CARBON FIBER IN AEROSPACE

LIGHTWEIGHTING THE FUTURE

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THE DEMANDING WORLD OF COMMERCIAL AVIATION

High Altitude Operations:

- Commercial jets fly around **35,000 feet**, where temperatures plummet to **-60°F** and air pressure is less than a quarter of sea level — requiring pressurized cabins and resilient materials.

Frequent Use:

- A single aircraft may complete **4–6 flights per day**, adding up to **thousands of flight cycles each year** and demanding materials that can withstand constant mechanical and thermal stress.

Heavy Payloads:

- Aircraft carry **hundreds of passengers and thousands of pounds of cargo**, so every structural component must handle significant weight while minimizing total mass.

Strict Regulations:

- Aviation is one of the most tightly regulated industries. Materials must meet rigorous **FAA and global certification standards** for safety, traceability, and performance.

Long Service Life:

- Airframes are expected to perform reliably for **20–30 years**, enduring **decades of wear, fatigue, and environmental exposure** without failure.

Harsh Weather Exposure:

- Jets face **UV radiation, lightning strikes, rain, snow, hail, and icing conditions** during operations.

KEY MATERIAL REQUIREMENTS FOR COMMERCIAL AIRCRAFT

Light Weight

Essential for fuel efficiency and reduced operational costs.

Corrosion Resistance

Maintain airworthiness over decades of service.

Strength-to-Weight Ratio

Build safe structures without excessive weight.

Fatigue Resistance

Critical for structural integrity during frequent flights.

MATERIALS USED IN COMMERCIAL AIRCRAFTS TODAY

Material	Pros	Cons
Aluminum Alloys	- Lightweight - Cost-effective - Easy to form and repair	- Prone to fatigue - Corrosion risk - Lower strength vs. composites
Titanium Alloys	- High strength - Excellent corrosion resistance - Heat resistant	- Expensive - Difficult to machine - Heavier than composites
Steel Alloys	- Extremely strong - High durability and toughness	- Very heavy - Limited use due to weight
Glass Fiber Composites	- Lightweight - Inexpensive - Easy to mold	- Lower strength and stiffness than carbon fiber - Not ideal for primary structures

WHY CARBON FIBERS ARE IDEAL FOR COMMERCIAL AIRCRAFT

High Tensile Strength

- Withstands extreme pulling forces – perfect for load-bearing parts.

Exceptional Stiffness (Young’s Modulus)

- Maintains aerodynamic shape under stress.

Low Density

- Lightweight structure reduces fuel consumption and CO_2 emissions.

Superior Fatigue Resistance

- Endures tens of thousands of flight cycles without structural failure.

Excellent Corrosion & Chemical Resistance

- Withstands hydraulic fluid, fuel, de-icing agents, and environmental wear.

CARBON FIBER VS. ALUMINUM: PERFORMANCE COMPARISON

Property	Carbon Fiber	Aluminum	Carbon/Aluminum
Modulus of Elasticity (GPa)	70	68.9	100%
Tensile Strength (MPa)	1035	450	230%
Density (g/cm^3)	1.6	2.7	59%
Specific Stiffness (E/ρ)	43.8	25.6	171%
Specific Tensile Strength (σ/ρ)	647	166	389%
Thermal Expansion	2 in/in/°F	13 in/in/°F	6.5

CARBON FIBER AT THE MOLECULAR SCALE

•Carbon fiber consists of **long molecular chains of carbon atoms** organized into **graphitic crystalline regions**.

