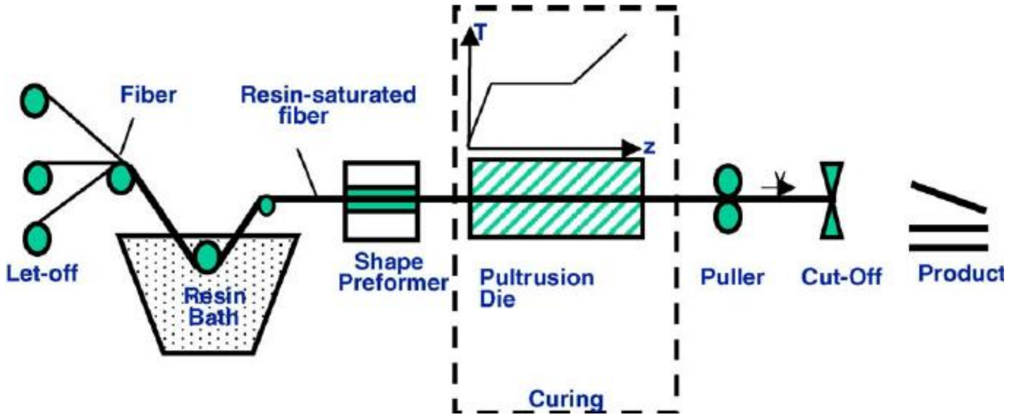


Figure 7 Pultrusion Method

3.2 Applications and Uses of Composite Materials

Composite materials are popular in various industries due to their lightweight, high strength, corrosion resistance, and design flexibility.
Aerospace: Composite materials are widely used in aircraft bodies, wings, and space vehicles, offering lightweight and high-strength solutions that improve fuel efficiency and performance. There are a few and most known examples about the application of composite materials below.

Aerospace:

-Aircraft Structures: Fuselages, wings, and tail sections.
-Spacecraft: Satellite components, rocket casings, and panels.
-Helicopter Blades: Lightweight and durable rotor blades.

Automotive:

-Body Panels: Lightweight panels to reduce vehicle weight and improve fuel efficiency.
-Frames and Chassis: Enhanced strength and reduced weight for better performance.
-Interior Components: Dashboards, seats, and other interior parts.

Marine:
-Boat Hulls: Lightweight and corrosion-resistant hulls for ships and boats.
-Deck Structures: Strong and durable deck materials.
-Propellers: High-performance and durable propellers.

Construction:
-Building Panels: Lightweight and strong panels for walls, roofs, and floors.
-Bridges: Durable and lightweight bridge components.
-Reinforced Concrete: Use of composite materials to reinforce concrete structures.

Wind Energy:
-Wind Turbine Blades: High-strength and lightweight blades for efficient energy conversion.
-Nacelles: Durable housings for turbine components.

Sports and Recreation:
-Bicycles: Lightweight and strong frames for bicycles.
-Golf Clubs: High-performance and lightweight golf club shafts.
-Fishing Rods: Durable and flexible fishing rods.

Medical:
-Prosthetics: Lightweight and strong materials for artificial limbs.
-Medical Implants: Durable and biocompatible materials for implants.
-Orthopedic Devices: Strong and lightweight materials for braces and supports.

Electronics:
-Printed Circuit Boards (PCBs): High-performance and lightweight materials for PCBs.
-Enclosures: Durable and lightweight housings for electronic devices.

Defense Industry:
-Armored Vehicles: Lightweight and strong armor for military vehicles.
-Protective Gear: High-strength materials for helmets and body armor.
-Aircraft and Naval Components: Lightweight and durable components for military aircraft and ships.

3.3 Most Common Composites

3.3.1 Carbon Fibers

What is Carbon Fiber?
Carbon fiber is composed of thin, strong crystalline filaments of carbon that are used to strengthen material. These fibers are extremely strong and are used in high-performance applications in a variety of industries. The development of carbon fiber began in the early 1960s and has since become a crucial material in modern engineering and manufacturing.

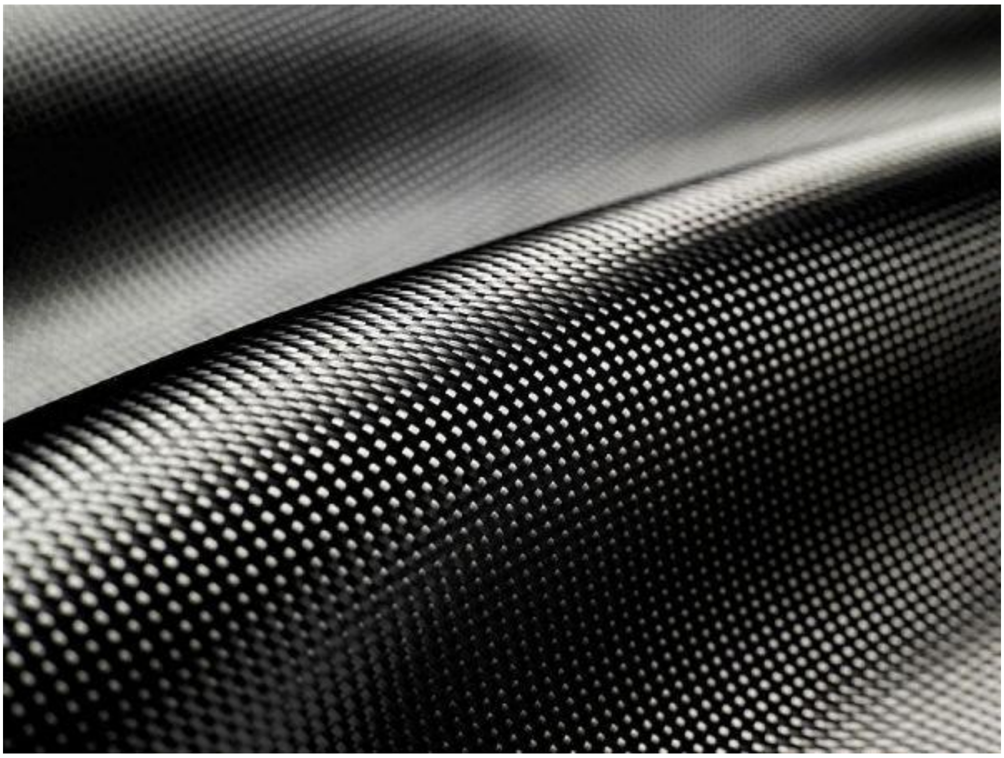


Figure 8 Carbon Fiber Fabric

Properties of Carbon Fiber
High Strength-to-Weight Ratio
Imagine something stronger than steel but much lighter – that's carbon fiber. It's perfect for situations where you need to cut down on weight without sacrificing strength.

High Stiffness
Carbon fiber is incredibly stiff, meaning it doesn't bend or deform easily, which is essential for many high-performance applications.

Corrosion Resistance
This material doesn't rust or degrade when exposed to harsh chemicals or environmental conditions, giving products a longer lifespan.

Thermal Conductivity
Carbon fiber can conduct heat well, which is great for applications that need efficient heat dissipation.

Low Thermal Expansion
It doesn't expand or contract much with temperature changes, so it stays stable and maintains its shape.

Electrical Conductivity
Because it conducts electricity, carbon fiber can be used in electrical applications.

Fatigue Resistance
Carbon fiber can withstand repeated stress and strain without losing its structural integrity, making it very durable.

Types of Carbon Fiber
PAN-Based Carbon Fiber
Made from polyacrylonitrile (PAN), these fibers are the most common and are known for their high

strength and stiffness. They're used in everything from airplanes to sports equipment.

Pitch-Based Carbon Fiber
These fibers come from petroleum or coal tar pitch and are known for their high modulus and thermal conductivity. They're used where high stiffness and heat management are needed.

Rayon-Based Carbon Fiber
These are less common and are used in specific applications that benefit from their unique properties.

Manufacturing Process of Carbon Fiber
Precursor Preparation
Raw Material
The starting material, usually PAN, pitch, or rayon, is spun into fibers. This process, called melt spinning or solution spinning, produces the initial fiber structure.

Spinning
The fibers are drawn out and aligned to form a continuous filament. How this is done can affect the final properties of the carbon fiber.

Stabilization
Oxidation
The precursor fibers are heated in an oxygen-rich environment at around 200-300°C. This step, known as stabilization, changes the chemical structure of the fibers, making them stable enough to handle the next step.

Carbonization
High-Temperature Treatment
The stabilized fibers are heated to very high temperatures (1,000-3,000°C) in an inert atmosphere like nitrogen or argon. This process removes non-carbon atoms, leaving behind fibers that are almost entirely carbon. This step gives the fibers their strength and stiffness.

Surface Treatment
Chemical Treatment
The fiber surfaces are treated to improve their bonding with the resin matrix. This often involves oxidizing the fiber surface to create functional groups that help with adhesion.

Plasma Treatment
Sometimes, plasma treatment is used to roughen the fiber surface, further enhancing resin adhesion.

Sizing
Protective Coating
A sizing agent, usually a polymer, is applied to the surface-treated fibers to protect them during handling and processing and to make them compatible with the resin matrix used in composites.

Spooling
Winding
The finished carbon fibers are wound onto spools for storage and transport, ready for use in various composite manufacturing processes.

Composite Manufacturing Processes
Prepreg Lay-Up
Pre-impregnated fibers with resin are laid up in molds to form the desired shape, then cured, often in an autoclave, to create a strong, lightweight composite structure.

Filament Winding

Continuous carbon fiber strands are wound around a mandrel in a specific pattern, then impregnated with resin, commonly used for cylindrical structures like pipes and tanks.

Pultrusion
Carbon fibers are pulled through a resin bath and then through a heated die to form continuous profiles, used for structural components like beams and rods.

