Benchmarking Commercial Carbon Fibers for Composite Pressure Vessels (CPV) for Hydrogen Storage

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1. Abstract

Composite Pressure vessels (CPVs) are designed to store safely hydrogen at high pressures (350 - 700 bars), which essentially deliver sufficient gravimetric energy density for practical use, especially in fuel cell vehicles. Carbon fiber is essential in this context due to its outstanding specific tensile strength, and resistance to fatigue and corrosion. CPVs are produced through filament winding process which involves winding continuous tows of fibers that are impregnated with a formulated thermoset resin around a rotating mandrel to create cylindrical shapes. Benchmarking commercial carbon fibers to produce hydrogen pressure vessels through the filament winding process is vital to identify the optimal materials that ensure both manufacturing efficiency and structural performance. This process involves evaluating different commercial carbon fibers based on parameters such as tow size, tensile strength and modulus and fiber sizing to ensure compatibility with resin systems used in filament winding.

In this paper, we have taken a multi-tiered evaluation approach that starts at the fiber level, moves to the fiber-matrix level, laminate level and finally, component level, each progressively simulating real-world performance. This systematic approach ensures that the chosen fiber delivers optimal mechanical properties, processing performance, and durability in hydrogen pressure vessel applications. By benchmarking across all four levels of scale, we have demonstrated that the manufacturers can comprehensively understand material behavior and optimize carbon fiber selection for safe and efficient high-pressure hydrogen storage.

2. Introduction

Composite Pressure Vessels (CPVs) are critical components in the storage and transportation of hydrogen particularly for applications in fuel cell vehicles. These vessels are designed to withstand high pressures while ensuring safety, durability, and efficiency under a variety of operating conditions. Pressure vessels are commonly classified into five types: Type I (all-metal), Type II (metal liner with hoop-wrapped composite), Type III (metal liner fully overwrapped with composite), Type IV (polymer liner fully overwrapped with composite) and Type V (a liner-less composite construction). Each type presents a trade-off between cost, weight, performance, and permeation resistance. Type IV vessels are especially favored in automotive and aerospace sectors

due to their lightweight structure and high gravimetric hydrogen storage efficiency, achieved using advanced carbon fiber composites and polymer liners [1-3].

Carbon fiber plays a pivotal role in enhancing the performance of composite pressure vessels, where high strength-to-weight ratios are essential. The primary function of carbon fiber in these vessels is to provide structural reinforcement to withstand high internal pressures while significantly reducing the vessel's weight. Key properties that make carbon fiber suitable for this application include high tensile strength, high modulus, low density, excellent fatigue and corrosion resistance. High Strength (HS) fibers (e.g., T700) are commonly used due to their balance of strength and cost, while Intermediate strength fibers (IM) (e.g., T800, IM7) are chosen when stiffness or pressure performance is prioritized. The careful selection of fiber grade, resin matrix, and winding architecture enables manufacturers to tailor vessel designs for optimal safety and energy density [1,4-5].

Benchmarking of commercial carbon fibers with different tow sizes is essential for optimizing the filament winding process used in manufacturing high-pressure hydrogen storage vessels. Tow size directly influences winding efficiency, resin impregnation, and final composite properties. Larger tow sizes can improve production speed and reduce cost but may lead to poorer resin penetration and increased void content if not carefully managed. Fiber shape and diameter also play crucial roles; smaller diameters offer higher surface area for bonding, enhancing mechanical performance, but may increase processing complexity. Additionally, fiber sizing affects fiber-matrix adhesion, processing compatibility, and composite durability [6]. An optimal balance among these parameters is critical to ensure uniform winding, structural integrity, and high burst strength of the final pressure vessel. Therefore, a systematic benchmarking helps identify the most suitable carbon fiber grades for efficient and high-performance composite manufacturing.

3. Experimental Procedure

3.1. Methodology

Benchmarking carbon fiber for high-pressure composite pressure vessels involves a multi-tiered evaluation across fiber level, fiber-matrix level, laminate level, and component level, each progressively simulating the real-world performance. This systematic approach ensures the chosen fiber delivers optimal mechanical properties, processing performance, and durability in hydrogen storage applications.

Fiber Level: This includes assessing the intrinsic properties of the dry fiber, such as tensile strength, modulus, elongation, filament diameter.

