

# Durability and Resilience of Hyperloop Infrastructure

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## Abstract

*The Hyperloop is a revolutionary concept for high-speed ground transportation that involves passenger pods traveling through low-pressure tubes at near-supersonic speeds. Originally proposed by SpaceX in 2013, the concept aims to offer a cost-effective and faster alternative to conventional rail systems and short-haul air travel. This study addresses a critical component of the Hyperloop's success – structural durability. Key concerns include material fatigue due to repetitive high-speed movement, pressure fluctuations within vacuum tubes, environmental degradation of materials, and thermal expansion under varying climatic conditions. Modern engineering solutions, such as carbon fiber reinforced polymers, magnetic levitation, and composite laminate structures, have been analyzed. The research also examines the effects of dynamic loading, vibration control, and the application of hybrid composite materials on enhancing both durability and efficiency. This paper presents a framework for understanding the mechanical and environmental challenges facing Hyperloop pod and tube structures and offers engineering solutions that can improve their resilience, cost-effectiveness, and sustainability. These findings contribute to advancing Hyperloop development for widespread, safe, and efficient public transportation. The Hyperloop represents an ambitious vision for high-speed ground transportation, where passenger pods travel through partially evacuated tubes at speeds approaching the speed of sound. Proposed initially by SpaceX in a 2013 white paper, the Hyperloop was designed to provide a faster and less costly alternative to California's proposed high-speed rail line between Los Angeles and San Francisco. The Hyperloop concept takes advantage of reduced air resistance within a low-pressure tube, enabling pods to achieve high speeds with less energy, making it a potentially revolutionary form of short-haul travel. This research aims to analyze the problems associated with structural durability in the design of hyperloops and the probable solution.*

**Keywords:** Hyperloop, material selection, carbon fiber, cost-effective, CFRP

## INTRODUCTION

The Hyperloop represents an ambitious vision for high-speed ground transportation, where passenger

pods travel through partially evacuated tubes at speeds approaching the speed of sound. Proposed initially by SpaceX in a 2013 white paper, the Hyperloop was designed to provide a faster and less costly alternative to California's proposed high-speed rail line between Los Angeles and San Francisco. The Hyperloop concept takes advantage of reduced air resistance within a low-pressure tube, to enable pods to achieve high speeds with less energy, making it a potentially revolutionary form of short-haul travel.

One of the critical advantages of the Hyperloop lies in its capacity to address inefficiencies associated with air travel, particularly for shorter routes. When traveling relatively short distances,

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such as Los Angeles to San Francisco or Boston to New York, a significant portion of the travel time is consumed by activities on the ground, including taxiing on runways, climbing to cruising altitude, descent, and waiting in holding patterns. These stages contribute to delays and inefficiencies, which are nearly unavoidable in air travel. The Hyperloop, by contrast, promises a high-throughput, point-to-point service that could significantly reduce these time-consuming steps.

By employing pods that depart frequently, the Hyperloop could further reduce the time travelers spend waiting. The experience could be closer to that of boarding a subway than waiting for an airplane, providing a more efficient solution for travel between major urban centers. Not only could this speed up transit times, but it also allows for the possibility of higher-frequency services, making it a flexible solution for commuters and travelers on tight schedules.

Recently, Hyperloop One – a company actively working to commercialize this technology – commissioned a study by KPMG to explore its impact on the Helsinki–Stockholm corridor [1]. The findings were promising: Hyperloop could potentially slash travel times between the two cities by as much as 75%, reducing the end-to-end journey to just 28 minutes. Such a drastic reduction in travel time would redefine what is feasible in terms of commuting distance, bringing major metropolitan areas closer together than ever before.

With demand for high-speed transport options projected to increase in the coming years, Hyperloop's potential market impact could be substantial [2]. The global push for more sustainable and efficient transportation options also plays into the appeal of Hyperloop, which could use renewable energy sources to power its pods, further reducing its environmental footprint. As airports and major highways face increasing congestion, the Hyperloop offers a promising way to ease some of this strain by redirecting passengers onto high-speed ground transport, thereby relieving some of the pressure on traditional transportation infrastructure.

