Investigation of Surface Shift Behavior Under Internal Pressure In Carbon Composite Tubes

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Introduction

The biggest obstacle to technological development has been the failure of materials science to keep pace with technological developments. In other words, materials science is the foundation of technological developments. Advances and discoveries in materials science have always led to technological developments throughout history.

Given the importance of technology today, materials science is important at least as a technological innovation. For this reason, materials science has created sub-sectors that represent different industries within itself. Examples of these sub-sectors include metals, non-metals, chemicals, organic and inorganic materials, polymers, etc. However, composites are the most important of these sub-sectors in modern technology. Composites first emerged as a new field of materials science during World War II. Since then, composites have found widespread application in technology and are materials that are frequently used in leading industries such as aerospace, automotive, and textiles, and continue to evolve to meet the demands of these applications.

In general, composites are materials with the highest properties formed by combining two or more substances with different chemical and physical properties at the macro level. When designing parts made from composite materials, it is necessary to know where the part will be used and what the specific needs of the application are. During the planning stage, factors such as raw material properties, environmental conditions, and production methods must be evaluated along with cost. One of the greatest challenges in composite material design is that composite materials do not exhibit isotropic properties. Therefore, the person producing the structure must calculate how much load will be applied to each part of the composite material and how much strength will be required, and position the fibers accordingly.

The matrix material prevents the propagation of cracks that may occur during plastic deformation and prevents damage to the composite material. Another purpose of the matrix material is to hold the fibrous material together under load and distribute the load evenly among the fibers. Thus, when forces causing plastic deformation of the fibrous material are applied, the propagation time of a crack that may occur will be extended. Various metal alloys can be used as the matrix, but resin matrices are more commonly used.

For a produced material to meet the definition of a composite material, it must possess certain properties. These include:

It must be produced using various methods. (Excluding composite structures such as bone, naturally occurring wood, etc.)

It must be formed by the combination of two or more materials with physically or chemically different properties.

It must achieve mechanical properties that cannot be obtained with a single component.

In this study, Atagün and colleagues addressed the detailed design of a filament winding machine, the design of composite pressure pipes, and the numerical analysis of their structural performance. The geometry of the pipe dome plays an important role in determining the performance of the structure. Therefore, the continuity theorem and mesh analysis methods were used to achieve the optimal dome geometry in the design. The optimal dome geometry was obtained using equations based on the radar radius, and the geometry of the resulting pipe was finalized. Various structural and modeling analyses were performed on the pipe geometry obtained during the study to determine the structural behavior and limits of the pipes. Since the burst pressure value, which is important for pipes, is related to the degree of detail of the dome geometry, there should be no structural deformation of the pipe from the side of the dome (rib). Any damage to the tip of the nozzle could cause the tube to rocket away under excessive internal pressure. Therefore, in designs, it is expected that the cylindrical region will bend outward beyond the limit load of the composite pressure tubes (Atagün, 2017).

Composite materials were examined within the scope of this project. When manufacturing a material using composites, there are many variables, such as resin and fiber, each with its own unique properties. However, the final product depends not only on the properties of these two variables but also on how the composite is manufactured, which greatly affects the final properties of the material. In this study, a fiber winding technique called filament winding was used as a method for making composites. This method is used in many fields, from aviation to the military, as it enables the production of strong and lightweight parts. In this thesis study, research was conducted in the field of pressure vessel applications, one of the areas where composite materials obtained by fiber adsorption are used. Models of high-pressure vessels with composite structures produced using fiber production technology under various loads were examined (Pehlivan, 2017).

This study examines pressure vessels, which are used in many fields today and exhibit different performance under changes in temperature and pressure. Pressure vessels differ depending on the type of material they are made of, particularly due to their physical properties. While analyzing the behavior of structures whose material properties are temperature-dependent under various loads, the experimental results were validated by applying hydrostatic pressure tests to pressure vessels under internal pressure. Since pressure vessels may pose potential hazards that could affect human health and safety, any issues that may arise before use must be identified and addressed. This requires a comprehensive and detailed analysis of the pressure vessel design, accurately defining and considering all loads that could affect the system in calculations. Therefore, the solution of the theoretical approach for a cylindrical pressure vessel subjected to an axially symmetric load was compared with the displacements and pressures obtained from the Von-Mises stress analysis in SolidWorks software. The “COSMOXpress Analysis Wizard” computer program was used to perform the analysis using the finite element method (Mestan, 2010).

