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Effect of Nano-SiO_2 on The Creep Behavior of Carbon Fiber/Polyester Composites for Oil Pipelines

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Abstract

The study focuses on enhancing the creep resistance of composite pipes made from carbon fiber, which contains 55% polyester and is reinforced with nano silicon dioxide nanoparticles for use in oil pipeline applications. The research investigates how varying the weight percentage of nanoparticles (0.16%, 0.2%, and 0.24%) affects the mechanical properties and creep behavior of the composite material. The results reveal that incorporating nanoparticles significantly improves creep resistance. Specifically, creep strain decreased by 21% as the nanoparticle ratio increased from 0.16% to 0.2%, and by 35% when the ratio increased to 0.24%. The results of the scanning electron microscope (SEM) analysis indicated a uniform distribution of nanoparticles at concentrations of 0.2% and 0.16%. However, at a nanoparticle weight of 0.24%, a small percentage of agglomerates was observed, leading to a lower improvement in creep strain resistance compared to the 0.2% concentration. The study utilized numerical analysis through the finite element method, employing ANSYS software to simulate the creep behavior of composite pipes over a period of eight years under a constant internal pressure of 6.8948 MPa. It was found that stresses and strains were concentrated at the connection points near the pipe ends, underscoring the importance of periodic inspections in these critical areas. Additionally, the constants from Norton's equation at constant temperature were extracted to predict the long-term creep behavior of the composite material. The results provide design guidelines for improving the long-term reliability of composite pipelines in oil transport systems.

Keywords: Creep, Composite Pipes, Nano Silicon Dioxide, Finite Element Analysis, Norton's Equation.

1. Introduction

Industrial sectors such as automotive, aerospace, and energy have shown considerable interest in the use of composite materials. In recent years, research has increasingly focused on the application of reinforced polymers in the chemical, petroleum, and electrical industries. In the energy sector, fiber reinforced composite polymer pipes have emerged as a practical alternative to conventional steel pipes. These composite pipes are approximately one-quarter lighter than steel, making them easier to install and assemble, and they also offer greater corrosion resistance in marine environments [8]. However, the long term performance of these materials under continuous mechanical and environmental loads remains a significant concern for infrastructure applications such as oil and gas pipelines. Previous studies have focused on the impact of manufacturing processes on material properties, identifying defects such as fiber misalignment and core cracking that compromise durability and strength [9]. Environmental factors, such as salt concentration in marine environments, have also been shown to affect the impact toughness and fracture resistance of composite materials [10]. While this research provides insight into the short-term behavior of materials and their environmental interactions, it does not fully address temporal deformation (creep) under continuous operating pressure. Other studies have modeled the viscoelastic and thermal responses of composite materials using analytical and numerical methods [11-13], and studies on nanoparticle reinforcement—such as graphene in rubber [14]. The creep behavior of composite materials reinforced with various types of hybrid fibers was predicted using an accurate model that considered the formation method. This study compared the results of finite element analysis with experimental results, where it was observed that changing the deflection angle led to an increase in creep [15]. Additionally, creep analysis of unidirectional composites was performed using various creep models, including micromechanics, homogenization techniques, the Mori-Tanaka method, and the finite element method [16]. However, the complexity of composite material behavior necessitates more specialized models. For example, one study investigated creep behavior using a least-squares model in carbon fibers, resins, and epoxy with viscoelastic properties [17]. Another study investigated the prediction of creep in viscoelastic composite sheets to determine the

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displacement field, deterioration variables, and strain response to a given time-domain stress using Laplace equations. The model was then compared with experimental results and synergistic deterioration mechanics solutions [18]. Despite advancements in creep modeling, long-term prediction accuracy remains a challenge. In this context, a creep model was developed as a function of time and temperature, employing a sophisticated gene expression programming algorithm to achieve higher accuracy. The model's results demonstrated its effectiveness in predicting long-term creep performance [19]. It is well established that continuous stress over time causes creep, a phenomenon that progresses through three phases: initial (temporary) creep, followed by secondary (stable) creep, and then tertiary (accelerated) creep [20, 21]. To understand the mechanisms of creep, various theoretical models were employed. The viscoelastic-elastic behavior of composite structures was explained using the Burgers model [22]. Furthermore, viscoelastic-elastic models were developed for SCF/PEI composites to predict long-term creep behavior using a model that considers the effects of time and temperature [23]. A study described the nonlinear viscoelastic-thermoplastic behavior of glass fiber-reinforced polyester composite sheets to predict creep and relaxation coefficients under different loads and temperatures, demonstrating good agreement between experimental, numerical, and theoretical results [24]. However, practical applications require understanding the effect of micro-nano admixtures. A study investigated the effect of reinforcing composite materials with multi-walled carbon nanotubes and their distribution within the microstructure on mechanical properties, using scanning electron microscopy (SEM) images. The study showed that properties improved significantly when the nanoparticle content increased from 0.2% to 0.24% [25]. Furthermore, innovative fabrication techniques, such as ultrasonic cavitation, improved nanoparticle mixing and reduced particle size in aluminum composites, significantly increasing their hardness [26]. In addition, other research investigated the effect of reinforcing aluminum composites with silicon dioxide (SiO_2) and iron oxide (Fe_2O_3) to improve mechanical properties such as hardness and compressive strength [27]. However, a clear research gap remains in the field of oil pipelines. This study aims to improve the reliability of composite oil pipelines by developing a model that predicts the creep life of nanoparticle reinforced composite pipes. Composite pipes are known for their resistance to chemical corrosion and their lighter weight compared to metal pipes, allowing for effective preventative maintenance plans that reduce the costs associated with unplanned failures and extend the economic life of oil installations. A three dimensional model of the pipe was created, and a finite element stress-strain analysis was conducted using ANSYS. Norton's law constants, derived from experimental results at a constant temperature, were used to describe creep strain over time until failure. This analysis assesses the pipes' performance and durability under realistic conditions, predicting their operational lifespan before failure.