While there are still technical and regulatory hurdles to overcome, the Hyperloop stands out as a forward-thinking response to the challenges of modern transportation [3]. If successful, it could drastically alter the landscape of short-haul travel, making fast, efficient, and eco-friendly travel between cities a reality.

## LITERATURE REVIEW

Recently, there has been a lot of media attention focused on the Hyperloop idea, pod speed competitions, and ongoing project advances. Through a system study of its primary goals, functional design, transport capacity, and demand, the Hyperloop vacuum tube transport project's transport technology is evaluated by researchers. It is compared to current commercial airplanes, high-speed rail, and Maglev lines [4]. The use of low-carbon synthetic fuels in high-speed trains and airplanes is the only way to lessen the climatic effects of high-speed passenger transportation over hundreds of km [5]. Alternatives, like battery-electric aircraft, may become available in the future. Moreover, automobiles that run in "hyperloop systems," or near-vacuum tubes, may be an option [6]. The main topic of discussion in many recent studies is the hyperloop, a highly fast transit system that includes a pod that carries passengers in a tube. The new study suggests a revolutionary hybrid levitation method that incorporates air cushions and Electro-Dynamic Suspension (EDS) for the pod in the hyperloop system, building on the most recent advanced discoveries [7]. A pod moves frictionless through a tube or network of tubes in the ultra-high-speed (UHS) Hyperloop, the next-generation form of passenger and freight transportation. The dynamic amplification factors of the Hyperloop-deck-pier system for lateral and vertical vibrations are compiled analytically by researchers. In comparison to the high-speed trains, it was discovered that the UHS Hyperloop trains produce more dynamic effects [8]. To meet the demands of high-speed passenger and cargo transportation, the idea of Hyperloop systems is proposed. Terminals, pods, and low-pressure tubes make up this technology. The pods move quickly between the terminals inside the low-pressure tubes. The design of suspension systems for pod stability is one of the most important components of this technology [9]. Designing a complicated, high-performance vehicle

and its supporting infrastructure at the same time makes the hyperloop system design a uniquely connected task. There is a great chance to apply rigorous system optimization approaches in the clean-sheet design of this new high-speed mass transit system [10]. Although the hyperloop, a novel tube-train system, has several transportation benefits, it also has built-in asymmetries due to the tube's construction and the pod's placement. Studies that presume an idealized tube-pod combination frequently ignore the fact that this asymmetry causes unbalanced stresses on the pod [11]. A detailed study of the structural durability of Hyperloop and issues related to it is required to understand the feasibility of making this a success.

## PROBLEM FORMULATION

Solutions, like using aluminum alloys for lightweight, strong structures help manage weight and withstand high-speed stresses, but they are costly and complex to manufacture. Active suspension systems mitigate vibrations for smoother rides but add weight and require significant power. Magnetic levitation reduces friction but demands high energy and costly infrastructure. Lastly, advanced thermal management systems address heat expansion but add complexity and can limit design flexibility.

**Vacuum-Induced Buckling:** The difference in air pressure between the inside and outside of the tube can lead to radial forces causing structural buckling, especially in thin-walled tubes. The required material strength and wall thickness must be optimized to prevent failure [12].