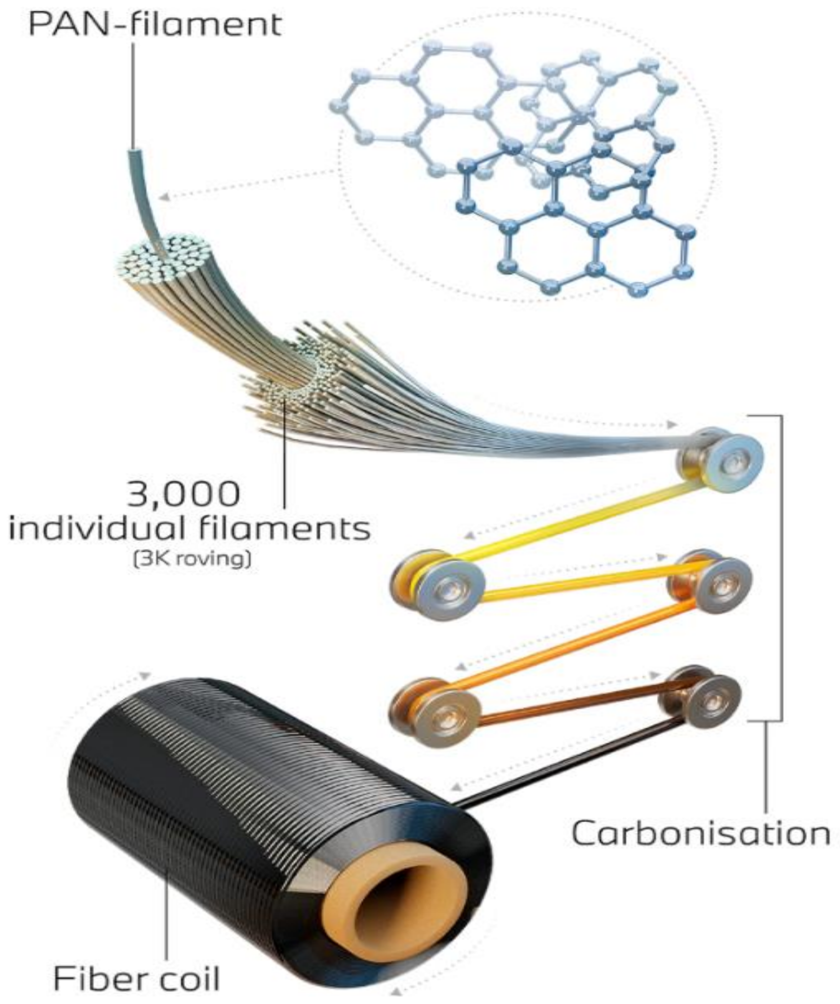
•Within these regions, carbon atoms are arranged in a **hexagonal lattice**, forming **graphitic planes** similar to those in graphite.

•During manufacturing, these planes are **aligned parallel to the fiber axis**, producing **directional (anisotropic) strength**.

•**Strong covalent bonds** within the planes provide carbon fiber with **exceptional tensile strength** and **high rigidity**.

•This anisotropic structure results in **much greater strength and stiffness along the fiber axis** compared to across the fibers.