In another study, a pressure vessel design was created using steel-lined and glass fiber-reinforced epoxy resin material wrapped in circumferential and tangential composite material. Compressed natural gas storage tanks were used as a reference when designing these pressure vessels. Axial and circumferential deformations occurring on the vessel wall at different pressure values were investigated. Additionally, the results from the prototype were compared with real-world results and analysis results from a virtual environment (J., 2009).

In another academic study, a tank to be used in a satellite response system was designed and analyzed in a virtual environment. While designing this tank, it was desired to be lighter than metal tanks of the same volume. The design model consists of composite layers wrapped in aluminum foil. Before using thick-walled cylinders, the process of relieving residual stress in the wall is called autoclaving. This eliminates some of the stress under high pressure. As a result, the pressure-bearing capacity of pressure vessels increases. Autoclaving can be performed mechanically or hydraulically. Hydraulic autofrettage is more costly than mechanical autofrettage. Numerical values were determined by conducting strain and stress analyses of the parts forming the composite-wrapped pressure vessel, identifying the optimal angle for the wrap, autofrettage, vibration, and model fiber analyses, and fatigue analyses of potential damage to the aluminum liner. The Ta-sai-Wu, Hashin, and Tsai-Hill criteria were used to determine these damages (Çetin, 2014).

Another study aimed to determine the burst pressure of cylinders exposed to environmental stresses during operation. In this study, HY 225 hardener was mixed with CY 225 epoxy and wound at an orientation angle of 55°. Repeated and single impacts were applied to hollow composite cylinders filled with water at different temperatures. In addition to the impact test, a static pressure test was also conducted. As a result, it was observed that the explosion pressure decreased as the impact energy and temperature increased. The number of repetitions did not affect this result. Finite element analyses were also conducted on samples that were not subjected to impact (İlki et al., 2008).

In another study, stress analyses under pressure were evaluated for two different steels in thin-walled pressure vessels. Designs were created using finite element software. Three-dimensional models were examined in two different ways. The explosion pressures were determined using maximum stress criteria on the damaged areas of the vessel. The damage results were evaluated using Von-Mises criteria. The importance of design effects in thin-walled pressure vessels was observed in the finite element analysis. It was determined that the explosion pressure was higher in the analysis than in the analytical results (Eruslu, 2008).

Another study aimed to investigate the fatigue behavior of filament-wrapped pipes under pressure. The wrapped pipes were obtained from four layers using a ±75° helical wrapping method with glass fiber and epoxy. The tests were conducted at a frequency of 0.42 Hz, a stress ratio of R:0.05, and in accordance with the ASTM D-2992 standard. Leakage and fracture tests were performed, and strength-time graphs were created based on the results of damage progression (Gemi et al., 2009).

In another study, the strength of composite pressure vessels for different layer arrangements was examined in real and virtual environments. As a result, it was determined that the first layer was the most significant factor in the damage to the pressure vessel. Graphite fiber and epoxy pressure vessels were used in this study. When examining the results, it was observed that the first layer burst pressure in analytical analyses was significantly higher than in real-world conditions. In real-world experiments, the value was lower. As a result, it was determined that the first-layer damage theory is an important theory for design (Khanna & W. P. Kuhn, 1997).

In another study, the stresses and deformations occurring in the wall of a composite-wrapped pressure tank with a metal liner under internal pressure were calculated for different layer arrangements. This study also used different composite materials. In addition, analytical studies were compared with real studies. The analyses utilized

Tsai-Wu damage criteria. According to the analyses, reducing the helical winding angle positively affects the burst pressure. The burst pressure values in the real-world experiments and analytical studies are similar. In the analytical studies, work was conducted on the cylindrical part of the pressurized container. In the real-world studies, two 6-liter prototypes made of Kevlar 49 fiber, epoxy, and carbon fiber, epoxy-coated metal were used (LD Landau et al., 1975).

In his academic work, the explosion pressures of composites produced with glass fiber and epoxy resin in anti-symmetrical and symmetrical layers with thin walls at different angles were examined, and as a result, the most suitable angle was evaluated. In other words, the effects of filament winding angles on composite pipes were evaluated. S.G. Lekhnitskii's theory was used as a numerical solution method to determine the damage condition in the container. The effects of different angles under the same temperature were calculated using this theory. The Tsai-Wu damage criterion was used for damage control. The results of this study showed that the optimal winding angle for composite pipes produced using the helical winding method was approximately 55°, while for pipes produced using the single-angle winding method, it was approximately 90° (Onder et al., 2009).