Compression Molding
Carbon fiber preforms are placed in a mold and subjected to heat and pressure to cure the resin, suitable for producing complex shapes with high strength and precision.

Resin Transfer Molding (RTM)
Carbon fibers are placed in a mold, and resin is injected to impregnate the fibers. The mold is then heated to cure the composite, used for medium to high-volume production of complex parts.

Applications of Carbon Fiber
Aerospace
Used in aircraft structures like wings, fuselages, and control surfaces due to its high strength-to-weight ratio and durability.

Automotive
High-performance vehicles and electric cars use carbon fiber for body panels, chassis components, and interior parts to reduce weight and improve fuel efficiency.

Figure 9 Carbon Fiber Application for Car Body Part

Sporting Goods
Found in bicycles, golf clubs, tennis rackets, and other sports equipment, carbon fiber enhances performance by reducing weight and increasing strength.

Wind Energy
Wind turbine blades made from carbon fiber composites achieve necessary strength and stiffness while minimizing weight.

Marine
Used in boat hulls, masts, and other marine components because of its resistance to corrosion and lightweight properties.

Medical Devices
Carbon fiber is used in prosthetics, orthopedic implants, and imaging equipment for its biocompatibility and radiolucency.

Advantages of Carbon Fiber
Superior Strength and Stiffness
High tensile strength and stiffness make it ideal for load-bearing applications.

Lightweight
Its low density helps reduce weight, which is crucial in aerospace, automotive, and sports applications.

Durability
Resistant to fatigue, corrosion, and environmental degradation, ensuring long service life.

Design Flexibility
Can be molded into complex shapes and tailored to specific performance requirements.

Thermal Stability
Maintains its properties over a wide range of temperatures, making it suitable for high-temperature applications.

Challenges and Considerations
Cost
Production is more expensive than traditional materials, limiting its use in cost-sensitive applications.

Brittleness
Carbon fiber can be brittle and prone to cracking or shattering under certain loading conditions.

Manufacturing Complexity
The processes are complex and require specialized equipment and expertise.

Recycling
Recycling is challenging because it's hard to separate the fibers from the resin matrix, though advances in recycling technologies are ongoing.

Carbon fiber is an incredible material offering unparalleled strength, stiffness, and lightweight properties, making it a crucial part of modern engineering and manufacturing. Its extensive use across various industries highlights its versatility and performance advantages. Understanding the properties, manufacturing processes, and applications of carbon fiber helps optimize its use and address challenges like cost and recycl

Figure 10 Carbon Fiber Tubes

Property	Value	Description
Chemical Composition	Carbon (C)	Contains 90% - 99% pure carbon
Density	1.6 - 2.0 g/cm³	High strength-to-weight ratio
Melting Point	~3500°C	High melting point due to graphite structure
Thermal Conductivity	24-34 W/mK	Lower than metals, higher than composites
Electrical Conductivity	$0.6 - 1.0 \times 10^4$ S/cm	Provides good electrical conductivity
Thermal Expansion Coefficient	-0.1×10^{-6} /°C	Near-zero thermal expansion
Heat of Combustion	~32 MJ/kg	High energy content

Table 1 Properties of Carbon Fiber

3.3.2 Aramid

Aramid, short for "aromatic polyamide," represents a class of synthetic fibers renowned for their heat resistance and exceptional strength. Famous examples include Kevlar and Nomex, both developed by DuPont. These fibers are indispensable in aerospace, military, and other industries demanding high-strength materials. Known for their excellent strength-to-weight ratio, thermal stability, and resistance to wear and chemical degradation, aramid fibers stand out in modern material science.

Properties of Aramid

High Strength-to-Weight Ratio
Aramid fibers offer outstanding tensile strength while being significantly lighter than metals, making them ideal for applications where weight is a critical factor.

Figure 11 Aramid - Kevlar Fabric

Thermal Stability
Capable of withstanding high temperatures without degrading, aramid fibers are suitable for use in extreme thermal environments.

Chemical Resistance
Aramid fibers resist a wide range of chemicals, ensuring durability in corrosive environments, which is vital for industrial applications.

Impact Resistance
With high energy absorption, aramid fibers provide excellent resistance to impact and ballistic threats, making them essential in protective gear.

Flame Resistance
Certain aramid fibers, like Nomex, are inherently flame-resistant and do not melt or drip when exposed to high temperatures, enhancing safety in fire-prone environments.

Dimensional Stability
Aramid fibers exhibit low thermal expansion, maintaining their shape and dimensions across varying temperatures, which is crucial for precision applications.

Low Electrical Conductivity
As non-conductive materials, aramid fibers are suitable for applications requiring electrical insulation, adding another layer of versatility.

Property	Value	Description
Chemical Composition	Poly(p-phenylene terephthalamide)	Contains aromatic polyamide
Density	1.44 g/cm³	Low density
Melting Point	Does not melt, decomposes at ~500°C	Decomposes rather than melting
Thermal Conductivity	0.04 W/mK	Very low thermal conductivity
Electrical Conductivity	Non-conductive	Non-conductive
Thermal Expansion Coefficient	2×10^{-6} /°C	Low thermal expansion
Heat of Combustion	~30 MJ/kg	High energy content

Table 2 Properties of Aramid

Types of Aramid

Para-Aramid
Known for its high tensile strength and modulus, para-aramid fibers like Kevlar are commonly used in body armor, aerospace components, and sporting goods.

Meta-Aramid
Featuring excellent thermal stability and flame resistance, meta-aramid fibers like Nomex are used in protective clothing, electrical insulation, and high-temperature filtration.

Manufacturing Process of Aramid

Polymerization

Monomers
The process starts with the polymerization of aromatic polyamides. Terephthaloyl chloride (TCl) and para-phenylenediamine (PPD) are typical monomers for para-aramid fibers, while isophthaloyl chloride (ICl) and meta-phenylenediamine (MPD) are used for meta-aramid fibers.

Condensation Reaction
These monomers undergo a condensation reaction to form the aramid polymer, resulting in long chains of aromatic polyamide.

Spinning

Dissolution
The aramid polymer is dissolved in a solvent, commonly concentrated sulfuric acid, to form a viscous solution.

Extrusion
The polymer solution is extruded through spinnerets to form continuous filaments in a process known as wet spinning.

Coagulation
Extruded filaments pass through a coagulation bath, where the solvent is removed, and the polymer fibers solidify.

Drawing

Orientation
The solidified fibers are drawn or stretched to align the polymer chains, increasing their crystallinity and enhancing their mechanical properties.

Heat Treatment
Drawn fibers undergo heat treatment to relieve internal stresses and further improve their mechanical properties.

Surface Treatment

Coating
Aramid fibers' surfaces are treated with coatings or finishes to enhance adhesion to the resin matrix in composite applications.

Spooling

Winding
The finished aramid fibers are wound onto spools for storage and transport, ready for use in various composite manufacturing processes.

Composite Manufacturing Processes

Prepreg Lay-Up

Pre-Impregnated Fibers
Aramid fibers are pre-impregnated with resin and laid up in molds to form desired shapes. The lay-up is followed by curing, often in an autoclave, to create strong, lightweight composite structures.

Filament Winding

Winding Process
Continuous aramid fiber strands are wound around a mandrel in specific patterns and impregnated with resin. This method is used for cylindrical structures like pipes and pressure vessels.

Pultrusion

Continuous Process
Aramid fibers are pulled through a resin bath and then through a heated die to form continuous profiles. Pultrusion is used to produce structural components with constant cross-sections, such as beams and rods.

Compression Molding

Molding Process
Aramid fiber preforms are placed in a mold and subjected to heat and pressure to cure the resin. This method is suitable for producing complex shapes with high strength and precision.

Resin Transfer Molding (RTM)

Injection Process
Aramid fibers are placed in a mold, and resin is injected to impregnate the fibers. The mold is then heated to cure the composite, used for medium to high-volume production of complex parts.

Applications of Aramid

Aerospace
Aramid fibers are used in aircraft structures, including fuselages, wings, and interiors, due to their high strength-to-weight ratio and resistance to impact and fatigue.

Military and Defense
Widely used in ballistic-resistant body armor, helmets, and vehicle armor, aramid fibers offer exceptional impact resistance and energy absorption capabilities.

Figure 12 Army Kevlar Made of Aramid

Automotive
In automotive components such as tires, brake pads, and hoses, aramid fibers enhance durability and performance.

Protective Clothing
Meta-aramid fibers like Nomex are used in fire-resistant clothing for firefighters, industrial workers, and military personnel due to their flame resistance and thermal stability.

Electrical and Electronics
Aramid fibers are used in electrical insulation materials, cables, and circuit boards for their non-conductive and heat-resistant properties.

Sporting Goods
High-performance sporting equipment such as helmets, rackets, and composite hockey sticks benefit from aramid fibers' lightweight and high-strength characteristics.

Advantages of Aramid

High Strength and Durability
Aramid fibers provide excellent tensile strength and durability, making them suitable for demanding applications.

Thermal and Chemical Resistance
Withstanding high temperatures and chemical exposure, aramid fibers ensure long-term performance.

Lightweight
The low density of aramid fibers contributes to weight reduction in various applications, enhancing performance and efficiency.

Impact and Abrasion Resistance
Aramid fibers' high impact resistance and energy absorption provide protection in ballistic and high-impact scenarios.

Flame Resistance
Certain aramid fibers are inherently flame-resistant, providing safety in fire-prone environments.

Challenges and Considerations

Cost
The production of aramid fibers is relatively expensive, which can limit their use in cost-sensitive applications.

Processing Difficulties
Due to their high melting point and chemical resistance, aramid fibers can be challenging to process, requiring specialized equipment and techniques.