2. Materials and Methods

2.1. Materials

The study utilized a polyester composite material, for which the specifications are provided in Table 1. This composite contains 55% carbon fibers, with additional details found in Table 2. It is reinforced with varying weight percentages of nanoparticles: 0.16%, 0.2%, and 0.24%. The finely ground silicon dioxide nanoparticles, measuring between 20 and 30 nm, were sourced from Hongwu International Co., Ltd. (China), and their specifications are outlined in Table 3. The mechanical properties of the experimental composite were input into a model designed based on standard pipe dimensions. The model simulated operating conditions of constant pressure and incorporated the time required for numerical analysis using ANSYS to predict the creep behavior under sustained oil pressure over time. This simulation effectively describes creep behavior using the Norton equation, which traditionally requires years of testing to accurately predict material behavior.

Table 1. The mechanical characteristics of polyester

Value	characteristics
65 N/mm^2	Tensile strength
3.0 %	The elongation ratio
3600 N/mm^2	Elastic modulus
1268 kg/m^3	The density
70	Rockwell hardness scales

Table 2. Characteristics of the Carbon Fiber Mat

Characteristic	Value
The mass per area	200 (g/m2)
Weave	Plain
The width’s size	1000/2000 (mm)
The thickness’s size	0.16 (mm)

Table 3. Specifications of silicon dioxide nanopowder

Code No.	M606
Form’s shape	Powder
The Purity ratio	99.8 %
The color	White
Odor	Odorless
Melting’s temperature	1610-1728 C°
Boiling’s temperature	2230
The density	At 20 C° 2.77-2.66 g/cm^3
solubility in water	insoluble
Cas No.	7631-86-9

2.2. Methods

Acrylic’s mold was fabricated by a CNC milling machine and consisted of two pieces secured with four screws to ensure a tight fit during the casting process. A high-precision balance with four-digit accuracy was used to determine the fraction's weight of carbon fibers and nanoparticles. The homogeneity of the nanoparticles with the polyester before the casting process and the optimal dispersion were achieved using a mixing device (Ultra-sonic processor UP200Ht), as in Figure 1. Tensile tests were conducted to determine the mechanical properties of the composite material according to the ASTM standard for tensile testing (ASTM D3039). A constant load was applied over time in a creep test apparatus at room temperature. The fraction's weight of carbon fibers was set at 55%, along with different proportions of nanoparticles in the prepared creep samples, as shown in Figure 2. The sample dimensions were determined according to the ASTM D2990 standard [28], as shown in Figure 3, to evaluate its creep behavior. The study relied on a Scanning Electron Microscopy (SEM) to describe the microstructure and grain distribution of the composite material. The current study agrees with M.R.T. Arruda's research [29], which uses a thickness of 7 mm to conduct the creep test on composite samples composed of carbon fiber and polyester at various nanoparticle ratios.

Figure 1. The ultrasonic processor UP200Ht device

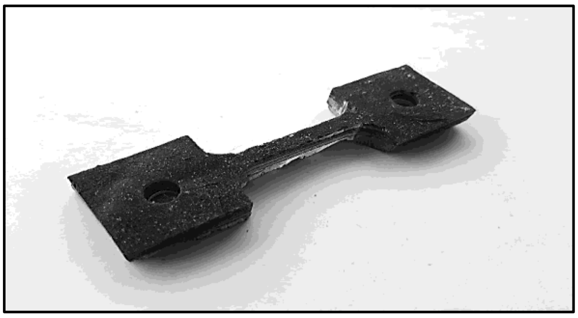

Figure 2. The Creep test specimens

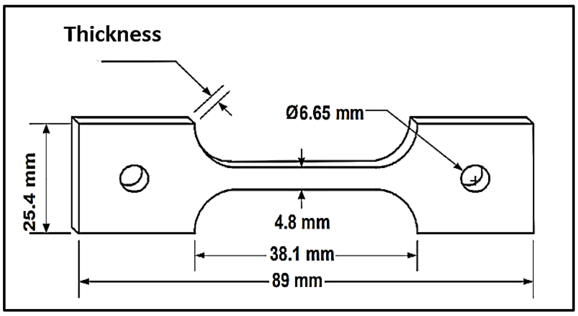

Figure 3. Standard Creep Test ASTM D2990

3. Methodology

Pipes transporting oil and gas under constant pressure are subjected to longitudinal and circumferential stresses. When the thin cylindrical shell is exposed to internal pressure, as described in Equation 1 and shown in Figure 4, it leads to annular or circumferential stress (i.e., tensile stress applied to the longitudinal section of the cylinder walls along the diameter X-X). The longitudinal tensile stress acting on the cross-section or circumference, as represented by Equation 2, is shown in the Y-Y section in Figure 5.

$$\sigma_h = \frac{p.d}{2.t} \quad (1)$$

$$\sigma_L = \frac{p.d}{4.t} \quad (2)$$

Where p is the internal pressure intensity, d is the internal diameter of the cylindrical shell, l is the length of the cylindrical shell, t is the thickness of the cylindrical shell, and σh is the circumferential (hoop) stress for the material of the cylindrical shell, while σL is the Longitudinal stress [30]. The study relied on circumferential stress calculations, as they are more influential in causing pipe failure, being twice as strong as longitudinal stress. Creep tests were conducted using a stress equivalent to the pressure rating applied in gathering lines, water injection lines, which is 6.8948 MPa.