Fiber-Matrix Level: This level focuses on the interfacial bonding between the carbon fiber and the resin system.

Laminate Level: At this stage, impregnated prepreg materials are tested in flat composite laminates. Standard tests include in-plane tensile, compressive, interlaminar shear strength (ILSS).

Sub-Component Level: This is the final validation stage where representative parts of the composite pressure vessel undergo functional testing.

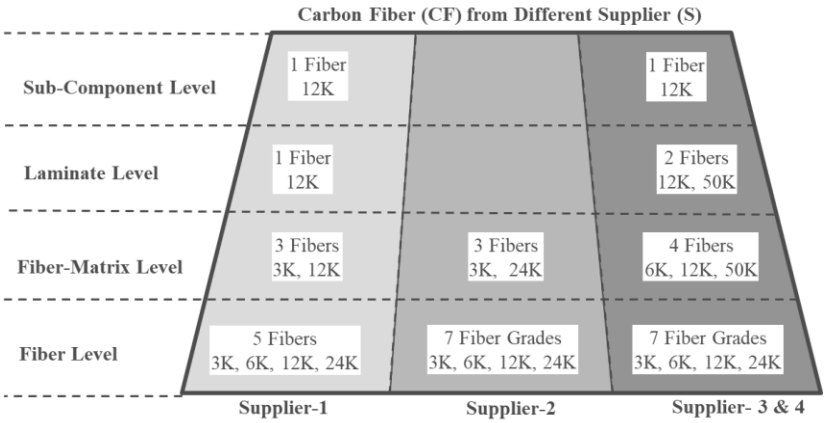

Figure 1. Multi-Tiered Evaluation Approach. The pyramid on the right shows the systematic down-selection of carbon fiber grades as one move from the bottom to the top. This was done to manage costs of evaluation.

3.2. Material

Carbon Fiber

Commercial grades of carbon fiber with tow sizes and different sizing chemistry used for the study are shown in Table 1 together with published performance data from their technical data sheet.

Table 1. Carbon fiber grade used for study.

Supplier	Code	Tow Size	Sizing		Mechanical properties	
			Type	Content (%)	Modulus (Gpa)	Strength (Mpa)
1	CF1-S1-3K	3K	PU	1.25	240	3800
	CF1-S1-6K	6K	PU	1.25	240	3800
	CF2-S1-12K	12K	PU	1.25	240	4200
	CF2-S1-24K	24K	PU	1.25	240	4200
	CF3-S1-12K	12K	PU	1.30	240	4900
2	CF1-S2-3K	3K	EP	1.30	238	3950
	CF1-S2-6K	6K	EP	1.30	238	3950
	CF2-S2-3K	3K	EP	1.00	237	4300
	CF3-S2-12K	12K	EP	1.00	239	4300
	CF3-S2-24K	24K	EP	1.30	239	4500
	CF4-S2-24K	24K	PU	1.00	240	4000
	CF5-S2-24K	24K	PU	1.00	240	4800
3	CF1-S3-3K	3K	-	2.00	245	5000
	CF1-S3-6K	6K	-	1.00	230	3530
	CF2-S3-3K	3K	-	1.00	230	3530
	CF2-S3-6K	6K	-	0.70	230	4410
	CF3-S3-6K	6K	-	1.00	230	4900
	CF3-S3-12K	12K	-	1.00	230	4900
	CF3-S3-24K	24K	-	1.00	230	4900
4	CF1-S4-50K	50K	-	1.00	242	4137

Resin

The selected resin materials used for work are shown in table 2:

Table 2. Resin Material used for the studies.

Study Level	Resin	Supplier
Fiber-Matrix Level	EPIKOTE™ Resin MGS™ RIMR 135 and EPIKURE™ Curing Agents MGS RIMH 134 - 137	Westlake, USA
Laminate Level	PMT-F1 (82 ºC cure toughened epoxy resin)	Patz Materials and Technologies (PMT), USA
Component Level	EPIKOTE™ Resin 04976 EPIKURE™ Curing Agent 04976	Westlake, USA

3.3. Sample Preparation and Testing Method

Fiber Level

Tests are done to evaluate the mechanical properties as well as the spreading behavior of the fibers as following: Tensile properties, Carbon fiber shape and diameter, surface quality and sizing distribution, Density, Sizing amount, and Spreading behavior:

Table 3. Table captions should be inserted above the table.