Brittleness
Despite their strength, aramid fibers can be brittle and prone to microcracking under certain conditions.

Recycling
Recycling aramid fibers is challenging, and efforts are ongoing to develop efficient recycling methods for these materials.

Aramid fibers are a remarkable class of materials offering exceptional strength, thermal stability, and resistance to impact and chemical degradation. Their extensive use across various industries highlights their versatility and performance advantages.
Understanding the properties, manufacturing processes, and applications of aramid fibers helps in optimizing their use and addressing the challenges associated with their cost and processing difficulties. As technology advances, aramid fibers are expected to play an increasingly vital role in innovative and high-performance solutions.

Figure 13 Gloves Made of Aramid

3.3.3 Fiberglass

Fiberglass, also known as glass-reinforced plastic (GRP) or glass-fiber reinforced plastic (GFRP), is a remarkable material that combines strength and lightweight properties. Made from fine glass fibers woven into a fabric and bonded with a resin, fiberglass is widely used in various industries due to its versatility, durability, and cost-effectiveness. This guide will provide a comprehensive overview of fiberglass, its properties, manufacturing processes, applications, advantages, and challenges.

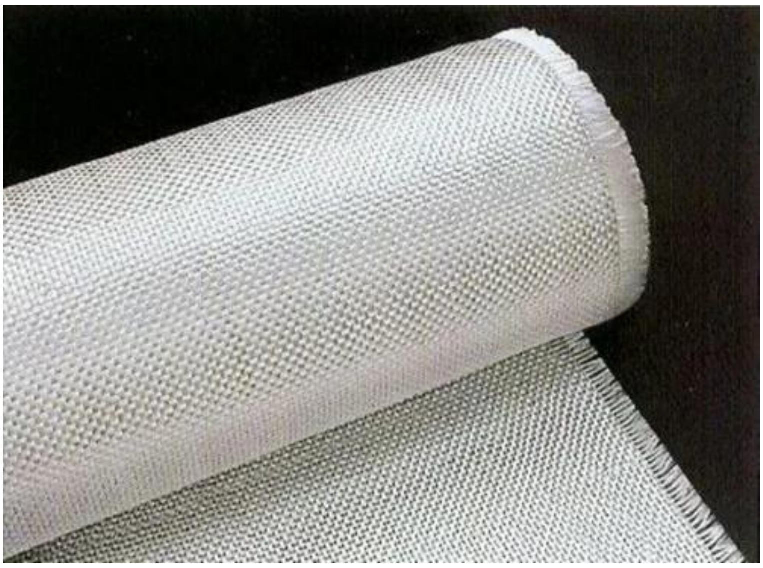


Figure 14 Fiberglass Fabric

Overview of Fiberglass
Fiberglass is a composite material made from thin strands of glass woven into a fabric and combined with a resin matrix. This combination results in a material that is both strong and lightweight, suitable for a wide range of applications in different industries.

Property	Value	Description
Chemical Composition	SiO_2, Al_2O_3, CaO, MgO	Contains silica, alumina, calcium oxide, magnesium oxide
Density	2.54 g/cm³	Moderate density
Melting Point	~1400°C	High melting point
Thermal Conductivity	0.04-1.4 W/mK	Varies with type
Electrical Conductivity	Non-conductive	Non-conductive
Thermal Expansion Coefficient	5×10^{-6} /°C	Moderate thermal expansion
Heat of Combustion	Non-flammable	Non-flammable

Table 3 Properties of Fiberglass

Importance in Modern Industries
Fiberglass has become an essential material in modern industries due to its unique properties. It is used in automotive, marine, construction, and sports equipment, among other applications. Its versatility

and performance make it a valuable choice for engineers and designers.

What is Fiberglass?

Definition and Basic Properties

Fiberglass is composed of fine glass fibers woven into a fabric and combined with a resin matrix. The resulting composite material is known for its high strength, lightweight, and resistance to corrosion and environmental degradation.

Properties of Fiberglass

High Strength-to-Weight Ratio

Fiberglass is strong yet lightweight, making it ideal for applications where reducing weight is crucial without compromising strength.

Corrosion Resistance

Fiberglass is highly resistant to corrosion, making it suitable for use in harsh environments and marine applications.

Electrical Insulation

Unlike carbon fiber, fiberglass is an excellent electrical insulator, which makes it ideal for electrical and electronic applications.

Thermal Insulation

Fiberglass has good thermal insulation properties, providing effective heat resistance and stability in high-temperature environments.

Flexibility and Durability

Fiberglass is flexible and durable, allowing it to withstand impact and stress without permanent deformation or damage.

Types of Fiberglass

E-Glass (Electrical Glass)

E-Glass is the most common type of fiberglass, known for its excellent electrical insulation properties and good mechanical strength.

S-Glass (Structural Glass)

S-Glass offers higher strength and stiffness compared to E-Glass, making it suitable for high-performance applications.

C-Glass (Chemical Glass)

C-Glass is designed for chemical resistance, making it ideal for applications involving exposure to corrosive chemicals.

Manufacturing Process of Fiberglass

Raw Material Preparation

The process begins with the preparation of raw materials, including silica sand, limestone, and soda ash, which are melted to form molten glass.

Fiber Formation

The molten glass is extruded through fine holes in a platinum bushing to create continuous glass filaments. These filaments are rapidly cooled and coated with a sizing agent to protect them during handling.

Weaving

The glass filaments are woven into a fabric using various weaving techniques to create different patterns and structures, depending on the desired properties and applications.

Resin Application

The woven glass fabric is impregnated with a resin matrix, typically polyester, vinyl ester, or epoxy resin, to form a composite material. The resin bonds the glass fibers together, providing additional strength and rigidity.

Curing

The resin-impregnated fiberglass is cured under heat and pressure to harden the material and achieve the desired mechanical properties.

Finishing

The cured fiberglass is cut, shaped, and finished to meet specific application requirements. This may include additional treatments such as surface coatings or painting.

Composite Manufacturing Processes

Hand Lay-Up

In the hand lay-up process, layers of fiberglass fabric are manually placed in a mold and impregnated with resin. The layers are then cured to form a composite structure. This method is suitable for producing large, complex shapes with moderate production volumes.

Spray-Up

The spray-up process involves spraying chopped fiberglass strands and resin onto a mold. This method is faster than hand lay-up and is used for creating large, relatively simple shapes.

Filament Winding

Continuous fiberglass strands are wound around a mandrel in a specific pattern and impregnated with resin. This process is commonly used for cylindrical structures like pipes and tanks.

Pultrusion

Fiberglass rovings are pulled through a resin bath and then through a heated die to form continuous profiles. Pultrusion is used to produce structural components like beams and rods with consistent cross-sections.

Resin Transfer Molding (RTM)

In RTM, fiberglass is placed in a mold, and resin is injected to impregnate the fibers. The mold is then heated to cure the composite, making it suitable for medium to high-volume production of complex parts.

Applications of Fiberglass

Automotive

Fiberglass is used in automotive components such as body panels, hoods, and roofs to reduce weight and improve fuel efficiency.

Marine

Fiberglass is extensively used in boat hulls, decks, and other marine structures due to its corrosion resistance and lightweight properties.

Construction

In construction, fiberglass is used for roofing, insulation, and reinforcement of concrete structures, providing strength and durability.


Figure 15 Fiberglass Prepared for Wind Turbine

Sporting Goods
Fiberglass is found in sports equipment such as skis, surfboards, and hockey sticks, enhancing performance through its strength and flexibility.

Electrical and Electronics
Fiberglass is used in electrical insulation, circuit boards, and other electronic components due to its excellent electrical insulating properties.

Figure 16 Fiberglass Sheets

Advantages of Fiberglass
Cost-Effectiveness
Fiberglass is more affordable than many high-performance materials like carbon fiber, making it a cost-effective choice for various applications.

Corrosion Resistance
Its resistance to corrosion and environmental degradation ensures long service life in harsh conditions.

Lightweight
The low density of fiberglass helps reduce weight, which is beneficial in applications like automotive and aerospace.

Versatility
Fiberglass can be molded into complex shapes and tailored to meet specific performance requirements.

Insulating Properties
Its excellent electrical and thermal insulating properties make it suitable for a wide range of applications.

Challenges and Considerations
Brittleness
Fiberglass can be brittle and may crack or shatter under certain loading conditions.

Health and Safety
Handling fiberglass can cause skin irritation and respiratory issues, requiring proper safety measures.

Environmental Impact
The production and disposal of fiberglass can have environmental impacts, though efforts are ongoing to develop more sustainable practices.

Fiberglass is a versatile and cost-effective material with a wide range of applications across various industries. Its unique combination of strength, lightweight, and resistance to corrosion and environmental degradation makes it an invaluable material in modern engineering and manufacturing. Understanding the properties, manufacturing processes, and applications of fiberglass helps optimize its use and address challenges like brittleness and environmental impact.

Few important questions about our main material:

What is the primary use of fiberglass?
Fiberglass is primarily used in automotive, marine, construction, and sporting goods industries due to its strength, lightweight, and corrosion resistance.

How is fiberglass different from carbon fiber?
Fiberglass is more cost-effective and has excellent electrical insulation properties, while carbon fiber offers higher strength and stiffness but at a higher cost.

Can fiberglass be recycled?
Fiberglass recycling is challenging due to the difficulty in separating fibers from the resin matrix, but advancements in recycling technologies are ongoing.

What makes fiberglass so versatile?
Fiberglass's versatility comes from its combination of strength, lightweight, corrosion resistance, and ability to be molded into complex shapes.

Is fiberglass expensive to produce?
Fiberglass is generally more affordable to produce than high-performance materials like carbon fiber, making it a cost-effective choice for many applications.