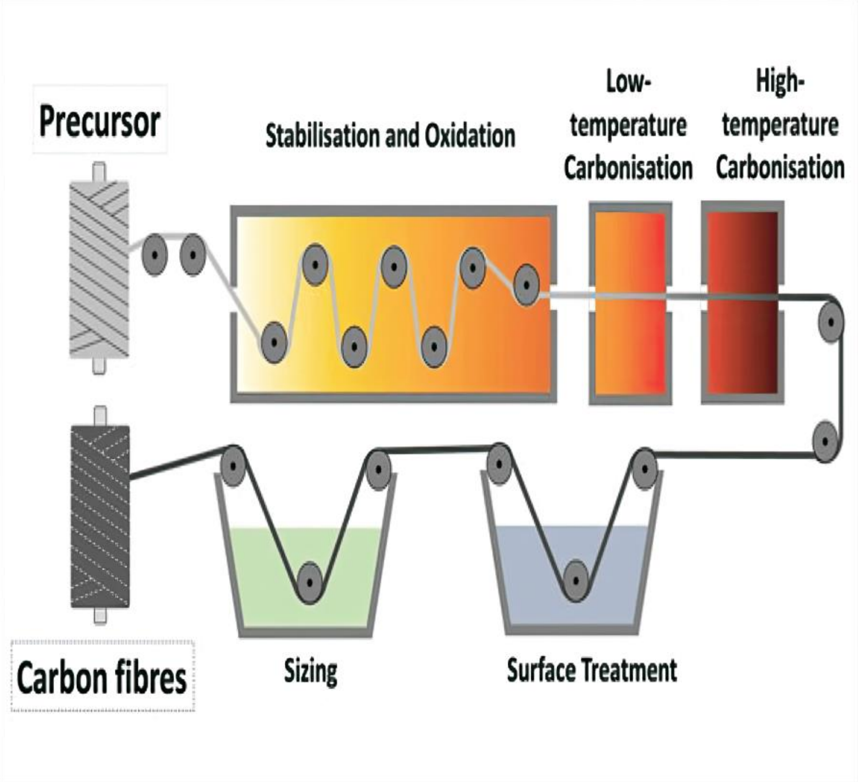
•The **high carbon content (>90%)** and the **ordered microstructure** are key to carbon fiber's **lightweight**, **mechanical performance**, and **thermal stability**.



TYPES OF CARBON FIBERS

Property	PAN-Based	Pitch-Based	Rayon-Based
Raw Material	Polyacrylonitrile (PAN)	Petroleum or coal tar pitch	Regenerated cellulose (rayon)
Strength	High	Moderate	Low
Stiffness (Modulus)	High	Very High	Low to Moderate
Cost	Moderate	High	Low
Applications	Aerospace, automotive, sports	Aerospace, satellites	Thermal protection, historical use
Market Share	~90%	Small	Minimal (obsolete in most uses)
Other Notes	Balanced performance	Very stiff but brittle	Rarely used today

MANUFACTURING PROCESS



Precursor Fiber Spinning

- Long, thin fibers are created from materials like polyacrylonitrile (PAN).

Stabilization

- Fibers are heated in air at around 200–300°C. This alters their chemical structure to prevent melting during the next stage.

Carbonization

- Stabilized fibers are heated to 1,000–3,000°C in an inert atmosphere to remove non-carbon elements, resulting in high-carbon content fibers.