Test Type	Standard	Equipment	Properties
Tensile	DIN EN ISO 1973 DIN EN ISO 5079	Favimat+	Strength, modulus, strain & Diameter
Shape & Diameter	ISO 11567	Optical microscope Leica DM4000M	Shape & Diameter
Density	ISO 10119	Gas pycnometer AccuPyc II 1340	Density
Sizing amount	ISO 10548	TGA/DSC1 Mettler	Sizing Amount

Fiber-Matrix Level

The interfacial adhesion strength between the fiber and matrix was evaluated using a custom-made single-fiber pull-out (SFPO) instrument of IPF Dresden as shown in Figure 2(a). A pre-selected embedding sample length was prepared and embedded accurately and perpendicularly to the surface of the epoxy matrix. EPIKOTE™ resin MGS™ RIMR 135 and EPIKURE™ curing agents MGS RIMH 134 – 137 supplied by Westlake Epoxy, (USA) was used as a model thermoset system.

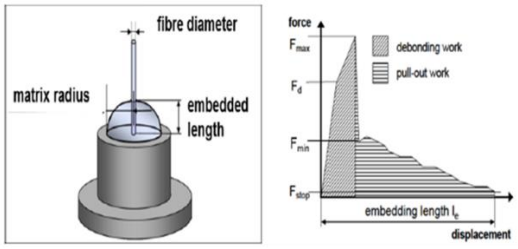

Figure 2. (a) Schematical drawing of the specimen, (b) Characteristic force-displacement curve (curtesy IPF).

The conditions during the fiber embedding process:

- Epoxy resin to hardener mixture ratio: 100:30
- Heating up to 45°C, hold 100 s

- Embedding of the fiber; embedding length: 100 µm
- Heating up to 85°C, hold 60 min
- Cooling down to room temperature
- Curing in the oven for 370 min (6 h + 10 min) at 80°C

The single fiber pull-out test (SFPO) was carried out with a loading rate of 10 nm/s. The force-displacement curves and the maximum force (Fmax) required for pulling the fiber out of the matrix were measured. After testing, the fiber diameter (df) was measured using optical microscopy; The embedded length (le) was determined using the force-displacement curve and cross-checked using a scanning electron microscope (SEM). The adhesion bond strength between the fiber and the matrix was characterized by the values of the apparent interfacial shear strength that is presented by Equation 1 [7-11].

$$\tau_{app} = \frac{F_{max}}{\pi * d_f * l_e} \quad (1)$$

Laminate Level

The next step in the chain of knowledge approach is to investigate performance at the laminate level. The prepreg required for the study was prepared through hot-melt pre-pregging process by Patz Materials and Technologies (PMT) using the selected carbon fibers and a typical 82 ºC cure epoxy resin formulation, PMT-F1. The target resin content (RC) and fiber areal weight (FAW) are 36% and 190gsm respectively.

The required laminates for testing are prepared in an autoclave using the recommended cure cycle from prepreg manufacturer:

- 2.78 ºCmin ramp to 82 ºC @ 80psi pressure & vacuum
- Hold 250 min
- Cool down to 60 ºC (2.78 ºC/min) followed by cool-down under no pressure

Table 4. Table captions should be inserted above the table.

Test type	Standard	Number of layers	Lay-up
Tension	ASTM D3039	6	$[0]_6$
In Plane Shear	ASTM D3518	12	$[-45/+45]_{3S}$
Bias Compression	ASTM D3410	15	$[90/0/90]_5$

The laminates are cut to the required size according to the standards and tabs and strain gauges are added to measure the strains during testing. Tests are done for evaluating the mechanical properties of the laminates according to the ASTM standard shown in Table 4.

Sub-Component Level

Finally, to translate the knowledge acquired to the sub-component level, carbon fibers were wound onto 146 mm diameter cores on the robotic filament winding machine with different winding angles. The process parameters were recorded in an SQL (Structured Query Language) database as well as video recordings of the fiber band formation.

The carbon fiber tension is applied with motors and a roving brake directly at the mounted bobbins. The fiber impregnation with a pre-tempered epoxy resin at 50 °C takes place in an open resin bath in the center of the laying head. The epoxy resin used for the trial was EPIKOTE 04976 (100 % by weight), curing agent EPIKURE 04976 (80 % by weight) and catalyst 04976 (1.5 % by weight), from Westlake Epoxy B.V., (Pernis, Netherlands). A doctor blade was engaged to scrape of excess resin at the impregnation roller, thereby controlling the resin loading on the impregnation roller. The winding angle and process parameter for different samples are shown in Table 5.