3.4 Calculation of Resin Content in Fiberglass Composites

3.4.1 Introduction

Fiberglass composites are widely used in various industries due to their excellent strength-to-weight ratio, corrosion resistance, and versatility. The performance of these composites largely depends on the resin content, which must be carefully calculated to achieve the desired mechanical properties. The resin acts as a matrix that binds the fibers together, providing shape and transferring loads between fibers. This article outlines the theoretical background and calculation method for determining the appropriate resin content in fiberglass composites.

Theoretical Background

The resin content in a composite can be estimated using the fiber volume fraction (FVF), which is the ratio of the volume of fibers to the total volume of the composite. The fiber areal weight (FAW) is the weight of the fibers per unit area and is typically provided by the fiber manufacturer. The total resin weight required can be calculated using these parameters.

Calculation Method

Parameters:

1. Fiber Volume Fraction (FVF): V_f
2. Fiber Areal Weight (FAW): W_f
3. Density of Fiber (ρ_f)
4. Density of Resin (ρ_f)
5. Composite Thickness (t)

Steps:

1. Calculate the Volume of Fibers per Unit Area:

$$V_f = \frac{Wf}{(\rho_f \times t)}$$

2. Determine the Total Volume of Composite per Unit Area:

$$V_c = \frac{1}{t}$$

3. Calculate the Volume of Resin per Unit Area:

$$V_r = V_c - V_f$$

4. Convert the Volume of Resin to Weight:

$$W_r = V_r \times \rho_r$$

5. Calculate the Total Weight of Resin Required for the Composite:

Total Resin Weight = W_r x A

where A is the total area of the composite.

Example Calculation

Given:

Fiber Areal Weight (FAW): 600 g / m^2
Density of Fiber (ρ_f): 2.54 g / cm^3
Density of Resin (ρ_r): 1.2 g / cm^3
Composite Thickness (t): 2 mm (0.2 cm)
Total Area of Composite (A): 1 m^2

Calculation:

1. Calculate the Volume of Fibers per Unit Area:

$$V_f = 600 \text{ g / m}^2 / (2.54 \text{ g / cm}^3 \text{ x } 0.2 \text{ cm}) = 600 / (2.54 \text{ x } 0.2) \approx 118.11 \text{ cm}^3 / \text{m}^2$$

2. Determine the Total Volume of Composite per Unit Area:

$$V_c = 1 / 0.2 \text{ cm} = 5000 \text{ cm}^3 / \text{m}^2$$

3. Calculate the Volume of Resin per Unit Area:

$$V_r = 5000 \text{ cm}^3 / \text{m}^2 - 118.11 \text{ cm}^3 / \text{m}^2 \approx 4881.89 \text{ cm}^3 / \text{m}^2$$

4. Convert the Volume of Resin to Weight:

$$W_r = 4881.89 \text{ cm}^3 / \text{m}^2 \text{ x } 1.2 \text{ g / cm}^3 \approx 5858.27 \text{ g/ m}^2$$

5. Calculate the Total Weight of Resin Required for the Composite:

$$\text{Total Resin Weight} = 5858.27 \text{ g / m}^2 \text{ x } 1 \text{ m}^2 = 5858.27 \text{ g}$$

The calculated resin content for a fiberglass composite with the given parameters is approximately 5858.27 grams per square meter. This method provides a systematic approach to determining the appropriate amount of resin, ensuring the composite achieves the desired mechanical properties and performance. Accurate resin content calculation is essential for optimizing the manufacturing process and the final quality of the composite material.

Now we shall see the cost calculation.

3.4.2 Cost Calculation

From the informations above, we will take these parameters.
Source of prices of resine, fiberglass and other things will giving at the references but they had taken from e-shopping site.

Fiberglass Cost:

Weight of fiberglass for 1 m^2: 600 g = 0.6 kg
Cost: 0.6 kg x \$5.00/kg = \$3.00

Resin Cost:

Weight of resin for 1 m²: 5858.27 g = 5.858 kg
Cost: 5.858 kg x $4.00/kg = $23.43

Total Material Cost:

Total Cost per m² = Fiberglass Cost + Resin Cost
Total Cost per m² = $3.00 + $23.43 = $26.43

Additional Costs:

Labor, energy, and equipment costs can vary widely depending on the manufacturing process and location. For estimation, assume an additional $15.00 per m² for labor, energy, and equipment.

Total Production Cost:

Total Production Cost per m² = Material Cost + Additional Costs
Total Production Cost per m² = $26.43 + $15.00 = $41.43

3.4.3 Conclusion

The estimated production cost for fiberglass composites is approximately $41.43 per square meter. This calculation provides a basic understanding of the costs involved and can be adjusted based on specific manufacturing conditions and material prices. Accurate cost estimation helps manufacturers and engineers optimize their production processes and manage costs effectively. If check for our robot its nearly 13600 mm^2 and its equal to 0.0136 m^2 it looks like so cheap but it definitely needs large sheets to produce and machinery. If we calculate the price except in machinery. Also for our project we supplied completed Fiberglass Sheet, Kapton film and Adhesive that increase cost per robot.

4. Design

Our source from which we obtained the parameters during the design process was Ori-Pixel, a multi-DoFs origami pixel for modular reconfigurable surfaces (M. Salerno, J. Paik and S. Mintchev, 2020) and A portable three-degrees-of-freedom force feedback origami robot for human–robot interactions (Stefano Mintchev, Marco Salerno, Alexandre Cherpillod, Simone Scaduto and Jamie Paik, 2019). A research mentioned in the article indicates that the 'd' distance shown below should be at least 70mm for 3 servo motors. In the light of this information, we drew our link 1 piece as 72mm. We used AutoCad and Solidworks. We carried out laser cutting and water jet cutting by uploading our AutoCad drawing to the machine.