In another study, a stress analysis method was developed for thick- and thin-walled multilayer composite cylinders under hydrothermal stresses. The layers were designed to be anti-symmetric and symmetric at different angles. During the analysis, the plane stress condition and the boundary condition of open or closed pipe ends were evaluated. Parabolic and uniform temperature distributions were preferred for heat loads. All integration values were obtained from normal directional deformations and radial stresses. In addition to hydrothermal properties, other mechanical properties were also found on a glass fiber epoxy composite. It was observed that the finite element solutions obtained from the analysis were consistent with the analytical results (Sayman et al., 2011).

In his study, he examined the increase in strength by creating pressure within the material or by selecting materials to increase strength. The main objective is to evaluate the increase in strength by creating pressure cells within the designed product. In the study, pressurized air was placed inside cylindrical aluminum tubes with thin walls, and different strength and stress tests were performed. In these studies, a finite element analysis program was used for analytical calculations. The results obtained were compared with each other. It was determined that the results were consistent. Subsequently, studies and analyses were conducted using the finite element method on real models to prove their applicability in real life (Yıldırım, 2012).

Materials And Methods

Properties of Carbon Fiber

The density of carbon fibers varies depending on the processing temperature and raw material used in production. The densities of raw materials used in production range from 1.6 g/cm^3 to 2.2 g/cm^3. After fiber production, there is a slight increase in density depending on the raw material. The increase in the produced fibers varies depending on the graphitization temperature.

The technical properties of the carbon fiber used in this study are given in the table below;

Table 1

Technical specifications of 24 K-type carbon fiber rope

Features	Unit	Value
Fiber Type	Carbon	HT
Number of Filaments		24000
Linear Density	Dtex	1600
Sizing Ratio	%	1,5
Elongation at Break	%	1,5
Tensile Strength	MPa	3950
Modulus of elasticity	GPa	238
Density	g/cm^3	1,77
Diameter	micron	7
Electrical Conductivity	Ohm*cm	1,6*10^{-3}
Carbon Ratio	%	93
Coil Weight	kg	4

Figure 2
Carbon Fiber Rope 24K

Hexion brand LR160 epoxy resin and LH160 hardener are used together in a 4:1 ratio as the matrix material. Detailed information about the matrix material is available in the tables below.

Table 2
Resin LH160 technical specifications

Density (g/cm^3)	1,13-1,17
Viscosity (mPas)	700-900
Epoxy Equivalent (gr/equivalent)	166-182
Epoxy Value (equivalent/100gr)	0,55-0,60
Refractor İndex	1,5480-1,5530
Flexural Strength (MPa)	110-140
Tensile Strength (MPa)	3.2-3.5
Compression strength (MPa)	80-100
Poisson Ratio	0,36

Table 3
Hardener lh160 technical specifications

Density (g/cm^3)	0,96-1,00
Viscosity (mPas)	10-50
Amine Value	550-650
Refractor İndex	1,5200-1,5210

Carbon Nanotubes (CNTs)

Carbon nanotube polymer composites are the most important carbon nanotube composites. Materials that provide electrical conductivity can be produced with carbon nanotube polymer composites. When 5% carbon nanotubes are added to the produced material, the electrical conductivity of the material is between 0.01 and 0.1 S (YAĞLIKÇI, 2012).

In this study, multi-walled 10-20 nm 95% purity Ӈ carbon nanotubes were used. The technical specifications of the nanotubes used are listed in Table 4.

Table 4

Technical properties of carbon nanotubes

Purity%	>%95(carbon nanotube) >%97(carbon content)
Outer diameter	10-20 nm
İnner diameter	5-10nm
Length	10-30 µm
Surface area	>200m²/g
Color	black
Ash	By mass<%1.5
Electrical conductivity	>100S/cm
Gravity(Tap)	0.22g/cm³
Gravity(True)	~2,1g/cm³

Manufacture of Pressure Vessels

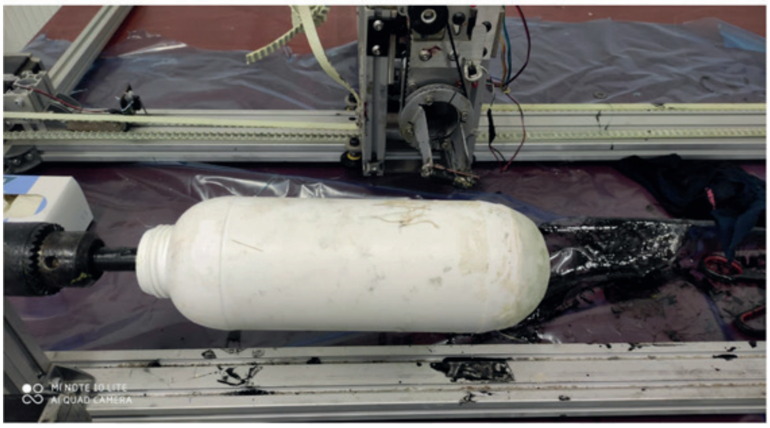
In this study, composite tubes were produced at different nanotube reinforcement ratios using carbon fiber, epoxy, and carbon nanotube reinforcement with the filament winding technique and the wet winding method at ±55°. The carbon filament material used to form the composite tube has a diameter of 17 µm, while the matrix materials used are LR160 Hexion resin, Hardener MGS LH160, and Multi-walled Carbon Nanotubes 10-20 nm 95%.