- *Thermal Expansion and Contraction:* Variations in temperature cause thermal expansion, which can induce compressive stresses in the pod and tube. Solutions, like expansion joints and prestressing, are needed to mitigate these forces.
- *Material Fatigue and Wear:* Long-term operation at high speeds, combined with pressure changes, can cause fatigue in materials, especially in areas under repetitive stress, leading to micro-cracks and eventual failure.
- *External Stress Factors:* Pods must withstand impacts from debris, external environmental forces (like wind), and even seismic events without compromising the structural integrity of the pod.
- *Corrosion Resistance:* While steel is a primary material, ensuring its long-term durability against corrosion, especially in varying environmental conditions, is essential. This may require advancements in coating technologies or alternative materials.
- *Dynamic Loading and Vibration:* The high-speed nature of the hyperloop system subject pods to significant dynamic loading and vibrations, which can lead to material fatigue and eventual failure if not properly mitigated. Continuous motion at high speeds causes cyclic stresses, making it necessary to ensure resilience through advanced material selection and vibration-damping technologies.
- *Impact Resistance:* Hyperloop pods must withstand unexpected impacts from foreign objects or debris within the vacuum tube. These impacts can potentially compromise the pod's outer shell, requiring advanced protective designs and materials, such as impact-resistant composites or reinforced structures [13].
- *Pressure Fluctuations:* Maintaining a stable low-pressure environment is essential, but variations in pressure, especially during pod acceleration and deceleration, could stress the structural integrity. Over time, this could lead to deformation, leaks, or fatigue in critical areas of the pod and tube.
- *Material Degradation Due to Environmental Factors:* Exposure to humidity, corrosion, or extreme weather can degrade materials used in the pod's construction. Steel, while commonly used, can be susceptible to rust or degradation in humid environments, necessitating the exploration of corrosion-resistant alloys or protective coatings.
- *Sustainability and Resource Use:* The environmental impact of manufacturing and maintaining such a large-scale transportation system is also a concern. The use of high-strength materials, like steel requires large amounts of resources, which can be costly and harmful to the environment. The durability of such materials needs to balance strength with sustainability.
- *Load Distribution During High-Speed Turns:* Hyperloop pods are designed to travel at very high speeds, and when navigating turns, the load distribution can become uneven. This induces

additional stress on the pod's frame and tube, requiring specialized engineering to ensure stability without compromising the pod's structural integrity.

- *Seismic and External Structural Threats:* Given the nature of high-speed travel, any external threat, such as seismic activity or ground vibrations, could pose a risk to the pod's durability. Hyperloop systems must be engineered to absorb these stresses without damage, which calls for reinforced structural elements or shock-absorbing systems.
- *Aging and Wear of Magnetic Levitation Systems:* The electromagnetic propulsion and levitation systems of hyperloop pods, which rely on superconducting magnets or other advanced technologies, also require durability over time. Repeated exposure to electromagnetic forces could cause degradation in the superconducting materials or magnets, which must be robust enough to endure the continuous cycles of acceleration and deceleration.
- *Energy Dissipation and Heat Generation:* As pods accelerate, the rapid motion creates friction and heat, especially in braking systems. High temperatures can cause material deformation or even failure if the systems are not properly engineered to dissipate heat without compromising the pod's structural stability.
- *Tensile and Compressive Stress on Joints and Seals:* The construction of the hyperloop pod involves connecting various sections of the tube and pod. Over time, the joints and seals could be prone to wear due to the tensile and compressive stresses they endure. These connections must be precisely engineered to prevent leakage or failure.
- *Aerodynamic Forces During High-Speed Travel:* The design must account for the aerodynamic forces generated at speeds nearing or exceeding Mach 1. These forces could lead to bending or flexing of the pod's structure, requiring careful analysis and reinforcement at key stress points.

## PROPOSED SOLUTION

The proposed solution involves integrating hybrid composite materials, primarily carbon fiber, to enhance strength, reduce weight, and improve impact resistance. This combination maximizes structural integrity while minimizing weight and manufacturing costs. Additionally, incorporating passive magnetic levitation with optimized aerodynamics lowers energy consumption and increases stability. The advantages include improved durability, enhanced safety, reduced operational costs, and greater efficiency in high-speed travel conditions, making the system more viable and sustainable for mass deployment.

### Carbon Fiber

#### *Composite Material*

Combining two materials with dissimilar physical and chemical characteristics results in a composite material. Combining them results in a material that is specialized to perform a given function such as being stronger, lighter, or electrically resistant. They can also increase stiffness and strength. Individual components are combined to produce composite materials. These separate elements fall into two primary groups and are referred to as constituent materials. The first is the reinforcement, while the second is the matrix (binder). At least some of each kind is required. Since the matrix envelops the reinforcement and keeps its relative locations, the reinforcement is supported by the matrix. As the reinforcements transfer their remarkable mechanical and physical capabilities, the matrix's qualities increase. Today's launch vehicles and heat shields for spacecraft's re-entry phase depend heavily on carbon composites. It is extensively utilized in spacecraft yokes, antenna reflectors, and solar panel substrates. It is also utilized in launch vehicle heat shields, interstate structures, and payload adapters. Additionally, carbon/carbon materials are used in racing automobiles and airplanes' disc braking systems, and luxury cars and sports cars have started adopting composite materials made of carbon fibers and silicon carbide matrix.