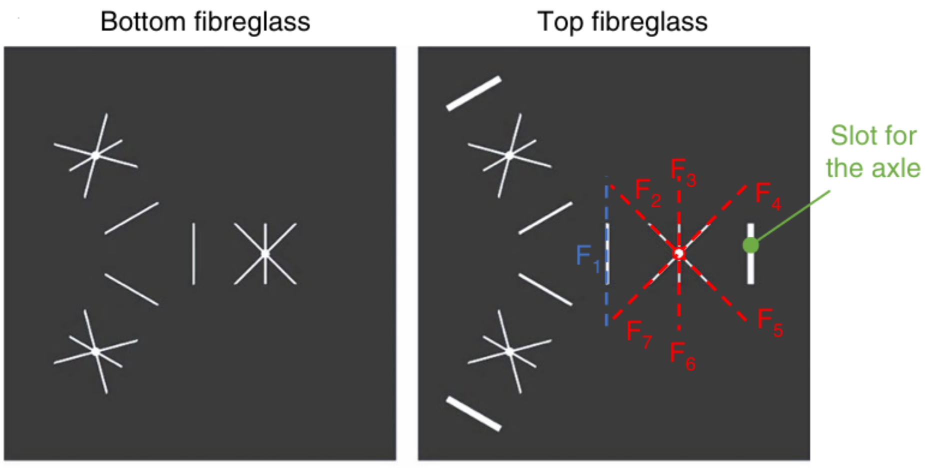


Figure 17 Bottom And Top Fiberglasses Cutting Sketch

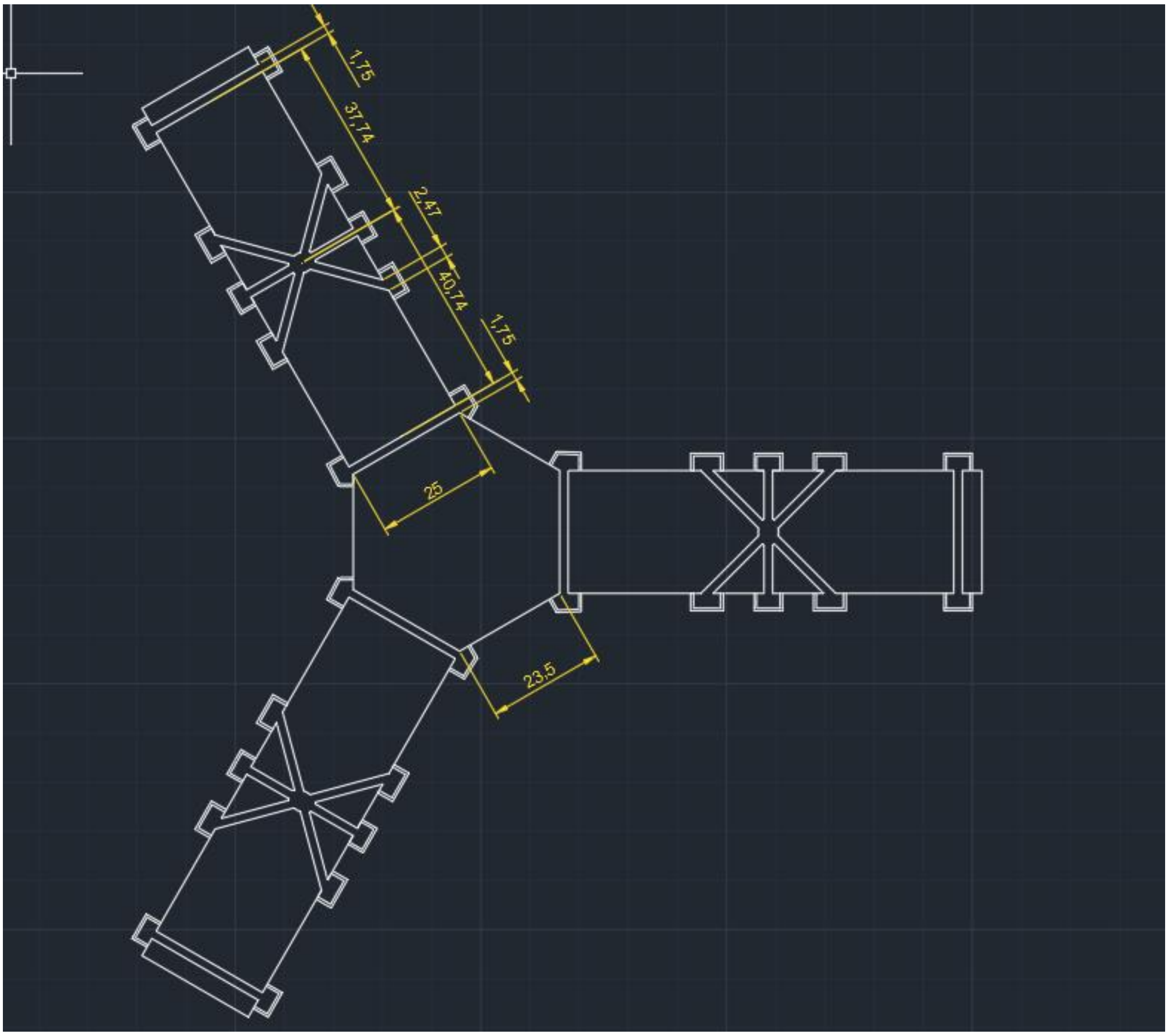


Figure 18 AutoCad Design for RSR Robot

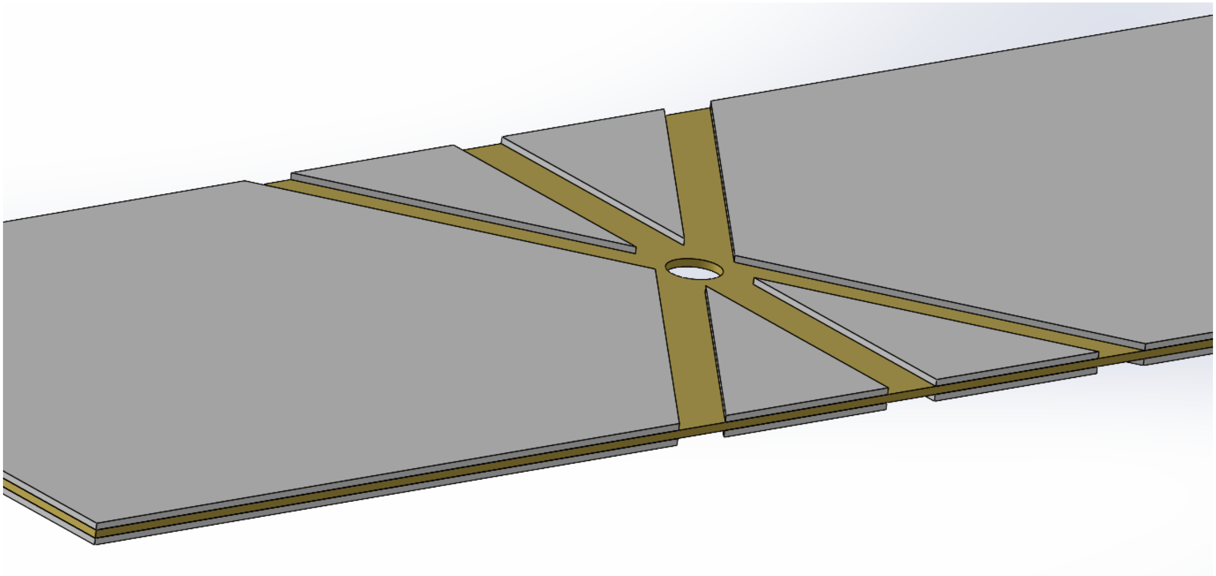


Figure 19 Spherical Joint Drawing on SolidWorks

Design Parameters

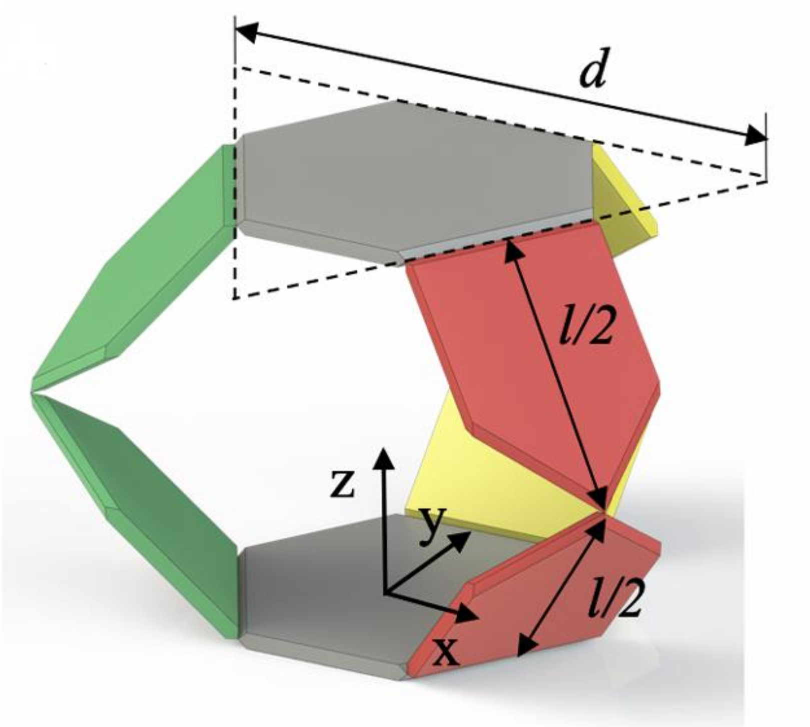


Figure 20 Minimum Diamension Allowance Shown as d [Salerno 70mm]

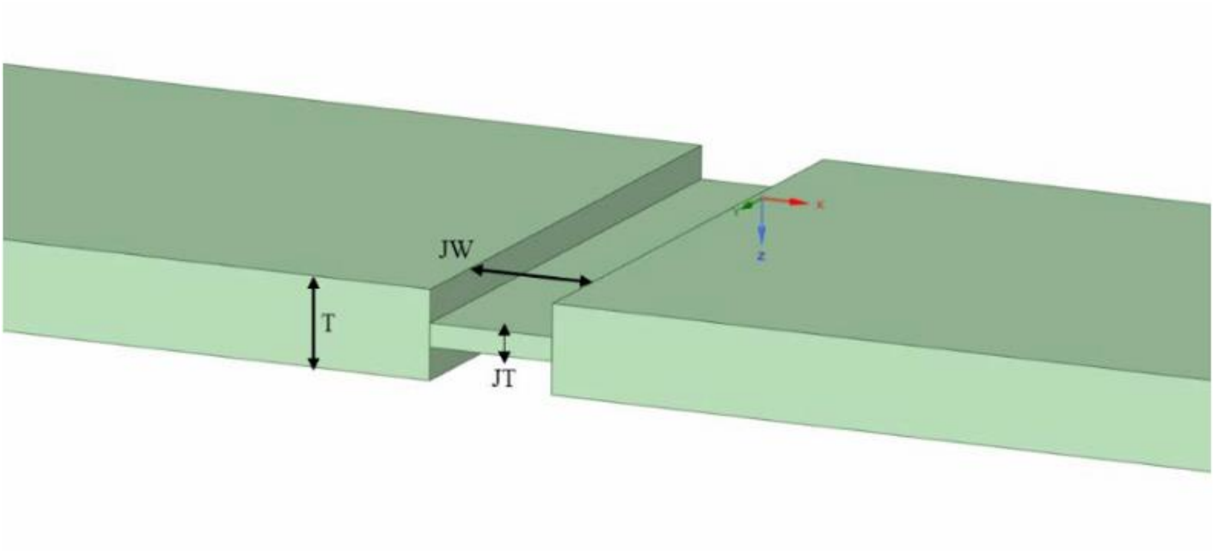


Figure 21 Revolute Joint Parameters

$$JW \geq 0.5 \times \pi \times T$$

Calculation for our design $0.5 \times \pi \times (0.5 + 0.5 + 0.075) = 1.69$ mm

5. Process and Experiments

The main purpose of this project is to conduct manufacturing. We aim to carry out this manufacturing using composite materials. At the beginning of the process, we decided to focus on Kevlar. Associate Professor Dr. Uğur Tümerdem left the material selection to our discretion. We chose Kevlar because it is the composite material we have encountered the least during our education or in the industry. We consulted with Professor Dr. Bülent Ekici to get his insights on this subject, and with his assistance, we contacted Dr. Lecturer Yalçın Boztoprak from the Faculty of Technology. Dr. Yalçın Boztoprak provided us with ideas at almost every stage of our project, and being a lecturer in metallurgical and materials engineering, he shared his experiences with us. He also helped us procure the necessary materials from the laboratories of the Faculty of Technology at Marmara University.

We started our work by using Kevlar and initially purchased a 30cm x 30cm Kevlar fabric. After designing our first prototype on the computer, we drew it onto the fabric ourselves. Our goal was to see if we could obtain a desired plate after applying epoxy resin to the Kevlar. We faced significant difficulties in cutting and processing the fabric while it was in cloth form. We tried mechanical cutting methods, such as using wood cutting equipment, a table saw, a saw, a coping saw, and a utility knife. These types of mechanical cutting tools proved to be impractical for composite fibers. We experienced and foresaw that both before and after curing, traditional mechanical cutting methods would not be beneficial for us.