Figure 3

Images of nanotube, resin, and hardener packaging are used

Figure 4

Image of the pressurized container (liner) connected to the machine before winding



In this method and technique, carbon fibers passed through a resin pool were wound at an angle of ±55° onto plastic liners 30 cm long and 72 mm in diameter. Winding was continued until the desired outer diameter of 94.7 mm was achieved. Using these windings, three different samples with varying carbon nanotube reinforcement ratios were produced. The matrix ratios of these samples are provided in Table 6. The produced samples were subjected to surface finishing using a universal lathe to achieve an outer diameter of 94 mm.

Figure 5

Surface finishing of the produced sample

After the surface finishing process, the test apparatus was prepared for the samples to withstand internal pressure tests. To attach the samples to the test apparatus, threading was performed using a universal lathe. Connection equipment was produced using a universal lathe to connect the samples to the internal pressure test apparatus, and threading was applied to the base of the threads to ensure sealing with the resin mixtures used in the production of each sample. After securing, the curing time was waited for, and the test fixtures were set up by applying leak-proof Teflon tape to the test fixture.

Experimental Setup

The equipment used for the experimental setup is as follows:

Hydraulic Pump: An Anca ACP-01 manual oil pump was used to generate internal pressure for the purpose of examining surface shape changes under internal pressure. The technical specifications of the oil pump are listed in Table 5.

Table 5

Manual oil pump technical specifications

Model	Pump Type	Body	Available oil capacity	Tank oil capacity	High pressure flow rate(cm^3)	High-pressure piston diameter	working size	low-pressure flow rate	low-pressure piston diameter	maximum arm force	connection type	manometer	working pressure
ACP-01	Single-acting double speed	Al	0,5	0,7	0,8	7	21	10,3	25	29	3/8”-NPT	Ø63,1000 Bar	700 Bar

Datalogger: A D4 Micro-Measurements brand 4-channel digital data logger was used in the study. Data was recorded on a computer at a sampling rate of 8 Hz via RJ-45 connectors and at intervals of 0.125 seconds via a USB interface.

Strain gauges; In this study, the m-Bond 200 strain gauge mounting adhesive kit was used. The m-Bond 200 kit consists of a cyanoacrylate strain gauge adhesive that cures instantly at room temperature and a catalyst. The general-purpose adhesive properties commonly used in hot environmental conditions are listed in Table 6.

Table 6

General-purpose adhesive technical specifications

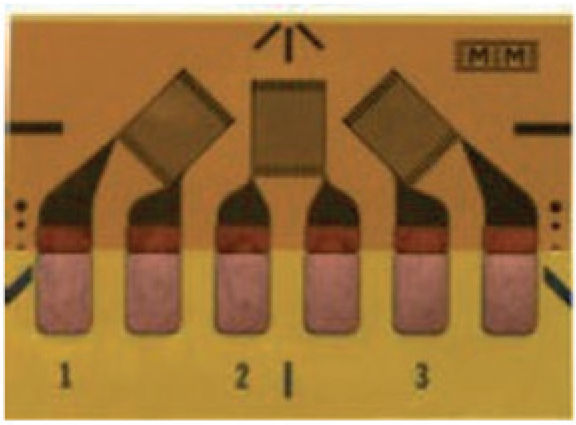
Maximum elongation (Strain in % at 75°F)	5
Lower temperature limit (FahrenheitȷH)	-25
Minimum curing temperature (FahrenheitȷH)	70
Container life	3 month
Shelf life	1 year
Upper temperature limit (FahrenheitȷH)	150

Badge: The CEA-06-062UR-120/P2 code badge product was used as a strain gauge in the study.

The P2 model is designed to be added to CEA series strain gauges with pre-installed main wires. No soldering is required during installation of the P2 model. The cables are color-coded, straight, and three-conductor. They are also manufactured with a thickness of 30 gauge (0.255 mm), vinyl-insulated multi-strand, and tin-plated copper solder. Each conductor of the cables has a nominal resistance of 0.1 ohm/ft (0.35 ohm/m). The temperature range for the connectors is –60° to +180°F (–50° to +80°C).