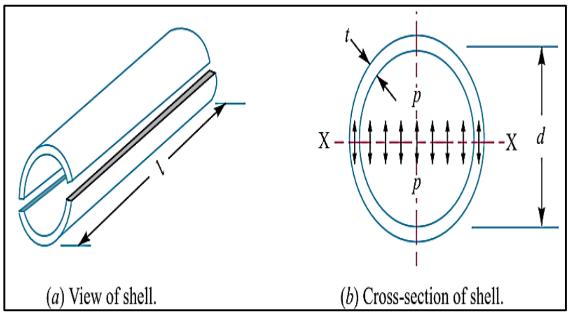

Figure 4. Circumferential or hoop stress.

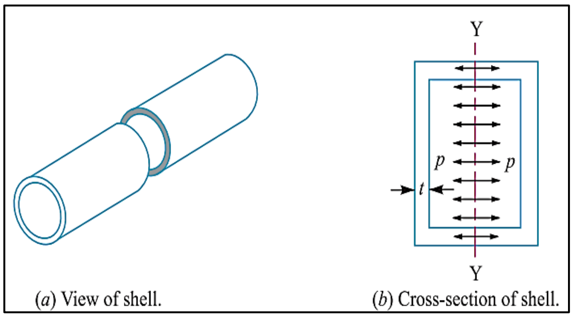

Figure 5. Longitudinal stress

Through the creep test procedures, the constants of the Norton equation at constant temperature shown below are determined [31]:

$$\varepsilon = K.\sigma^n \quad (3)$$

The constants (A), (n), and (m) represent values that depend on the time-strain relationship obtained from a creep test, taking into account the effect of temperature. Note that (n) and (m) are unitless, while (A) is derived from the time-strain relationship, (t), and stress, (σ).

4. The Experimental Results

Figure 6 presents the experimental results of tensile tests conducted on a carbon fiber-polyester composite reinforced with varying weight percentages of Nano-Sio_2 (0.16%, 0.2%, and 0.24%). The results indicate that increasing the percentage of nanoparticles generally leads to a reduction in elongation due to the increased brittleness of the composite. Conversely, this increase in nanoparticle content enhances the strength of the composite, allowing it to withstand higher stress levels before failure. Specifically, increasing the nanoparticle percentage from 0.16% to 0.2% results in an increase in tensile stress of (11.5%) and a decrease in elongation of (10.28%). Additionally, raising the percentage from 0.2% to 0.24% produces an increase in tensile stress of (11.27%) and a decrease in elongation of (0.55%).

To determine Norton's constants, a creep test was performed over a duration of 30,000 minutes (or 500 hours) based on the experimental results for the second stage of the creep test at a constant stress. Figure 7 shows the creep test for carbon fibre-polyester composite samples reinforced with different ratios of nano silicon dioxide particles. The results showed that creep decreased with increasing nanoparticle ratio, resulting in improved mechanical properties of the composite. Nanoparticles improve the strength of the material, which increases its resistance to creep over time and thus increases its working life in the application field. The stress applied to gathering lines and water injection lines is 6.8948 MPa on the creep specimen. The results showed that increasing the nanoparticle ratio from 0.16% to 0.2% reduced creep by 21%, while increasing the nanoparticle ratio from 0.2% to 0.24% reduced the creep stress by 35% when applying a constant stress over time at room temperature. The extended period of failure during the application of this stress, which simulates the stress experienced in oil pipelines, is utilized to determine the Norton equation constants, as shown in equation 3 and detailed in Table 4. This approach is meant to model the creep process in pipelines over long durations.