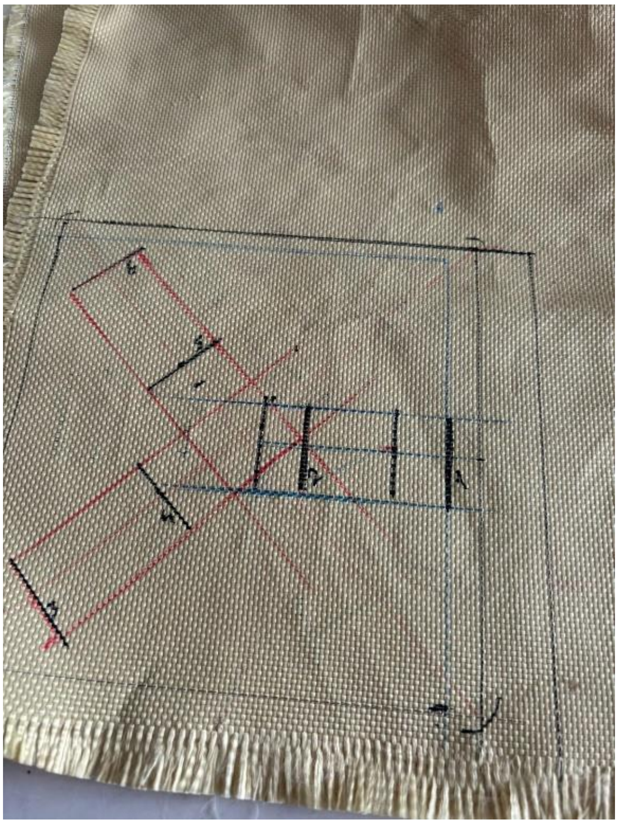


Figure 22 Sketch on Aramid

Meanwhile, we also obtained carbon fiber from the laboratory of the Faculty of Technology. To see if carbon fiber would provide the desired strength and structural properties after curing before producing the first prototype, we applied epoxy resin ourselves. As part of the learning outcomes of this project, we needed to experience and manage the processes of turning fiber into sheets. In our first attempt, we applied epoxy resin to the carbon fiber fabric using a brush and the hand lay-up method. During this process, we used garbage bags, which are easily accessible on the market, as they are polymer-based. We cured it at 250 degrees Celsius for 7 minutes, but the initial results were not satisfactory because the resin burned from the heat.

Figure 23 Preparing and Applying Epoxy Resin

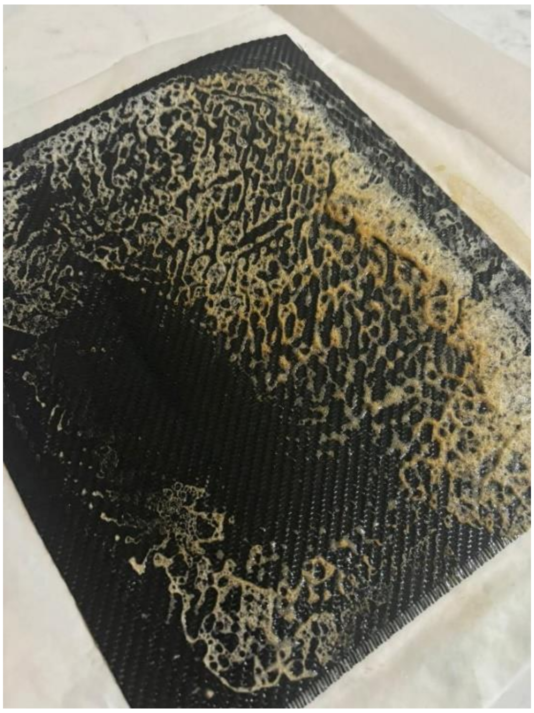


Figure 24 Manufacturing Defect

After further research, we learned that the resin needed to be pre-cured before hot press application. We repeated the same process, trying to eliminate all air gaps between the carbon fibers to be cured in the bags and the polymer structure, and left it to pre-cure for 12 hours. After 12 hours, we placed the brittle carbon fiber sheets in the oven with weights added for pressure. Before placing them in the oven, we noticed unwanted production defects during the pre-curing process, such as air gaps and uneven resin distribution.

One of the gains from this process was encountering production errors. After removing the carbon fibers from the oven after 7 minutes, we found that they had lost some of their flatness but had reached the hard structure we had anticipated and expected. We realized that with the support of a flat plate and pressing, we could achieve the exact sheets we desired. When we tried to correct the production errors on the sheets by sanding, it posed a significant physical challenge. When flattened, the epoxy layer was removed, and it started to resemble a prepreg fiber.

Figure 25 Testing Lazer Cutting Machine

While preserving the sheet we had, we also wanted to obtain prepreg carbon fiber. Having it in a prepreg state would help us avoid all the errors we might encounter during the epoxy resin application. After obtaining prepreg carbon fiber, we cured this material as well, resulting in two different carbon fiber sheets from two production methods. We subjected both to laser cutting. Laser cutting caused severe burns in the prepreg, despite it having a nicer structure and no aesthetic defects due to production errors. The first sheet we produced, despite causing minor deformations in the epoxy resin, seemed to yield a better result. We decided to use both materials to minimize our risk of making mistakes during the actual production. Prepreg provided a smooth surface.

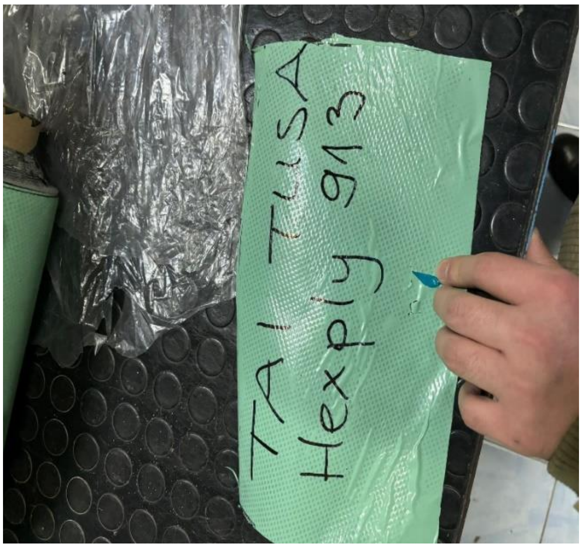


Figure 26 Carbon Fiber Prepreg which we used

We conducted extensive research for the polyamide layer to be used between the sheets, as mentioned in articles. During this research, we sought help from our school's chemistry and metallurgy instructors and external experts knowledgeable in materials science. The materials suggested for use as polyamide included nylon, nylon fabrics, flexible plastics, and similar products. We procured nylon from an awning shop. This material provided the flexibility we desired but posed challenges in adhesion and was a thick material.

Figure 27 Measuring Thickness of Carbon Fiber with Caliper

The thickness was 0.3 mm, which would cause problems for us because it would require the thickening of the robot arm and the expansion of the connecting elements. We began to focus on finding an adhesive. The adhesive is actually the second most important parameter of the system because it needs to provide good rigidity and strength while not compromising the flexibility of the polyamide piece in between. We conducted various research online. Some companies and individuals we tried to get help from were not able to assist us, either in terms of ideas or materials. Our expectation from the adhesive we would use in our robot was that it should fully adhere the polyamide structure between the carbon fiber sheets without losing the flexibility of the polyamide piece. We tried various adhesives and finally decided to use cyanoacrylate adhesive because this adhesive, by heating the polyamide piece during initial application, increased the adhesion strength to the sheets without causing damage to the plates. However, we encountered an issue at this stage as well, and the cyanoacrylate adhesive altered the structural and possibly chemical properties of the sheet. We observed that it became more brittle.

Figure 28 Manufacturing Defect and Material Testing

We tried to create the best prototype we could with the materials we had, and ultimately, we obtained a robot that was far from perfect and amateurishly produced. When we presented this robot to Associate Professor Dr. Uğur Tümerdem, he mentioned that it fell short of his expectations and that we needed to do a better job. He advised us to deviate less from what was done in the articles and to create an example as close as possible to what was done there.

In the second term of our project, we replaced our part with fiberglass as used in the article, and we also replaced the polyamide piece to be used in between with Kapton Film, as mentioned in the article.

We used 60x10 Laser Cutting Power for Kapton Film
60x100 Laser Cutting Power for Fiberglass, the power parameters can be change on machine depending on material properties.

Property	Value	Description
Chemical Composition	Polyimide	Contains polyimide
Density	1.42 g/cm³	Low density
Melting Point	~500°C	High melting point
Thermal Conductivity	0.12 W/mK	Low thermal conductivity
Electrical Conductivity	Non-conductive	Non-conductive
Thermal Expansion Coefficient	20 x 10^{-6} /°C	High thermal expansion
Heat of Combustion	~30 MJ/kg	High energy content

Table 4 Properties of Kapton Film

Figure 29 Hot Press Machine

Figure 30 Hot Press Machine Operating

Unlike the article, it was not possible for us to obtain or produce a 0.3mm thick sheet, as we were informed by suppliers that such sheet production is only done by special order for bulk and industrial purposes. We obtained a 0.5 mm thick fiberglass. This time, we got it as a pre-cured sheet because we had already experienced the production errors in the process and realized that manufacturing such composite materials is really difficult without professional conditions. To minimize the negative impact of the production errors on the robot and the project, we opted for ready-made sheets when making the actual design.

The article used two important materials: 0.05 mm thick DuPont Kapton film and DuPont PyraLux LF Bond adhesive. We contacted DuPont Turkey. As a result of our communication, we regret to inform that the brand's Turkish representative office did not operate even as a small dealership. We learned that neither of the two materials we named were available in Turkey.