Glass-reinforced plastic and carbon fiber-reinforced polymer (CFRP) are examples of fiber-reinforced polymers. Thermoplastic composites, short fiber thermoplastics, long fiber thermoplastics, and long fiber-reinforced thermoplastics are the different types of thermoplastics based on their matrix.

Paper composite panels are among the many thermoset composites available. Carbon fiber and aramid fiber are often incorporated into an epoxy resin matrix in a number of sophisticated thermoset polymer matrix systems. High-performance composites known as shape memory polymer composites are made with fiber or fabric reinforcement and a matrix of shape memory polymer resin. When heated above their activation temperatures, these composites may be readily manipulated into a variety of shapes since the matrix is a shape memory polymer resin. At lower temperatures, they will demonstrate great strength and stiffness. Additionally, they retain their material qualities even after being repeatedly warmed and molded. These composites are perfect for uses like dynamic reinforcement, quick production, and lightweight, stiff, deployable constructions.

### Carbon Fiber-Reinforced Polymer Composites (CFRP)

CFRP are robust, lightweight materials that are utilized to make many everyday items. This phrase refers to a fiber-reinforced composite material in which the main structural element is carbon fiber. Notably, the “P” in CFRP might alternatively represent “plastic” rather than “polymer”. “Thermosetting polymers”, like vinyl ester, polyester, or epoxy, are typically used in CFRP composites. Despite using thermoplastic resins, “Carbon Fibre Reinforced Thermoplastic Composites” are more commonly referred to as CFRTP composites. Knowing the terminologies and acronyms used in the composites business is crucial when dealing with composites. More significantly, knowledge of the characteristics and potential of FRP composites is essential.

### Properties of CFRP Composites

Carbon-fiber-reinforced composites vary from other FRP composites made of more conventional materials like fiberglass or aramid fiber [14]. The following are some of the CFRP composites’ beneficial qualities:

#### Lightweight

The density of a conventional fiberglass reinforced composite with continuous glass fiber, which has a glass content of 70% (weight of glass/total weight), is typically .065 pounds per cubic inch. A CFRP composite, on the other hand, may normally have a density of .055 pounds per cubic inch with the same 70% fiber weight. Enhanced strength: CFRP composites are significantly stronger and stiffer per unit of weight in addition to being lighter. Comparing carbon fiber composites to glass fiber demonstrates this, but comparing them to metals demonstrates it even more. When comparing CFRP composites to steel, for instance, it’s a good idea to keep in mind that a carbon fiber construction with the same strength would often weigh one-fifth as much as steel [15]. You can see why automakers are looking towards replacing steel with carbon fiber. It is common practice to assume that an aluminum construction of equivalent strength would weigh 1.5 times as much as a carbon fiber structure when comparing CFRP composites to aluminum, one of the lightest metals employed. Naturally, there are a lot of factors that might alter this comparison. Materials can vary in grade and quality, and in the case of composites, the fiber architecture, manufacturing process, fiber architecture, and quality need to be considered, as shown in Figure 1.

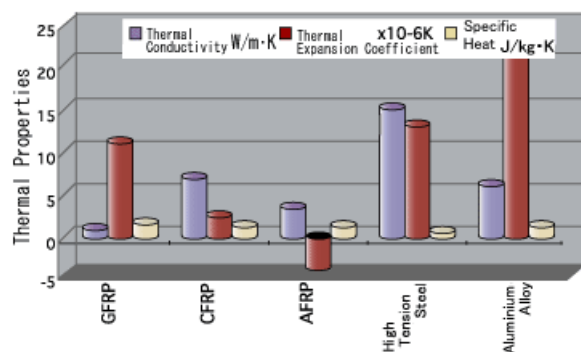


Figure 1. Thermal properties of different materials.