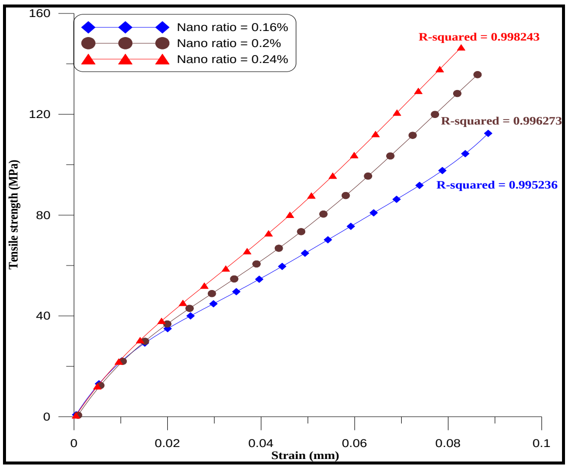

Figure 6. The experimental results for strain and tensile strength

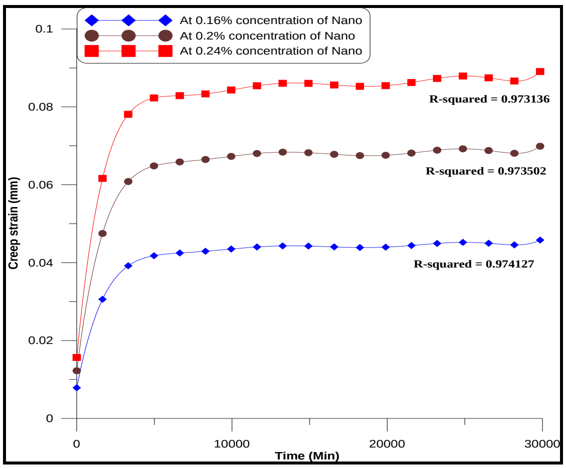

Figure 7. Shows the experimental results of the creep test

To evaluate the performance of composite materials under high-stress conditions, samples underwent an accelerated testing protocol over a short period. A stress equivalent to six times the design creep stress applied to pipes in normal operating conditions was applied. The study evaluated three different composite material compositions with reinforcement ratios of 0.16%, 0.2%, and 0.24%. All three demonstrated the ability to achieve creep under a load six times the assumed maximum operating load in realistic engineering scenarios. The experimental results were compared with numerical predictions generated by an advanced numerical simulation model. This model relied on Norton's Power Law to describe the relationship between strain rate, stress, and temperature, using Norton's material-specific constants. The model calculated the theoretical time required to reach the critical creep strain value under applied stress, as shown in a comprehensive comparison in Table 5.

The comparison revealed a remarkable agreement between the experimental data and the predictions of the numerical model, confirming the reliability of the model and the constants used.

A key finding of the experiments was that the total elongation recorded in the creep test samples was higher than that measured in rapid single-stroke tests of the same material.

This significant difference in behavior is attributed to the different deformation mechanisms enabled by the loading characteristics in each test. In the creep test, applying a constant and continuous load for an extended period creates favorable conditions for the activation of complex and cumulative deformation mechanisms within the material.

These mechanisms include the movement and sliding of crystal dislocations over longer timescales and the gradual redistribution of internal stresses resulting from the formation and development of microscopic cracks. Other processes, such as matrix flow, the initiation of material-fiber interface separation, and fiber pullout, also contribute to significant energy consumption and increased deformation displacement before failure. In contrast, conventional tensile testing is characterized by a rapid and escalating loading curve, which leads to the material transitioning from the elastic phase to the abrupt failure phase in a very short time. This does not allow sufficient time for intrinsic deformation mechanisms, especially time-dependent ones, to develop and evolve.

Consequently, the sample rapidly loses its potential elongation before reaching its maximum potential elongation under gentler conditions. This behavior is expected and perfectly consistent with the fundamental principles of composite mechanics. These findings and analyses support foundational research in this field, especially that presented by Daniel, I. M., and Ishai, O. [32].

Table 4. The constants of the Norton equation at stress 6.8948 MPa room temperature

Nano Ratio (%)	n	K	Norton equation, $\varepsilon^{\cdot} = K\,.\,\sigma^{n}$
0.16	0.18323623	1.201098111	$\varepsilon^{\cdot} = 1.201098111\,.\,\sigma^{0.18323623}$
0.2	0.169677	1.184922564	$\varepsilon^{\cdot} = 1.184922564\,.\,\sigma^{0.169677}$
0.24	0.166599	1.181280466	$\varepsilon^{\cdot} = 1.181280466\,.\,\sigma^{0.166599}$

Table 5. Creep time of oil pipes made from composite materials at different weight ratios of nano silicon dioxide

Nano Ratio (%)	The creep strain limit is experimentally determined to be six times the creep stress of 6.8948 MPa.	Max. numerical creep strain (mm)	Time (year)	Percentage of error (%)	Correlation coefficient (R^2)
0.16	1.0585	1.0201	(8 year)	3.63%	0.998
0.2	0.911	0.891	(8 year)	2.20%	0.999
0.24	0.861	0.85	(8 year)	1.28%	0.999

5. Finite Element Analysis (FEA)

5.1. Boundary Conditions

Creation of a 3D model of offshore oil and gas pipelines, such as offshore flowlines, risers, and gathering lines, according to standard dimensions with a thickness of 4 mm, a length of 448.5 mm, and an internal diameter of 110 mm [33]. SOLID185 elements in ANSYS were utilized for 3D creep modeling, with the creep model activated and Norton constants applied. The ends of the tube were securely fixed, and a uniform internal pressure was applied. The mesh sensitivity study confirmed the convergence of the results at an element size of approximately 3 mm, where the difference in equivalent stress dropped to less than 1%. This effectively balanced computational accuracy with efficiency. The ends of the pipe were connected to another pipe, as illustrated in Figure 8. An internal pressure of 6.8948 MPa was applied to the inner surface of the pipe, simulating the oil pressure during the transportation process, as depicted in Figure 9.The meshing process for the 3D tube model involves a total of 83,057 nodes and 41,327 elements. This setup is essential for accurately describing and simulating the creep behavior under the applied constant stress on the internal surface of the tube, as illustrated in Figure 10.The model included a hydrostatic pressure of light oil density of 830 kg/m³ and an acceleration of 500 mm/s².

5.2. Results and Discussion

The results of numerical analysis are distinguished by their strong capability to simulate engineering problems that are challenging to describe and analyze. This difficulty may arise due to the complexity of the products, such as those with intricate shapes, the potential dangers involved, as seen in the study of nuclear reactor behavior, or the extended testing periods required to fully understand their behavior, which can span several years. Consequently, this research utilizes numerical analysis to investigate the creep behavior of carbon fiber/polyester composite pipes reinforced with nanoparticles at various ratios.