Surface Treatment

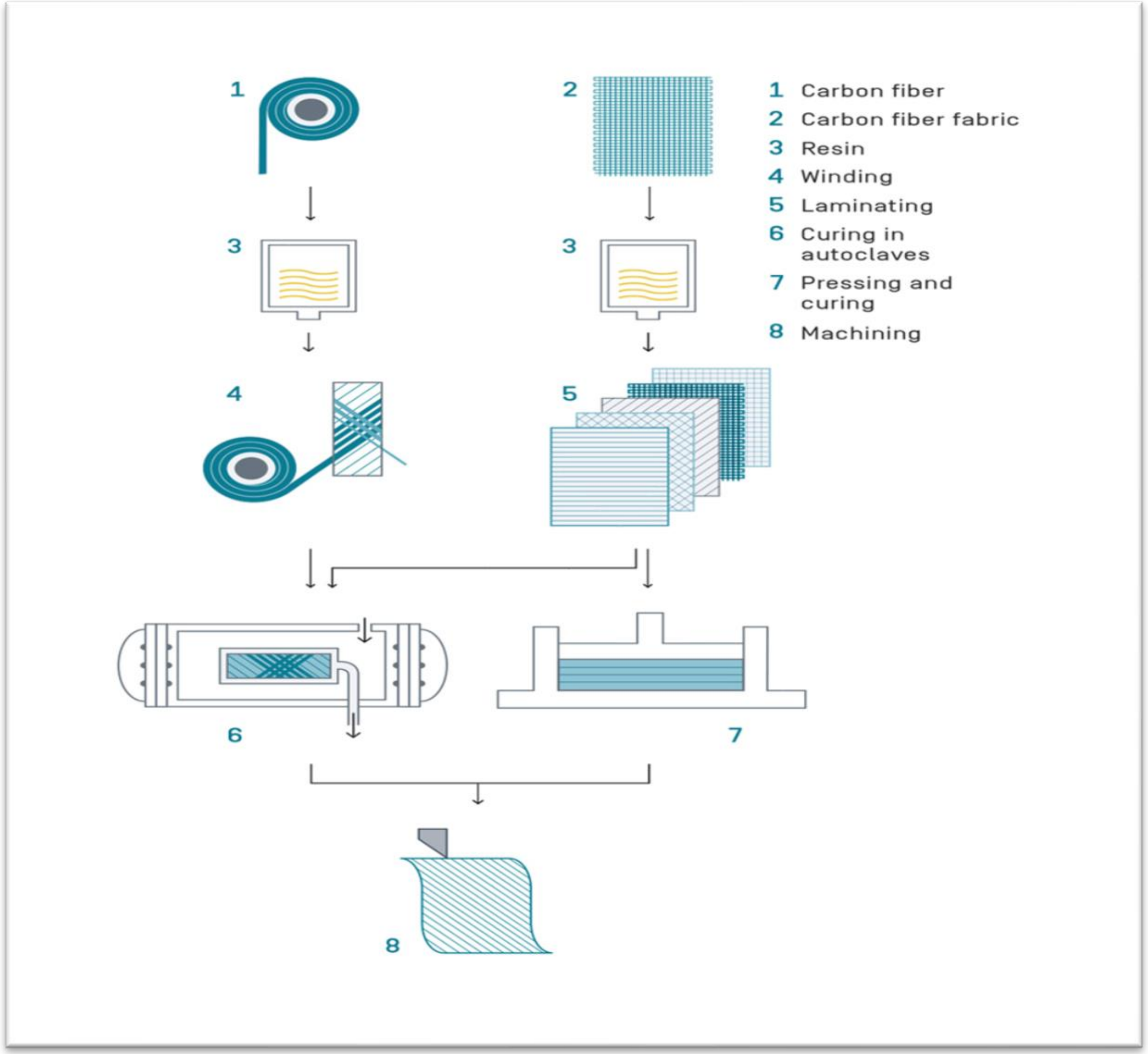
- The surface of the fibers is treated to improve bonding with the matrix material in composites.

Sizing

- A protective coating is applied to the fibers to improve handling, weaving, and compatibility with resins.

FROM CARBON FIBER TO CARBON FIBER REINFORCED POLYMER

- While carbon fibers are incredibly **strong, lightweight, and stiff**, they are **brittle and difficult to shape** on their own.
- To unlock their full potential, they are combined with **resins (usually epoxy polymers)** to form a **composite material**.
- This combination creates **Carbon Fiber Reinforced Polymers (CFRPs)** — materials that are **strong, lightweight, corrosion-resistant, and formable**.
- CFRPs can be molded into complex aircraft structures while maintaining **exceptional mechanical performance**.



RESIN SYSTEMS IN CFRPS

- **Key Functions**
  - Load Transfer
  - Fiber Support
  - Environmental Protection
  - Toughness
  - Resin Selection

- **Selection**
  - Mechanical properties
  - Temperature resistance
  - Chemical resistance
  - Processing
  - Cost

Resin Type	Strength	Stiffness	Toughness	Temperature Resistance	Cost	Common Use
Epoxy	High	High	Moderate	High	High	Primary Structures
Polyester	Moderate	Moderate	Moderate	Moderate	Low	Secondary Structures
Vinyl Ester	Moderate	Moderate	Good	Good	Moderate	Corrosion Resistance
Thermoplastic	Good	Moderate	High	Variable	Moderate	Emerging Applications

PRIMARY STRUCTURAL COMPONENTS MADE FROM CFRPS

Fuselage:

- Main body of the aircraft; houses passengers, cargo, and systems while maintaining cabin pressure

Wings:

- Provide lift and contain fuel tanks; designed to handle bending and twisting forces during flight

Tail Section:

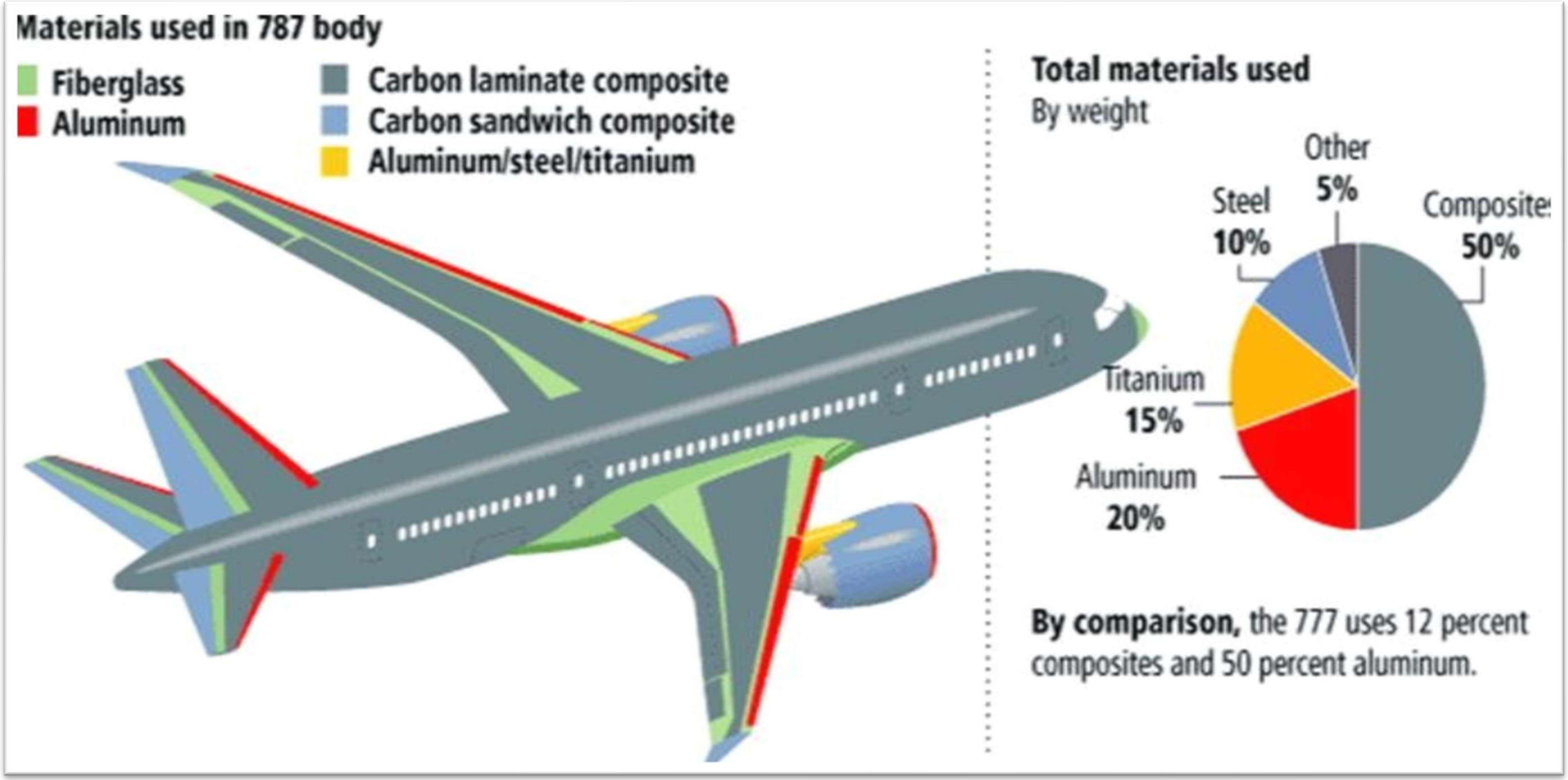
- Controls aircraft stability and direction; includes vertical and horizontal stabilizers