Figure 6

CEA-06-062UR-120/P2 coded badge scheme



The experimental setup consists of a thin-walled cylindrical pressure vessel with a length of 38 cm, a wall thickness of 0,32 cm, and a diameter of 11.5 cm. In addition, there is an auxiliary system to increase the pressure of the thin-walled pressure vessel. The auxiliary system uses a hydraulic hand pump to increase the pressure of the vessel.

Strain gauges are used to measure the strain values that will occur on the vessel wall due to internal pressure. These strain gauges are attached to the outer surface of the vessel with special adhesives. The stresses that will occur in the axial and circumferential directions are measured with the 1st and 3rd strain gauges, while the shear stress that may occur on the cylinder wall is calculated with the values read from the 1.2. and 3rd strain gauges.

The resistance values provided by the strain gauges will also be read using an auxiliary device. Additionally, a manometer integrated into a hydraulic hand pump is used to measure the pressure inside the vessel and to apply regular pressure increases.

The experiment aimed to determine and verify the axial and circumferential strain values of thin-walled pressure vessels under internal pressure using strain gauges. The oil-filled samples were connected to a manual hydraulic oil pump using a leak-proof band. Three strain gauges were attached to each sample. During the experiment, resistance data were measured at 0.125 ms intervals and recorded in real-time on a computer.

Research Findings And Discussıon

The aim of the tests conducted on composite cylindrical pressure vessels was to develop pressure vessel types. For this purpose, surface shape change tests were performed under internal pressure. The variables in the study were carbon nanotubes in the composite resin. The parameters covered in the study are shown in Table 7.

Table 7

Parameter charts

Parameter No	Carbon nanotube/Resin ratio
1	*0*
2	*%1*
3	*%3*

Parameter 1, Stress Test Results of Carbon Nanotube-Free Pressurized Containers Under Internal Pressure

Three pressure vessels made of carbon fiber wrapped with carbon-free resin were produced, and as a result of the application under internal pressure, the tubes burst at an average pressure of 45 bar. The experiments lasted an average of 24 minutes, and the data were recorded on a computer using a data collection device every 0.125 seconds. During the first 2-3 minutes of the experiments, a manual oil pump with its own mechanism evacuated the air to create internal pressure. The samples were monitored for stress sounds associated with internal pressure increases, and surface changes were observed during the experiments. Since the experimental setup included a manual manometer, pressure values were tracked manually, and the final values of the samples before rupture were recorded. Figure 6 and 7.

Figure 6

Experimental setup

Figure 7

Parameter 1 screenshot with instant results

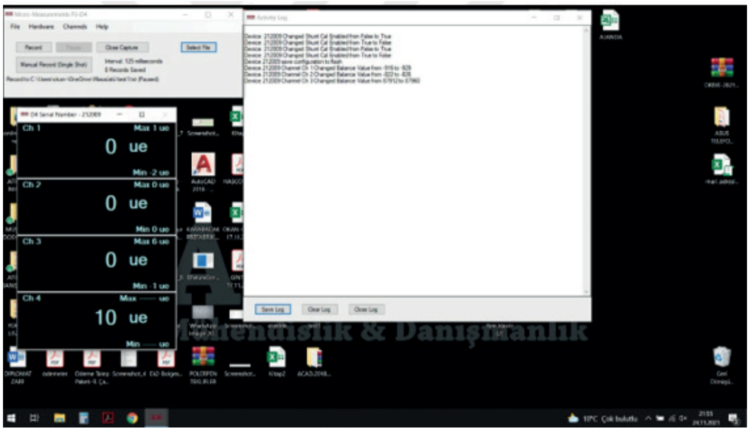
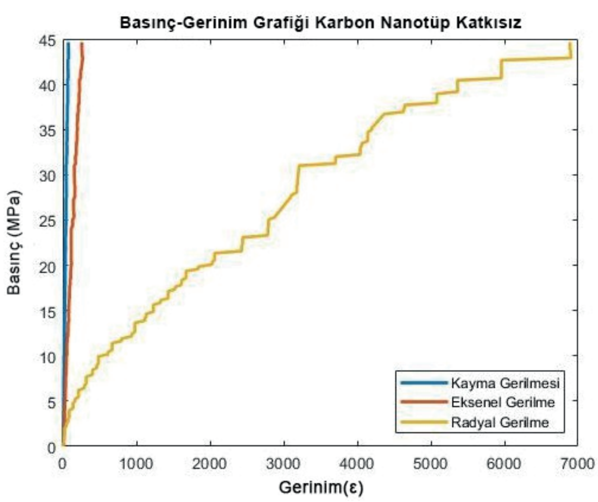


Figure 8 shows the stress-strain ratio graph for the carbon nanotube-free composite cylindrical pressure vessel. The maximum pressure resistance of the samples was found to be 45 bar, with an average axial elongation of 0.258286, an average radial elongation of 0.075429, and an average shear stress of 6.889905 corresponding to this resistance.