Figure 31 Testing Adhesive with Kapton Film

Figure 32 Kapton Film

We immediately started researching equivalent products. Kapton film could be ordered from abroad, but the order was valid only for bulk purchases and was expected to take more than 2 months due to the import processes. We found the polyamide film we were looking for at an electronics repair materials supplier in Ankara, Turkey. We will also address the information about Kapton within the project. The reason we found what we were looking for in a store that sells electronics repair materials is that this material is generally used in the windings of wires in electrical circuits because it is a high heat and electrical resistance, non-flammable material.

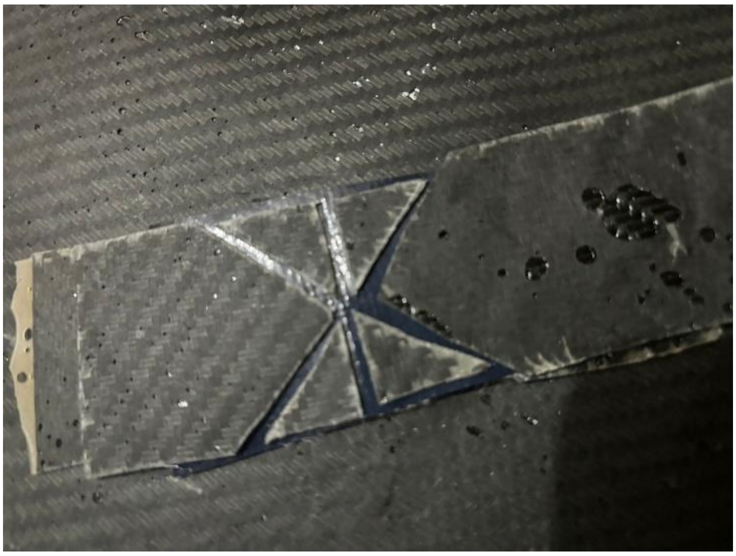


Figure 33 Joint Testing and Prototype

Figure 34 Material Testing for Poliamide

As for the adhesive, we contacted many companies in Turkey. Companies generally do not prefer to support student projects. Besides not providing support, they also chose not to share information from their own R&D or what they know. As a result of our research, we tested two different adhesives. Finally, we decided to use an acrylic-based adhesive or 3M super spray adhesive. Since laser cutting damaged our film, we decided to cut it with a water jet. The water jet's precision is less compared to the laser, but it was the best solution. We received support for programming the servo motors with an Arduino board.