Floor Beams:

- Support passenger cabin and cargo areas; transfer loads between the fuselage sides

CFRP IN THE BOEING 787 DREAMLINER

- **50% of the 787’s structure (by weight)** is made from carbon fiber reinforced polymers (CFRPs) — including the **fuselage and wings**.
- Using CFRPs helps reduce the aircraft’s **overall weight by about 20%** compared to traditional aluminum designs.
- This results in a **20% improvement in fuel efficiency**, saving airlines **millions of dollars annually** in fuel costs.
- CFRPs also allow for **higher cabin humidity and lower cabin altitude**, improving **passenger comfort** during long-haul flights.
- Fewer parts and better corrosion resistance lead to **lower maintenance requirements and costs** over the aircraft’s lifetime.
- The 787 is one of the most advanced and efficient aircraft in the world — much of that is thanks to the use of **carbon fiber composites.**


Materials used in 787 body
Fiberglass
Aluminum
Carbon laminate composite
Carbon sandwich composite
Aluminum/steel/titanium
Total materials used
By weight
Other
5%
Steel
10%
Composites
50%
Titanium
15%
Aluminum
20%
By comparison, the 777 uses 12 percent composites and 50 percent aluminum.

787 DREAMLINER VS. OLDER AIRCRAFT

Feature	Boeing 787 Dreamliner	Older Aircraft (e.g., 767, 747)
Material Use	50% CFRP (Carbon Fiber Reinforced Polymer)	Primarily aluminum alloys
Fuel Efficiency	~20% more efficient	Baseline (higher fuel consumption)
Weight Reduction	~20% lighter airframe	Heavier, especially fuselage and wings
Maintenance	Lower (corrosion-resistant, fewer parts)	Higher (more inspections, corrosion risks)
Cabin Comfort	Higher humidity, lower cabin altitude	Drier air, higher cabin pressure
Lifespan & Durability	Longer fatigue life, better chemical resistance	Susceptible to fatigue and corrosion
Environmental Impact	Lower CO_2 emissions per passenger	Higher emissions

CHALLENGES AND LIMITATIONS OF CARBON MATERIALS IN COMMERCIAL AEROSPACE

- **High Manufacturing Cost:**
  - **Carbon fiber production (especially PAN-based) is energy-intensive and expensive, making it less cost-effective than metals like aluminum.**
- **Complex Manufacturing Process:**
  - **CFRPs require specialized curing, molding, and bonding techniques**, which increase production time and complexity.
- **Difficult to Inspect:**
  - **Unlike metals, internal damage (e.g., delamination)** in CFRPs may not be visible on the surface and requires **advanced non-destructive testing (NDT)** methods.
- **Limited Recyclability:**
  - **Carbon composites are not easily recyclable**, posing environmental challenges at end-of-life compared to metals.
- **Brittle Failure Behavior:**
  - **CFRPs can be less ductile** than metals, leading to sudden failure under certain conditions (no plastic deformation to signal it).
- **Repair Challenges:**
  - **Repairing damaged CFRP structures can be labor-intensive and costly**, requiring special procedures and adhesives.

CONCLUSION

- **Review of Benefits**
  - High strength-to-weight ratio, fatigue, and corrosion resistance are crucial.
  - Leads to better fuel efficiency, lower emissions, and reduced costs.
- **Challenges**
  - High manufacturing costs and complex processing.
  - Inspection and recyclability difficulties.
- **Future Directions**
  - Cost-effective manufacturing.
  - Improved NDT techniques.
  - Recyclable CFRPs.
  - Self-healing composites .