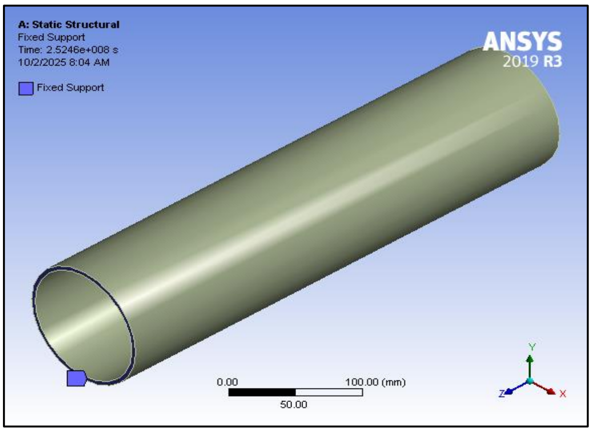

Figure 8. The clamping condition represents the joining ends in pipelines

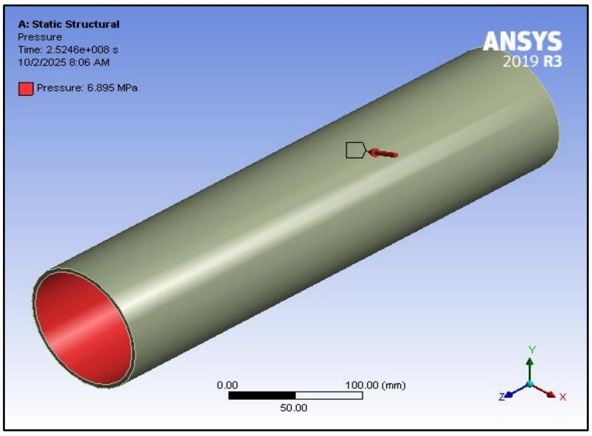

Figure 9. Apply the internal pressure according the field conditions

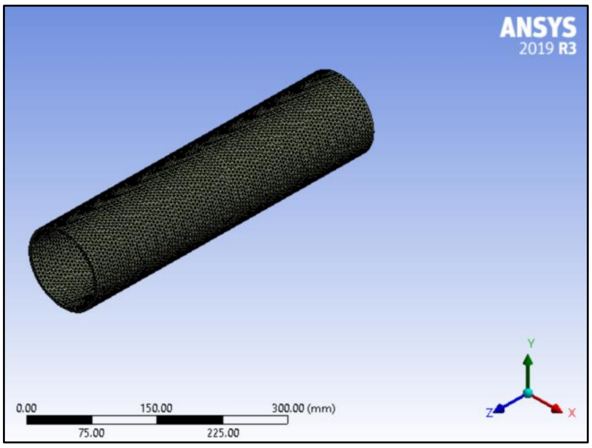

Figure 10. Illustratesthe meshing of the pipe model with 83057 nodes and 41327 elements

5.2.1. The Effect of Nano-SiO_2 on Creep Behavior

The elastic strain distribution model for a carbon fiber-polyester composite pipe, reinforced with 0.16% nanoparticles, is illustrated in Figure 11. This pipe is subjected to constant compression over a duration of 252,460,800 seconds, which is equivalent to eight years of oil transport. A numerical analysis, based on the material's experimental properties for the time-dependent creep process, reveals that stress concentrations are primarily located at the connection points with adjacent pipe sections, where failures are likely to occur. Therefore, periodic inspections of the pipelines should focus on these critical regions. The results indicate that the maximum elastic strain experienced by the pipe after eight years of continuous compression is 7.0999 e-5, while the minimum strain at the connection points with the neighboring pipe sections is 2.2555 e-5. Figure 12 illustrates the results of a numerical analysis conducted based on the experimental outcomes of a creep test for a composite material. This material consists of 55% carbon fiber and polyester as the matrix, reinforced with 0.2% nano silicon dioxide particles. The maximum elastic strain decreased to 6.0181e-5, which is attributed to the enhanced mechanical properties resulting from the increased nanoparticle percentage. Similarly, the minimum elastic strain decreased to 1.8976e-5. The addition of nanoparticles significantly improved the material's resistance to elastic deformation and increased its durability under the constant and continuous internal pressure experienced by the tube over time. Figure 13 illustrates that the strain continued to decrease as the mechanical properties improved, caused by a rise in the proportion of nano silicon dioxide particles in the composite to 0.24% at a fraction's weight of carbon fiber of 55%. The outcomes of the numerical analysis indicated that, after eight years of continuous and constant compression, the maximum strain recorded was 5.066e-5, while the minimum strain was 1.5894e-5. The analysis also showed that the maximum strain was concentrated at the ends of the tube.

5.2.2. The Effect of Nano-SiO_2 on equivalent stress During Creep

Figures 14, 15, and 16 present the equivalent stress results from the numerical analysis of the composite pipe model under constant and continuous stress over a duration of 252,460,800 seconds. The analysis revealed that the highest equivalent stress values were 87.91, 87.958, and 87.982 for the composites reinforced with nanoparticles at ratios of 0.16%, 0.2%, and 0.24%, respectively. Notably, the composite with a 0.24% nanoparticle addition experienced the highest stress; however, it also exhibited the lowest elastic strain. This phenomenon is attributed to the enhanced strength of the composite. Similarly, the 0.2% nanoparticle composite showed lower elastic strain than the composite with a 0.16% addition. The observed decrease in elastic strain alongside the increase in stress suggests improving the composite material's mechanical properties, enhancing its resistance to failure and offering better performance from a design perspective. The maximum equivalent creep stress experienced by the 0.16% carbon fiber composite pipe under a creep load for a period of 8 years was 80.94% of the ultimate stress. When this pipe was reinforced with 0.2% nanoparticles, the equivalent creep stress was 65.2% of the ultimate stress. In the case of reinforcement with 0.24% nanoparticles, the equivalent creep stress was reduced to 58.74% of the ultimate stress.