Figure 8

Parameter 1 stress/strain graph



When the results of the Parameter 1 experiment are examined, it is seen that the numerical values of shear and axial elongation are approximately equal, and the numerical value of radial stress is high.

The samples were cut into two pieces with an automatic saw in order to examine the deformations in the cross sections. The cross-section images are shown in Figures 9 and 10.

Figure 9

Parameter 1 sample image

Figure 10

Parameter 1 cross-sectional image 1

Figure 11

Parameter 1 cross-sectional image 2

Figure 12

Parameter 1 section microscope image 1

Figure 13

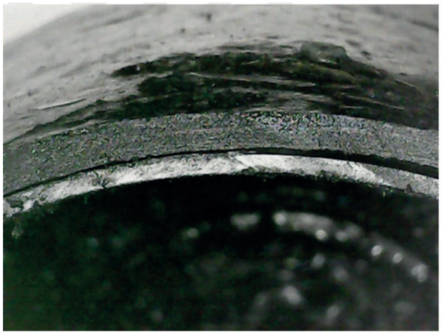
Parameter 1 section microscope image 2

Figure 14

Parameter 1 section microscope image 3

Figure 15

Parameter 1 section microscope image 4



Parameter 2, Carbon Nanotube Ratio 1% Internal Pressure Surface Shape Change Test Results

In the pressure test on the 2nd sample, the tubes burst at an average pressure of 95 bar as a result of the stable application of load. The test duration averaged 38 minutes, and data were recorded on a computer using a data collection device every 0.125 seconds. During the first 2-3 minutes of the tests, a manual oil pump with its own mechanism evacuated the air to create internal pressure. Stress sounds associated with the increase in internal pressure in the tubes were monitored, and surface changes were observed during the test. Since the test setup included a manual manometer, pressure values were tracked manually, and the final values of the tubes before bursting were recorded.

Figure 16

Parameter 2 screenshot with instant results

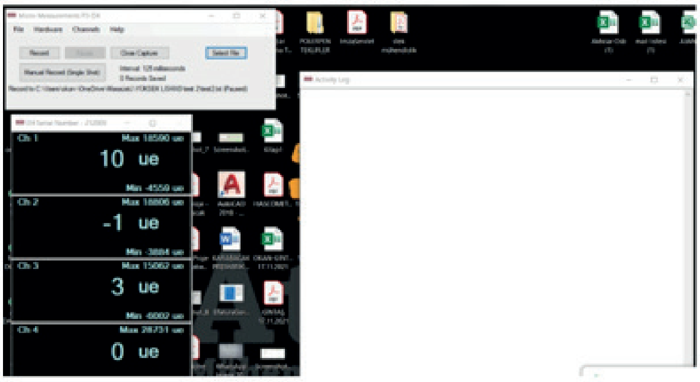


Figure 17 shows the stress-strain ratio graph for a composite cylindrical pressure vessel with a carbon nanotube ratio of 1%. The maximum pressure resistance of the sample was found to be 95 bar, with an average axial elongation of 7.315875, an average shear elongation of 5.725125, and an average radial stress of 3.299625 corresponding to this resistance.