Table 5. Filament wound specimen with winding process parameters.

#	CF Code	Winding angle (º)	# Layers	Fiber Tension (N)	Doctor Blade gap (mm)
1	CF3-S3-12K	[90]	4	20	200
2	CF3-S3-12K	[±55]	4	20	200
3	CF3-S3-12K	[90]	4	20	300
4	CF3-S1-12K	[90]	4	20	200
5	CF3-S1-12K	[90]	4	20	300
6	CF3-S1-12K	[±55]	4	20	300

After winding, the test specimens were cured in an oven with a rotation axis. The following curing cycle was used:

- 2 h at 80 °C (Ramp: 1 K/min)
- 6 h at 120 °C (Ramp 1 K/min)
- Cooling to room temperature (Ramp ~ 0.5 K/min)

The filament-wound pipes were successively separated into uniform ring sections for mechanical testing using a saw. The ring samples were mechanically tested with the split-disc-test according to ASTM D2290. This is a widely used test method to determine the tensile strength of a ring in the circumferential direction.

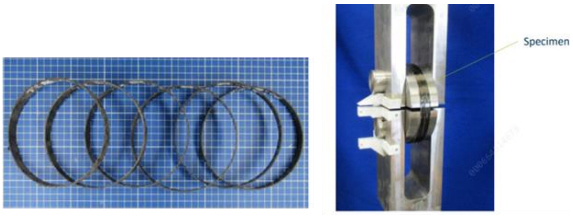

Figure 3: Ring samples for mechanical testing

4. Results and Discussion

4.1. Fiber Level

Some of the fiber grades and their respective cross-sectional shapes are shown in Figure 4. Most fibers tested have near circular cross-sectional shapes, however Carbon fiber 2 & 3 from supplier 1 and carbon fiber 1 from supplier 3 have kidney-shaped cross-sectional shape. This may be due to non-uniform distribution of tension during the wet-spinning step in precursor production or uneven solvent extraction rates. CF manufacturers usually overlook this fact since kidney shaped fibers may yield better mechanical results.

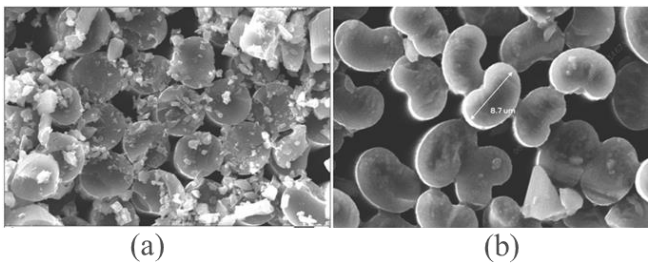

Figure 4: Cross Section of the selected fibers (a) Circular (b) Kidney-shaped cross sections

The tensile properties of some of the tested fibers/filaments are shown in Figure 5. The measured modulus and strength values are slightly lower than the data sheet numbers.

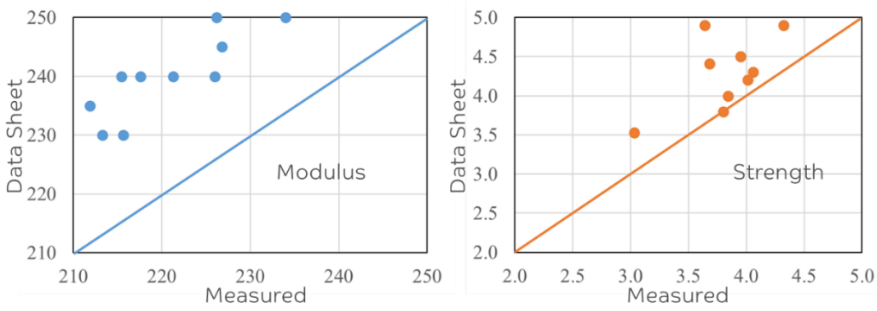

Figure 5: Measured Fiber modulus and strength compared with data sheet numbers

4.2. Fiber-Matrix Level

The force – displacement curves and the SEM images of the fiber surface are shown in the Figure 6. As shown in the figure, the fiber shape, tow size and sizing can impact the fiber – matrix interaction. In terms of sizing, fibers from Supplier 1 have polyurethane sizing, but fiber from Supplier 2 has epoxy sizing which reflects on the higher debonding force and the failure surface.