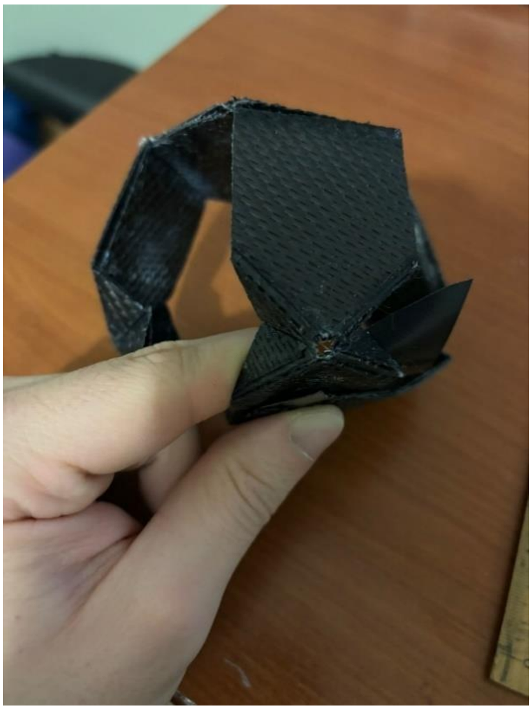


Figure 35 First Prototype

6. Analysis

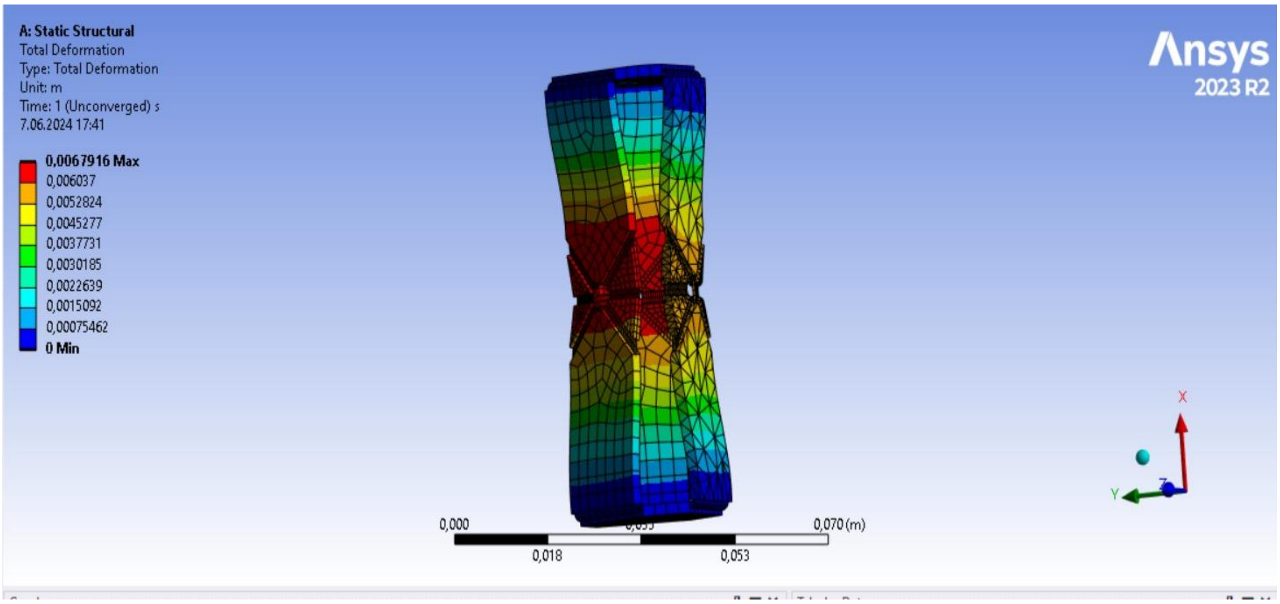


Figure 36 Total Deformation

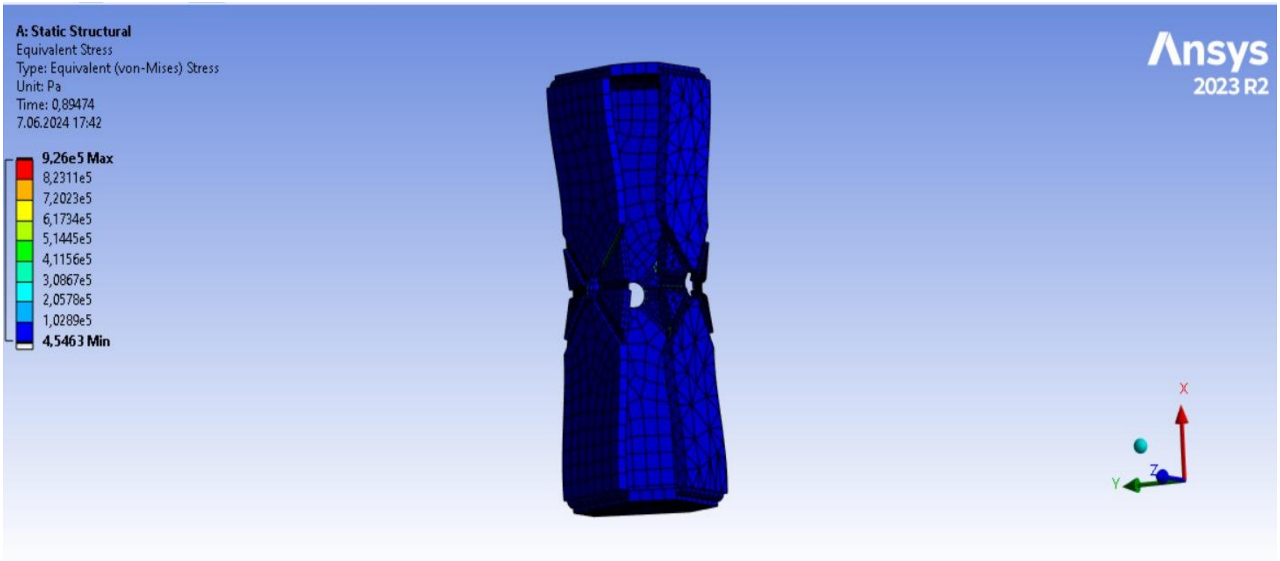


Figure 37 Equivalent Stress

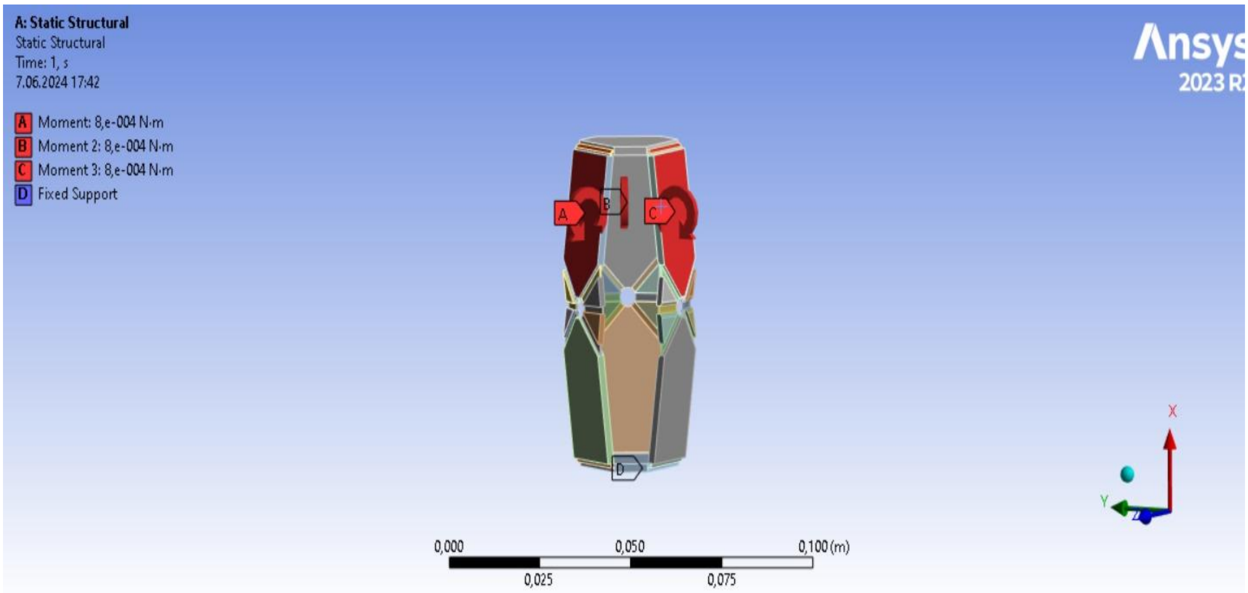


Figure 38 Moment Applying

Kapton Film

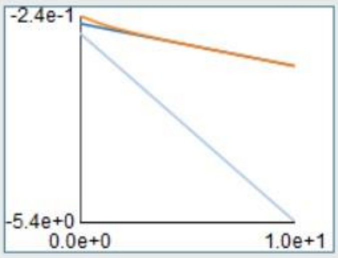
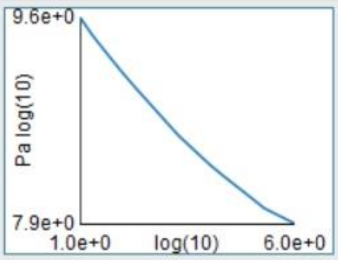
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	2,5e+09 Pa
Poisson's Ratio	0,34000
Bulk Modulus	2,6042e+09 Pa
Shear Modulus	9,3284e+08 Pa
Isotropic Secant Coefficient of Thermal Expansion	2e-05 1/°C
Compressive Ultimate Strength	2,3e+08 Pa
Compressive Yield Strength	8,5e+07 Pa
Strain-Life Parameters	
S-N Curve	

Figure 39 Kapton Film Properties

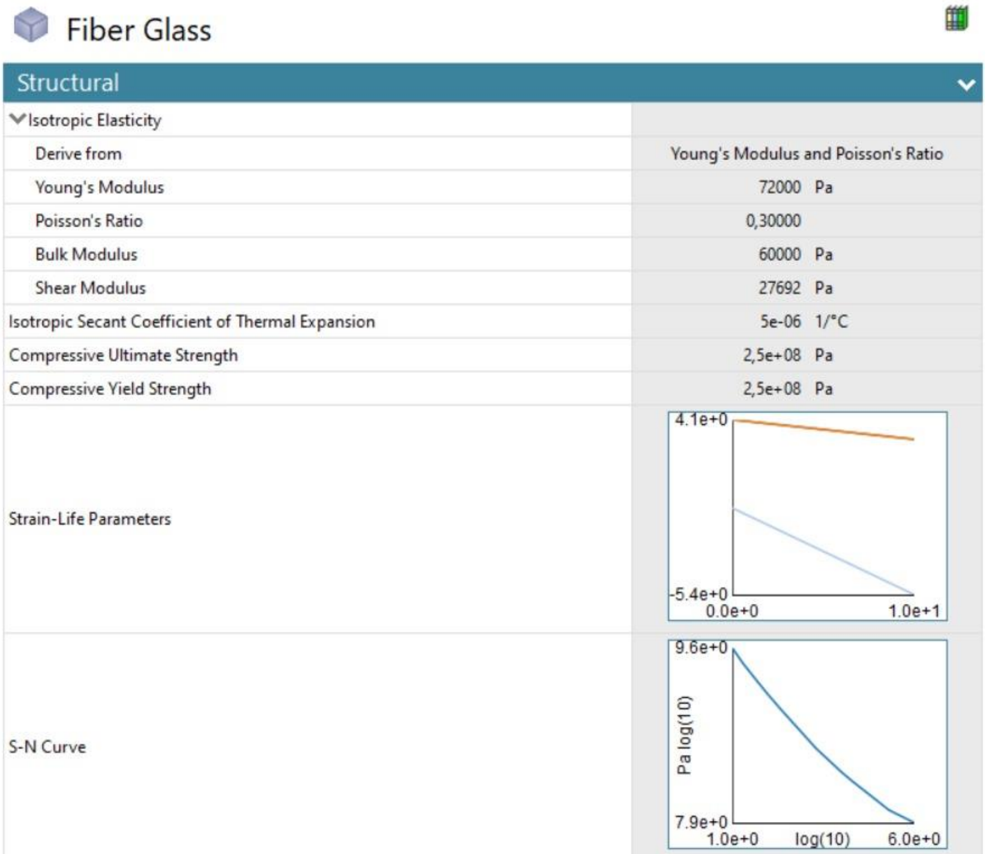


Figure 40 Fiber Glass Properties

7. Conclusion

This study examines the composite production of 3-degree-of-freedom (DOF) RSR parallel robots inspired by origami principles. Its aim is to produce an origami robot based on the water bomb mechanism by obtaining optimum values for working area and load capacity. Carbon fiber, Kevlar and Fiber glass were considered in the selection of composite materials, but fiber glass was preferred because it provides cost and ease of production. PVC and kapton film were emphasized as polyamide, and kapton film was preferred because it is more suitable for laser production. Due to epoxy burning, undesirable material brittleness and deformations in the production of composite materials. Flawless fiber glass sheets obtained by ready-made resin transfer method were preferred. The main reasons for these errors can be listed as follows; Poor workmanship, lack of materials, wrong equipment selection. The suitability of the materials selected for origami robots was also tested with the FEA half. By applying certain loads, the deformations that will occur in the robot, especially in the joints, allowed to obtain more informative data about the working area and load resistance.

Solutions to be suggested in terms of design and production in similar studies that can be done in the future can be listed as follows; To obtain the most flawless flat plate, the resin transfer method is used. Although it is important to process the plate in the same mold and with the same laser device in order not to change the orientation between the plate and the polyamide, the cutting intensity between kapton and plates is optimally 9-10 times. Acrylic adhesives are the best for polyamides such as kapton. These are the issues that are important as a result of the gains and experiences we gained in our study, and we hope that they will shed light on future studies.

8. References

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9. Appendix

All figures in appendix are for Arduino Board, Servo motor operations.

servos | Arduino 1.8.12

File Edit Sketch Tools Help

servos

```
#include <Servo.h>


Servo servo1;
Servo servo2;
Servo servo3;


const int minAngle= 90;
const int maxAngle= 110;
const int rpm= 7;

int pos1= minAngle;
int pos2= minAngle;
int pos3= minAngle;

bool forward= true;
int servoState= 1;
const int servoStateTime= 20000; //20 seconds delay to change the motors
unsigned long lastStateTime= 0; //the last time information of the transition


void setup() {

  // setting digital pins to the servo motors
  servo1.attach(5);
  servo2.attach(6);
  servo3.attach(7);

}

void loop() {

  //for all servos working
  if(servoState == 1){
```

Figure 41 Arduino Programming

```
void loop() {
\\for all servos working
if(servoState == 1){
  if(forward){
      pos1++;
      pos2++;
      pos3++;
         if(pos1 >= maxAngle){
            pos1= maxAngle;
            pos2= maxAngle;
            pos3= maxAngle;
            forward= false; \\start to rotate reverse
         }
  }
  else{
      pos1--;
      pos2--;
      pos3--;
         if(pos1 <= minAngle){
            pos1= minAngle;
            pos2= minAngle;
            pos3= minAngle;
            forward= true;  \\start to rotate forward
         }
  }
}
\\only servo1 is to work
else if(servoState == 2){
  if(forward){
      pos1++;
         if(pos1 >= maxAngle){
            pos1= maxAngle;
```

servos

Figure 42 Arduino Programming

servos

```
}

//only servo1 is to work
else if(servoState == 2){
  if(forward){
      pos1++;
        if(pos1 >= maxAngle){
           pos1= maxAngle;
           forward= false; //start to rotate reverse
        }
  }
  else{
      pos1--;

        if(pos1 <= minAngle){
           pos1= minAngle;
           forward= true;  //start to rotate forward
        }
  }
}

//only servo2 is to work
else if(servoState == 3){
  if(forward){
      pos2++;
        if(pos2 >= maxAngle){
           pos2= maxAngle;
           forward= false; //start to rotate reverse
        }
  }
  else{
      pos2--;

        if(pos2 <= minAngle){
           pos2= minAngle;
```

Figure 43 Arduino Programming

servos

```
            pos3= maxAngle;
            forward= false; //start to rotate reverse
         }
   }
   else{
       pos3--;

         if(pos3 <= minAngle){
            pos3= minAngle;
            forward= true;  //start to rotate forward
         }
   }
  }


  servo1.write(pos);
  servo2.write(pos);
  servo3.write(pos);


  // rpm_delay variable is set to arrange rpm
  int rpm_delay= (60 * 1000) / (rpm * (maxAngle - minAngle));
  delay(rpm_delay);

  // servoState transition conditions
  unsigned long currentTime = millis();
  if (currentTime - lastStateTime >= servoStateTime) {
  servoState++;
  if (servoState > 4) {
      servoState = 1;
    }
    lastStateTime = currentTime;
  }

}
```

Figure 44 Arduino Programming