Figure 17

Parameter 2 stress/strain graph

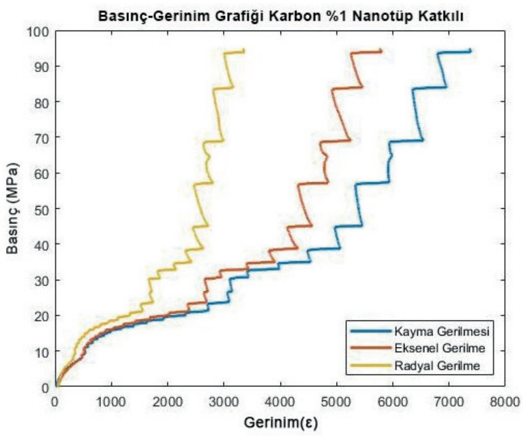


Figure 18

Parameter 2 sample image after experiment 1

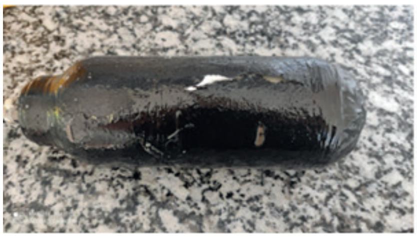


Figure 19

Parameter 2 sample image after experiment 2

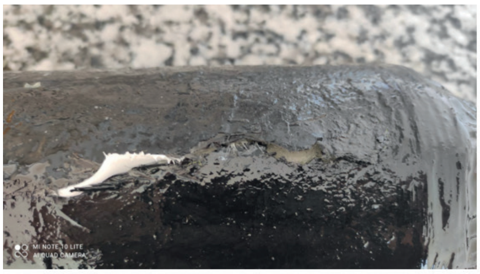


Figure 20

Parameter 2 cross-sectional image 1

Figure 21

Parameter 2 cross-sectional image 2

When the results of the Parameter 2 experiment are examined, it shows that the axial and shear strain values are approximately low, and the radial stress is low.

Figure 22

Parameter 2 section microscope image 1

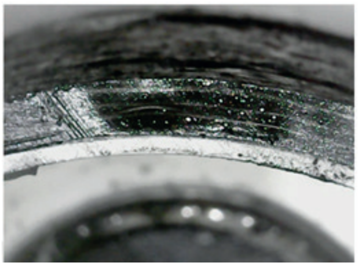


Figure 23

Parameter 2 section microscope image 2

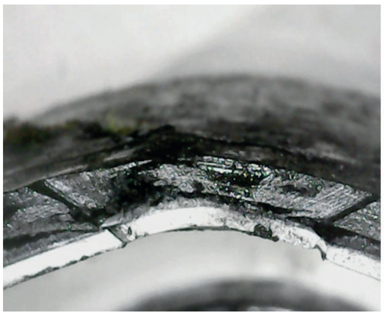


Figure 24

Parameter 2 section microscope image 3

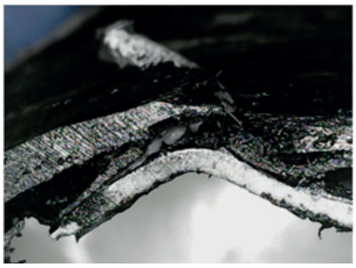
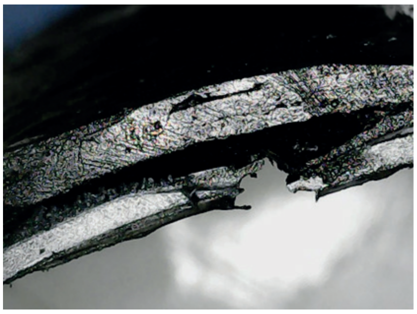


Figure 25

Parameter 2 section microscope image 4



Parameter 3, Carbon Nanotube Ratio 3% Internal Pressure Surface Shape Change Test Results

Parameter 3 pressure test reached a value of 140 bar as a result of stable load application and exploded. The test lasted 42 minutes, and data were recorded on a computer using a data collection device every 0.125 seconds. During the first 2-3 minutes of the test, a manual oil pump with its own mechanism discharged the air to create internal pressure. Stress sounds associated with the increase in internal pressure were monitored, and surface changes were observed during the test. Since the test setup included a manual manometer, pressure values were tracked manually, and the final values of the samples before the explosion were recorded.

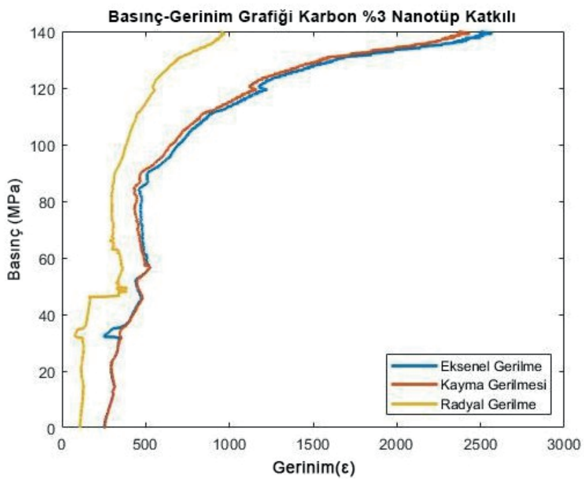
Figure 26

Parameter 3 screenshot with instant results

Figure 27 shows the stress-strain curve for a cylindrical pressure vessel made of a composite material containing 3% carbon nanotubes. The average maximum pressure resistance of tubes with parameter 3 is 140 bar, with an average axial elongation of 2.36775, an average shear elongation of 2.499, and an average radial stress of 0.947625 corresponding to this resistance.