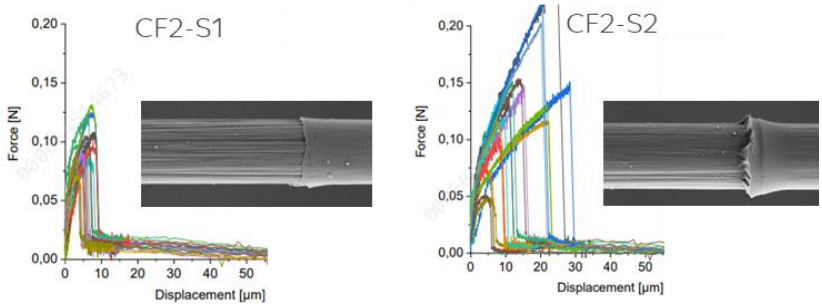

Figure 6: Force-displacement curves and SEM of fiber surface after testing

Figure 7 shows the interfacial shear strength (IFSS) of different fibers. As shown, CF1-S1 fiber performs slightly better than CF2-S1 and CF23-S1 fibers due to the influence of the fiber shape. The fiber from supplier 2, CF2-S2, performed best due to epoxy sizing. The huge scattering of the results of CF2-S2 may be due to an irregular sizing coverage. On average, the IFSS values of all the fibers are closer to the yield strength of the epoxy resin used (65 -75 MPa) which indicate that the failure is predominantly due to yielding of the resin rather than debonding.

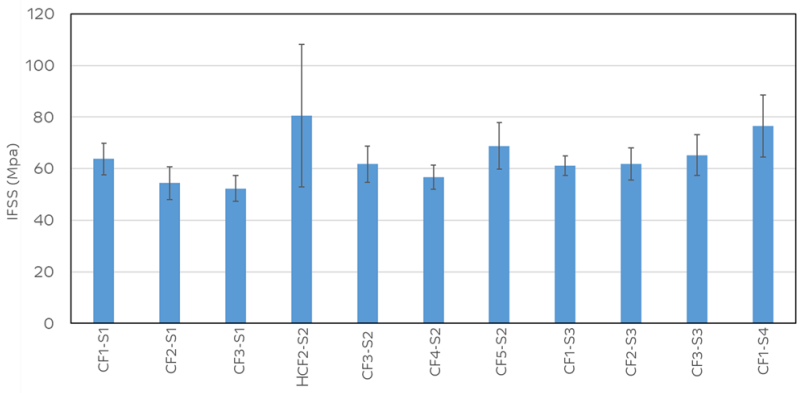

Figure 7: Interfacial Shear Strength from SFPU test

4.3. Laminate Level

The results from tensile tests conducted on unidirectional laminates for the selected three fibers are shown in Figure 8. As shown, the modulus values are similar for all three fibers, but there are differences in the strength results. Given that the fiber from Supplier 4 has lower strength (4137 MPa) compared to other two fibers (4900 MPa), it is expected that laminate with CF1-S4 shows lower results. The difference in strength between the fibers from Supplier 1& 2 may be the type of sizing used and the shape consistent to the results obtain in the single fiber pull out test (Figure 7).