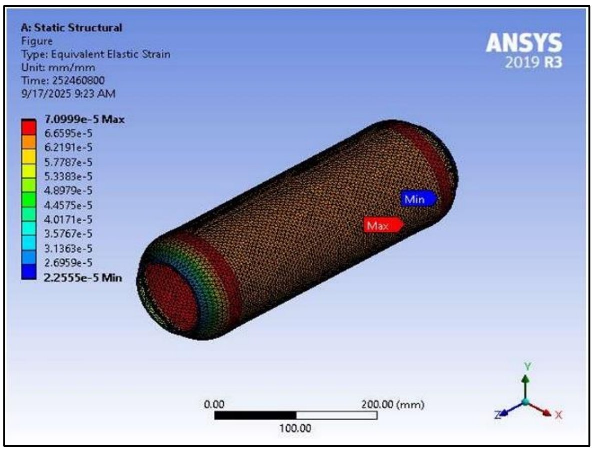

Figure 11. Illustratesthe equivalent elastic strain at a concentration of 0.16% nano silicon dioxide with a weight fraction of 55%.

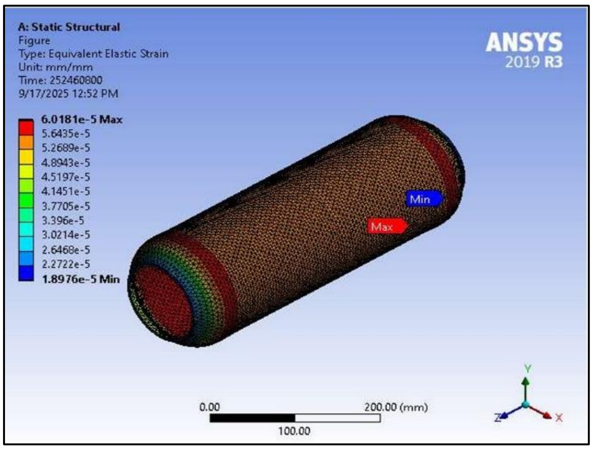

Figure 12. Illustratesthe equivalent elastic strain at a concentration of 0.2% nano silicon dioxide with a weight fraction of 55%.

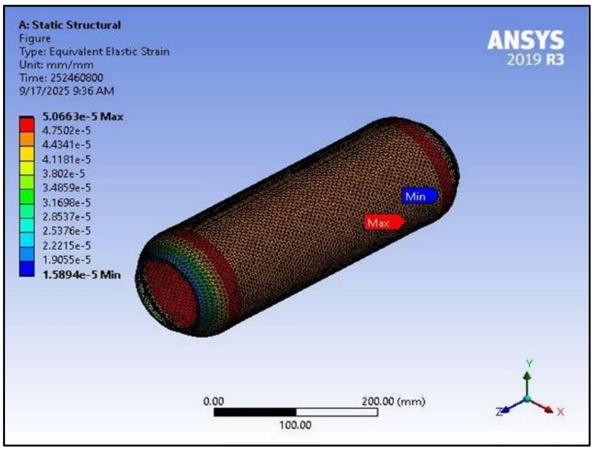

Figure 13. Illustratesthe equivalent elastic strain at a concentration of 0.24% nano silicon dioxide with a weight fraction of 55%.

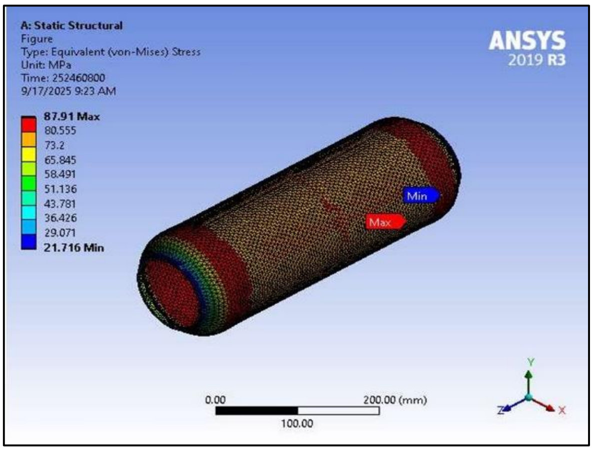

Figure 14. Illustratesthe equivalent stress strain at a concentration of 0.16% nano silicon dioxide with a weight fraction of 55%.

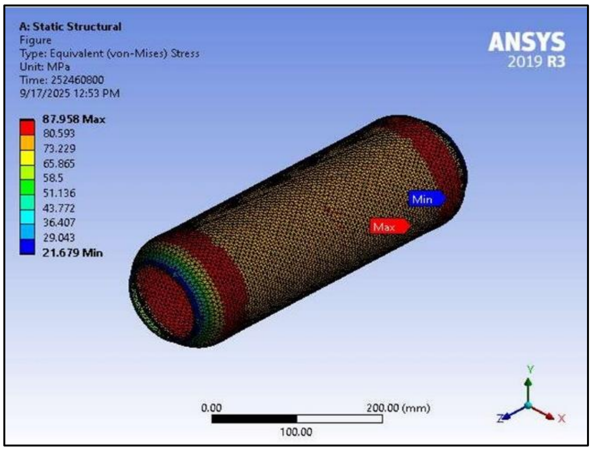

Figure 15. Illustratesthe equivalent stress strain at a concentration of 0.2% nano silicon dioxide with a weight fraction of 55%.