### ***Lamina***

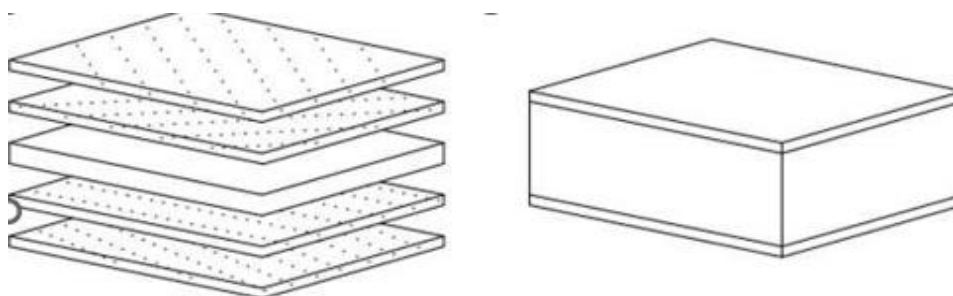
Compared to traditional graphite, C/C has far better mechanical qualities. Three-dimensional C/C composites are very appealing. There are three ways to customize their preform structure. When compared to 2D laminate C/C composites, the 3D integrated preform structure yields better damage tolerance and less delamination crack propagation during interlaminar shearing [7]. In contrast to traditional materials, the fracture in 3D C/C composites spreads tortuously, most often following existing voids or microcracks. A sequence of stable fracture propagation phases throughout the matrix and yarn bundles, followed by unstable crack propagation, is involved in the failure of 3D composites. Matrix cracking and bundle breaking are the main damaging processes.

There are three phases in the damage history of a unidirectional C/C with flexural strength of 200.9 MPa and flexural modulus of 50.5 GPa. Brittle fracture occurs in the initial stage due to strong interfacial adhesion. In the final state, quasi-ductile fracture is caused by weak interfacial bonding. The stress-strain curve fluctuates in the intermediate stage as a result of cracks that alternatively propagate parallel and perpendicular to the loading direction.

The curvature of the fiber bundles determine how they break in 2D C/C composites with reinforcements made of plain weave fabric under tension. Tensile stress or a combination of tensile and bending pressures can cause fiber bundles with tiny curvatures to break. Shear pressures at the location where the local fiber direction is most inclined to the applied load cause fiber bundles with considerable curvatures to break. The threshold for the commencement of damage rises as the density of the C/C increases, according to acoustic emission (AE) measurements made during mechanical testing. There are three steps in the damage progression that lead to failure. There is no AE activity during Stage I, whereas the number of AE counts gradually increases throughout Stage II, until it jumps suddenly, and in Stage III, the number of AE counts increases exponentially. Multilayer cracking, fiber bundle breaking, interfacial matrix debonding, and microcrack development are most likely the primary damage processes; the primary mechanism for C/C of low density is fiber bundle breaking.