Figure 27

Parameter 3 stress/strain graph



When the results of Parameter 3 experiments are examined, they show that the axial and shear strain values are approximately low, and the radial stress is low.

Figure 28

Parameter 3 sample image before experiment

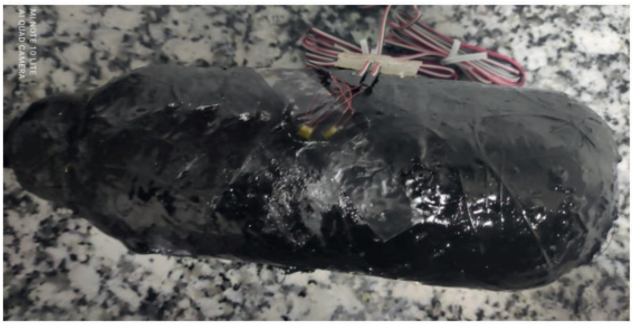


Figure 29

Parameter 3 cross-sectional image 1

Figure 30

Parameter 3 cross-sectional image 2

Figure 31

Parameter 3 section microscope image 1

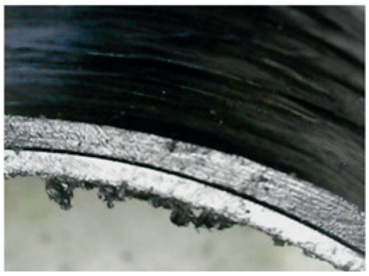


Figure 32

Parameter 3 section microscope image 2

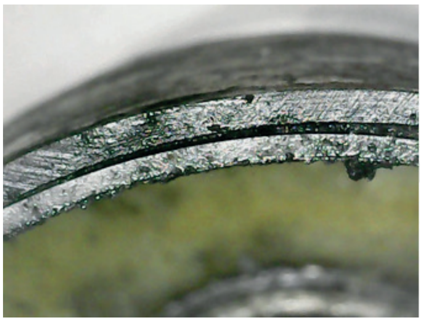


Figure 33

Parameter 3 section microscope image 3

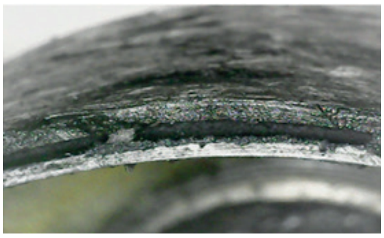
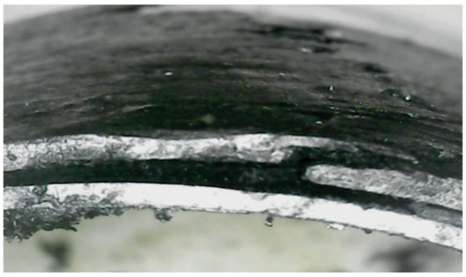


Figure 34

Parameter 3 section microscope image 4



Results And Recommendations

- In internal pressure tests of carbon fiber-wrapped pressurized cylindrical composite tank samples, it was observed and confirmed by test results that carbon nanotube-reinforced composite materials and their ratios have a significant effect on surface stress displacement.
- When the carbon nanotube ratio, which is the experimental variable, increases, the strength of the composite samples increases compared to the carbon-nanotube-free composite tubes. This is because the carbon nanotubes are homogeneously mixed into the resin, giving the composite material new properties.
- The addition of carbon nanotubes has also increased the burst pressure of the tubes proportionally. There has been an average increase of 9.33 times between the empty liner and the composite tube with 3% additive. Here, carbon nanotubes have generally increased the strength of the material, making crack formation and fiber/matrix separation more difficult.
- In the study, damage was expected in the areas where teeth were cut into the material and connection and filling devices were mounted in the geometries of the tank's end sections, and the composite throat section was added later. However, since epoxy was used as a sealing and bonding agent, no damage was

encountered here. In the study, it was observed that the critical region of the tube suffered axial separation damage in the main body. The material did not show any geometric planar displacement while being damaged. It retained its cylindrical structure. This prevents negative effects on the environment during use and damage.

- As a result, it has been concluded that tubes or tanks made of composite materials using aluminum, plastic, or other liners can store much more gas (approximately 20 times more) in a much smaller volume, and that the use of much lighter materials creates an ideal combination of weight, volume, and pressure.

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