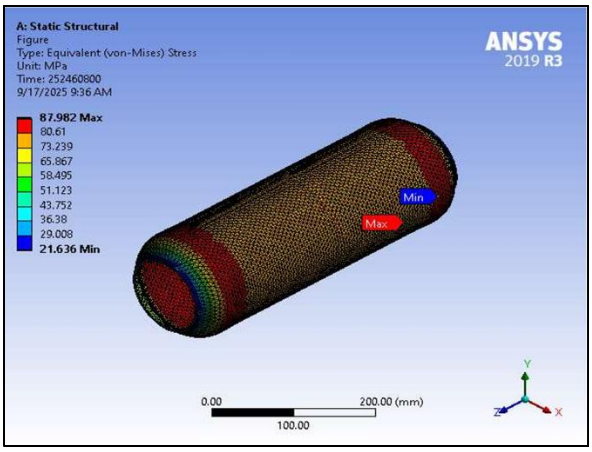

Figure 16. Illustrates the equivalent stress strain at a concentration of 0.24% nano silicon dioxide with a weight fraction of 55%.

5.2.3. The Effect of Nano-SiO₂ on equivalent creep strain During Creep

Figure 17 illustrates the equivalent creep strain obtained from a numerical analysis of a carbon fiber composite made up of 55% polyester and reinforced with 0.16% nano silicon dioxide. The Norton equation constants were determined from experimental results at a constant temperature to predict the creep behavior over time. The findings indicated that the equivalent creep strain was concentrated at the ends of the composite pipe, subjected to a constant internal stress of 6.8948 MPa over a period of 252,460,800 seconds, which is equivalent to 8 years of operation. This results in the need for periodic inspections of oil pipelines, especially at the junctions between the current and adjacent pipes. The numerical analysis revealed that the maximum equivalent creep strain measured 1.0201 mm, while the minimum was 0.25903 mm.

The maximum equivalent creep strain shown in Figure 18 decreased to 0.8791 mm and was concentrated at the ends of the tube, while the minimum equivalent strain was 0.2258 mm for the 55% carbon fiber composite reinforced with 0.2% nano silicon dioxide particles. The lower equivalent creep strain compared to the 0.16% nanoparticle-reinforced composite is attributed to the improved creep properties of the composite, resulting in a longer service life. The numerical analysis results indicate that the equivalent creep strain is concentrated at the ends of the composite tube, whereas the minimum equivalent strain is observed at the clamped ends in the connection zone between the preceding and succeeding tubes.

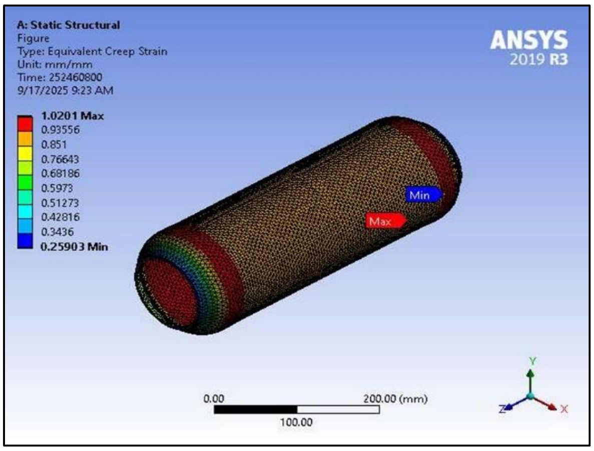

Figure 17. Illustratesthe equivalent creep strain at a concentration of 0.16% nano silicon dioxide with a weight fraction of 55%.

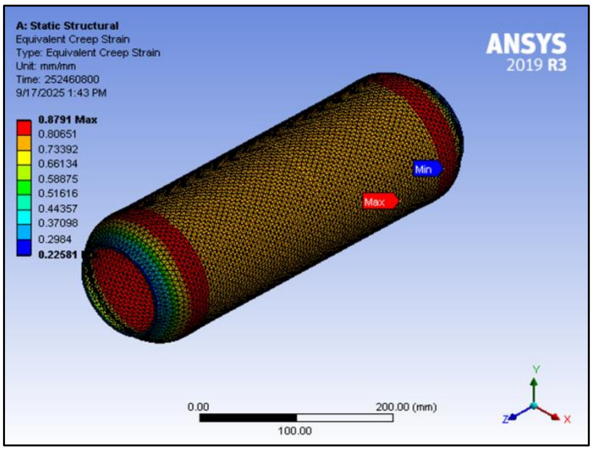

Figure 18. Illustratesthe equivalent creep strain at a concentration of 0.2% nano silicon dioxide with a weight fraction of 55%.