### ***Laminate***

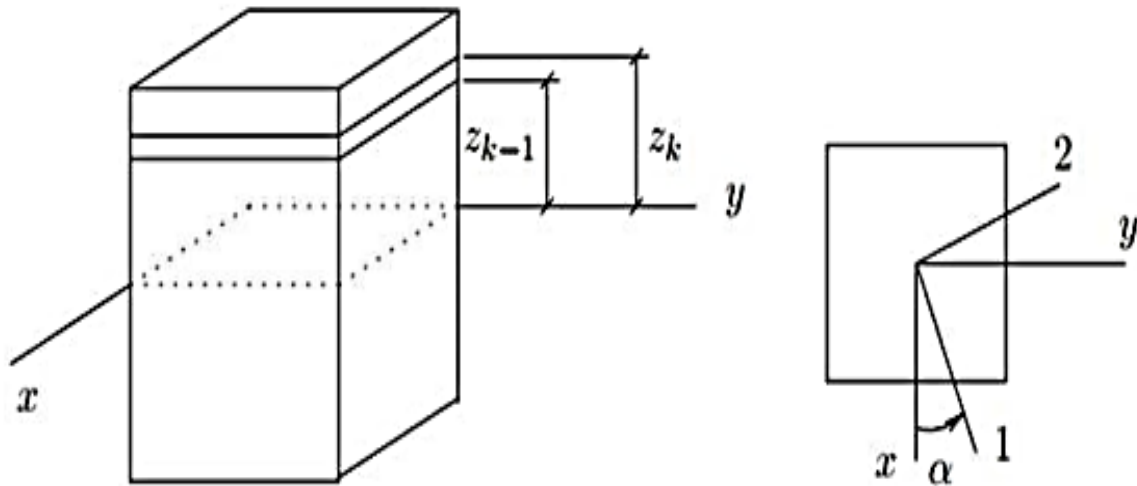
An arrangement of layers of fiber composite materials that may be bonded to give the necessary technical attributes, such as strength, bending stiffness, in-plane stiffness, and coefficient of thermal expansion, is called a composite laminate [15]. Laminates, also known as plies or laminae, are plates created by stacking many layers. Every ply has a wide range of mechanical qualities and may be made from a variety of materials. The characteristics might be orthotropic, totally anisotropic, or isotropic. The latter happens when a ply is a composite material made up of long fibers that enforce a matrix in one direction. The fiber, longitudinal, and transverse directions of the material are indicated by the numbers 1 and 2, respectively. An arrangement of layers of fiber composite materials that may be bonded to give the necessary technical attributes, such as strength, bending stiffness, in-plane stiffness, and coefficient of thermal expansion, is called a composite laminate. The stiffness matrix of the laminate, which can be computed from the characteristics of the plies, their thicknesses, and their stacking order, determines its mechanical qualities. Figure 2 illustrates how the laminate behaves in accordance with linear plate bending theory.



**Figure 2.** Laminate as a stack of plies.

### **Ply Strains**

For one ply ( $k$ ), the strain components in the global coordinate system can be related to the strain in the mid-plane and the curvature of the mid-plane. The strain components in the material coordinate system – indicated with superscript 7 – are  $T^7$ , as shown in Figure 3.



**Figure 3.** A ply as a laminate.

### **Ply Stresses**

The material stiffness matrix  $C$  may be used to calculate the stress components in the material directions, assuming linearly elastic material behavior as defined by Hooke's law. The transformation matrix  $T^{-1}\tilde{A}$  is used to determine the stress components in the global coordinate system.

## **METHODOLOGY**

The methodology involves analyzing the shell structural design and the composite layup definition, which are discussed in detail.

### **Shell Structural Design**

A glass fiber or carbon fiber shell is preferred since the aerodynamic shell must be light due to the small forces acting on it. Moreover, these materials are favored by the aerodynamic shell's complex form. It was determined that the shell would be made of carbon fiber. The shell was made into two distinct sections to provide easy removal and access to the dummy. The dividing line was positioned at the junction of the pod center and the curving nose. Because the steep corners of the junction and the enclosure of the bottom front portion of the shell would necessitate a deep mold, which would make it more difficult to remove the layup component, this separation also significantly simplifies manufacture. Furthermore, relative to the benefits and criteria being met, the weight penalty of the item being composed of two distinct sections (overlapping laminates and fasteners), was negligible.

### **Composite Layup Definition**

The design process used in Ansys ACP Pre to define composite layup involved:

- Choosing fabric.
- Shape of fabric and fabric stackup.
- Ply location based on mold design (female mold or male mold).
- Fiber directions and orientation.
- Ply sequence and modeling.
- *Fabric stackup*: After defining the fabric material and thickness, the thickness and stackup sequence of the fabric is defined. Various angles and ply orientation are checked for this purpose to get the optimum orientation, as shown in Figures 4–6.