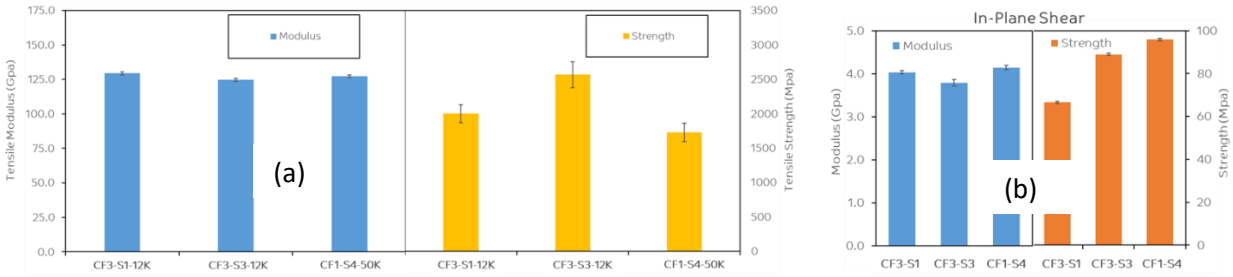

Figure 8: (a) Tensile (b) in-plane shear properties of the laminate

The in-plane shear tests on quasi laminates for the selected three fibers are shown in Figure 8(b). As shown, the modulus values are similar for all three fibers. The difference in composite level strength between the Supplier 3 and Supplier 1 fibers may be due to the type of sizing similar to the tensile strength results. But the higher in plane shear strength of the Supplier 4 fiber compared to the Supplier-3 is unexpected.

4.4. Component Level

Figure 9 shows the conditions of the bobbins during the filament winding process. Compared to the bobbin from Supplier-3, bobbins from Supplier-1 shows some fluffiness in the fiber during winding. This points to the importance of the role of sizing and care in fiber packaging.

Figure 9: Quality of the carbon fiber bobbins

Figure 10(a) shows the gap per layer during winding. Fiber from Supplier-1 consistently produces more gaps per layer than fiber from Supplier-3 in hoop winding. In helical winding the fiber from Supplier-1 shows very good performance. One explanation for this is that the fiber fuzziness at lower winding speeds can compensate for inhomogeneous tension in the fiber band and thus prevent gap formation. This leads to importance of packaging quality of carbon fiber on bobbins.

The ring disc samples were mechanically tested with the split-disc-test according to ASTM D2290. The tensile strength from split disc test for both Supplier-1 and Supplier-2 samples are shown in Figure10(b).

As shown in the figure, fiber from Supplier-3 performed better than the fiber from Supplier-1 in terms of mechanical strength for the Hoop wound samples while the fiber Supplier-1 performed better for the helically wound samples. This corresponds well with the gaps observed during winding: Higher gaps lead to lower tensile strength.

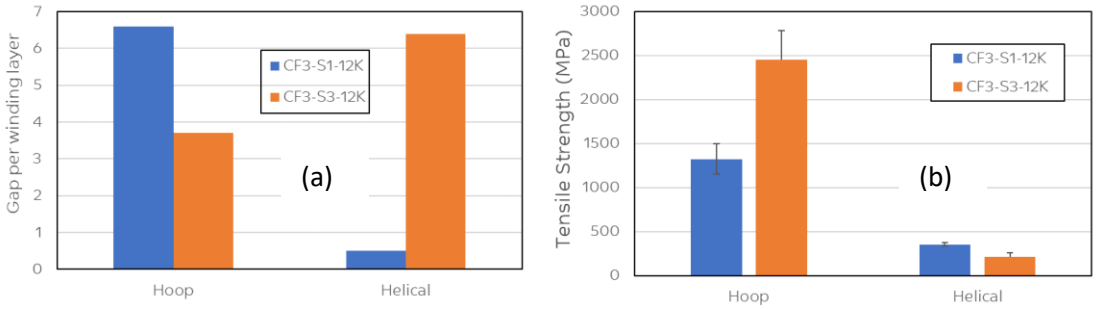

Figure 10: (a) Gaps per layer during winding (b) Tensile strength

5. Discussion

The mechanical performance of carbon fiber filament wound composite pressure vessels is influenced by a variety of intrinsic and extrinsic parameters related to fiber geometry, sizing chemistry, and processing conditions. Benchmarking commercial carbon fibers to produce composite pressure vessels through the filament winding process is vital to identifying the optimal materials that ensure both manufacturing efficiency and structural performance. This process involves evaluating different commercial carbon fibers based on intrinsic and extrinsic parameters as discussed above. Benchmarking the carbon fibers at component level such as a section of the pressure vessel that is produced through filament winding process will be difficult to clearly identify the influence of these parameters on the mechanical performance of the pressure vessel.

In this work, we have demonstrated that by taking a systematic chain of knowledge, multi-tiered evaluation process that starts at the fiber level, moves to the fiber-matrix level, laminate level and finally, sub-component level, ensures that the chosen fiber delivers optimal mechanical properties, processing performance, and durability in hydrogen pressure vessel applications. By taking this approach the manufacturers can comprehensively understand material behavior and optimize carbon fiber selection for safe and efficient high-pressure hydrogen storage.

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