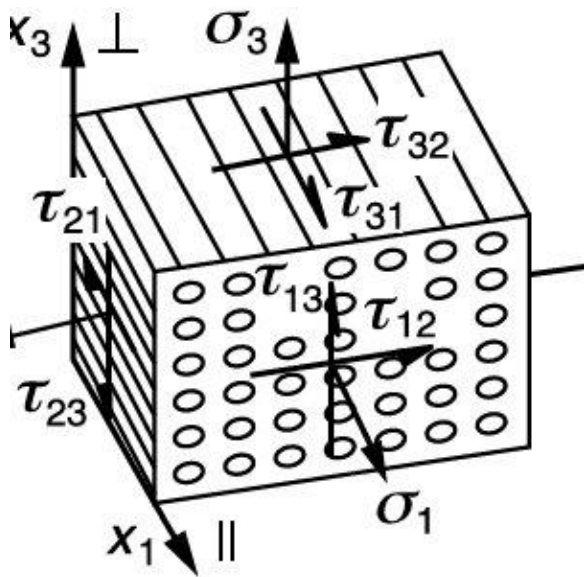


Figure 4. Ud 2 lamina 0,90.

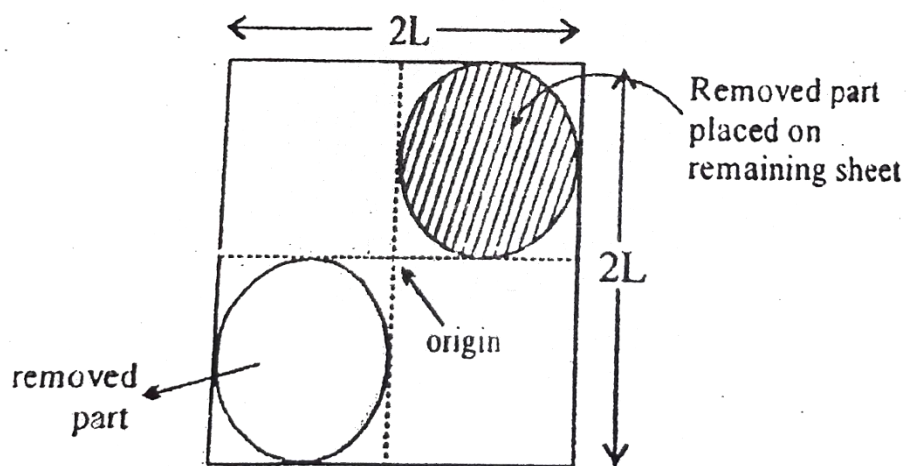


Figure 5. Ud 2 lamina 0,45°.

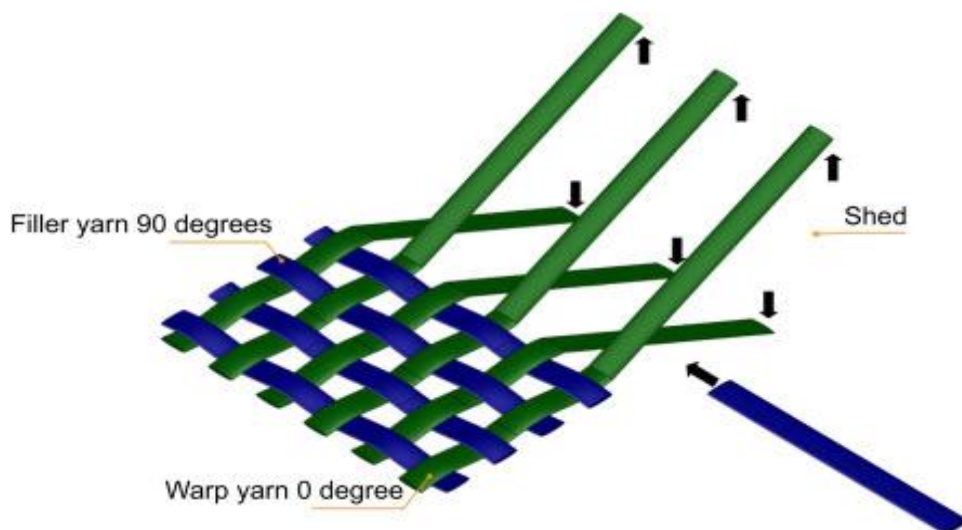


Figure 6. Woven 2 lamina 0,90°.

After checking various combinations of 0° and 45° orientation with 1 mm as fiber thickness is selected as stackup sequence is selected for both unidirectional and woven carbon fiber. In case of woven fiber, this sequence helped in achieving a pseudo isotropic behavior.

A comparison table of materials used is shown in Tables 1 and 2.

**Table 1.** Inverse reverse factor analysis for different materials.

| Material                 | Equivalent Elastic Strain | Equivalent Stress (MPa) | Total Deformation (mm) | Inverse Reverse Factor |
|--------------------------|---------------------------|-------------------------|------------------------|------------------------|
| Woven                    | $3.5 \times 10^{-5}$      | 1.7744                  | 0.054003               | 0.0062368              |
| Epoxy Carbon_ud Edgewise | $2.0 \times 10^{-4}$      | 3.805                   | 0.20974                | 0.02013                |
| Epoxy Carbon_ud Parallel | $1.9 \times 10^{-4}$      | 2.7637                  | 0.22586                | 0.017892               |
| Honeycomb_woven          | $5.1 \times 10^{-4}$      | 8.891                   | 1.3294                 | 0.03773                |

**Table 2.** Comparison of material properties for aluminum and steel.

| Material Parameter | Aluminum |                    | Steel   |                    |
|--------------------|----------|--------------------|---------|--------------------|
|                    | Maximum  | Minimum            | Maximum | Minimum            |
| Stress (MPa)       | 152.13   | 0.020              | 155.19  | 0.188              |
| Deformation (mm)   | 10.57    | 0.029              | 3.835   | 0.009              |
| Life               | $10^8$   | $1.54 \times 10^7$ | $10^6$  | $6.32 \times 10^5$ |
| Factor of Safety   | 15       | 0                  | 15      | 0                  |

## RESULT

The results of this study demonstrate the potential of CFRP composites for improving the structural durability of Hyperloop pods. The analysis of various materials and layup configurations reveals that:

- Carbon fiber woven composites exhibit minimum weight, minimum deformation, and maximum factor of safety, making them an ideal choice for pod manufacture.
- Hybrid composite materials, combining carbon fiber with other materials, can enhance strength, reduce weight, and improve impact resistance.
- Optimized layup configurations, such as 0° and 45° orientation with 1 mm fiber thickness, can achieve pseudo-isotropic behavior and improved structural integrity.

### Comparison of Materials

The comparison of materials used in the study highlights the advantages of carbon fiber composites over traditional materials like aluminum and steel. The results show that:

- Carbon fiber composites offer a superior strength-to-weight ratio, making them ideal for lightweight and high-strength applications.
- Steel is preferred over aluminum due to its higher strength and durability, but carbon fiber composites outperform steel in terms of weight and deformation.

### Implications for Hyperloop Development

The findings of this study have significant implications for the development of Hyperloop systems. By utilizing carbon fiber composites and optimized layup configurations, Hyperloop pods can be designed to be:

- Lighter, reducing energy consumption and increasing efficiency.
- Stronger, ensuring structural integrity and safety at high speeds.
- More durable, withstanding repetitive stress and environmental degradation.

These results contribute to advancing Hyperloop development, enabling the creation of safe, efficient, and sustainable transportation systems.

## CONCLUSIONS

There is a sound reason to implement a mass transit system over the entire state. Having an alternative to driving or flying would be fantastic, but obviously only if it is superior to those options. In comparison to flying, the train in issue would be two orders of magnitude slower, more costly to run (if not subsidized), and less safe. If we invest a lot of money on a new transit system, we should expect an equally large return. It should ideally be safer, quicker, less expensive, more convenient, weatherproof, sustainably self-powering, earthquake resistant, and not disturbing to those using the route as compared to the alternatives. The Hyperloop is unique, even if there are still technological and legal obstacles to be addressed.

In our study, we found that steel is preferred than aluminum, but out of all the material types, carbon fiber woven has the minimum weight, minimum deformation, and maximum factor of safety. Hence, it is the best material for pod manufacture.

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