The results of the numerical analysis based on experimental tests for creep testing and determination of the Norton equation constants at a constant temperature of 25°C are shown in Figure 19 for a composite material under constant and continuous stress with time. The numerical analysis results showed that the equivalent creep strain showed its best value in the composite material reinforced with 0.24% nano silicon dioxide, with a maximum value of 0.85 mm in the vicinity of the clamping zones at the tube ends at 6.8948 MPa over a period of 252,460,800 seconds, while its minimum value was 0.2192 mm, concentrated at the clamped ends. The 0.24% decrease in the equivalent creep strain value in the reinforced composite compared to the 0.2% and 0.16% reinforced materials indicates an increase in the failure resistance of the material over time. The maximum equivalent creep strain decreased by 13.8% when the percentage of nanoparticles increased from 0.16% to 0.2%. In contrast, it decreased by only 3.3% when the percentage rose from 0.2% to 0.24%. This reduction in maximum equivalent strain at the 0.24% nanoparticle level occurs because the material becomes saturated with nanoparticles. Consequently, the effectiveness of increasing the nanoparticle content from 0.2% to 0.24% diminishes. This saturation leads to increased brittleness in the material's properties; on the other hand, it also results in enhanced toughness and improved resistance to failure stress.

Figure 20 presents a comparison of the numerical analysis results for creep strain in carbon fiber pipes reinforced with three different levels of nanoparticle reinforcement: 0.16%, 0.20%, and 0.24%. This analysis was conducted under constant stress for a duration of eight years. The findings revealed a direct correlation between the increasing concentration of nanoparticles and improved pipe performance, which resulted in a reduction in creep strain. Specifically, the 0.24% nanoparticle concentration exhibited the lowest creep strain along the pipe, while the 0.20% concentration demonstrated the highest creep strain over time under consistent stress. The stress distribution pattern across the three concentrations was homogeneous, suggesting that the effect of nanoparticle reinforcement is uniformly distributed within the pipe material. The enhanced performance of the nanoparticle-reinforced materials can be attributed to the filling of microscopic voids and pores within the composite structure. These nanoparticles create a physical barrier that hinders the movement and displacement of polymer chains when under load. Furthermore, the interfacial bonding between the core material and the reinforcing fibers improves, leading to more efficient load distribution. Overall, this figure conclusively demonstrates that adding nano-silicon dioxide is an effective strategy for enhancing the creep resistance of pipelines used in the oil industry.

5.2.4. The Effect of Nano-SiO_2 on the shear stress During Creep

The shear stress distribution in a composite pipe composed of 55% carbon fiber by weight, reinforced with 0.16% nano silicon dioxide, is presented in Figure 21. The highest concentration of shear stress occurs at the ends of the pipe. This shear stress extends along the length of the pipe, along the z-axis, at the intersection of its diameter with the x- and y-axes, as indicated by the numerical analysis results for the composite pipe model. The numerical analysis revealed that the maximum shear stress value in the x-y plane reached 50.702 MPa, a result of the creep stress generated by the constant internal pressure of the oil on the pipe walls, which persisted for a duration of eight years. Figures 22 and 23 depict the shear stress of the composite pipe reinforced with nanoparticles at ratios of 0.2% and 0.24%, respectively, while maintaining a weight fraction of 55% carbon fiber. The stress distribution in these figures is similar to that of the previous one. The numerical results, based on experimental tests, demonstrated a convergence in the maximum shear stress. This is attributed to the consistent conditions of applying constant internal pressure over time and the clamped state of the pipe without any applied torque. The difference in maximum shear stress was only 0.053% when the nanoparticle content increased from 0.16% to 0.2%, and 0.0276% when the nanoparticle weight increased from 0.2% to 0.24%.

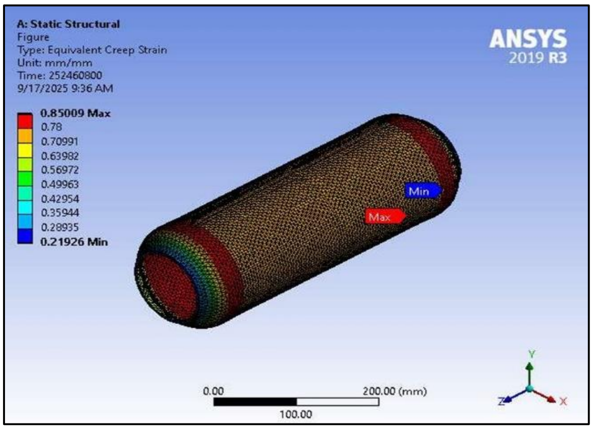

Figure 19. Illustratesthe equivalent creep strain at a concentration of 0.24% nano silicon dioxide with a weight fraction of 55%.

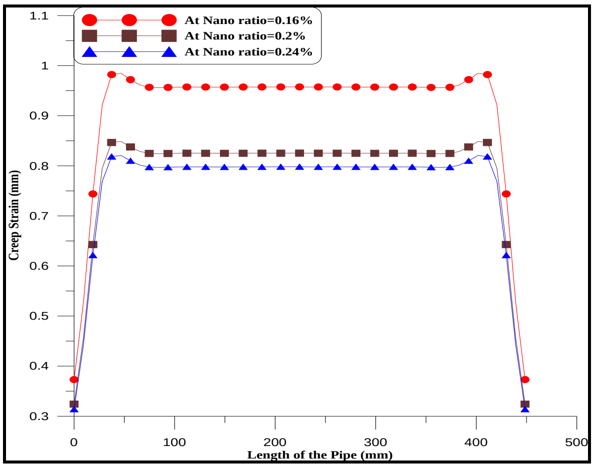

Figure 20. The equivalent creep strain along an oil pipeline with varying concentrations of nano silicon dioxide (0.16%, 0.2%, and 0.24%) and a fiber weight fraction of 55% over a period of 8 years.

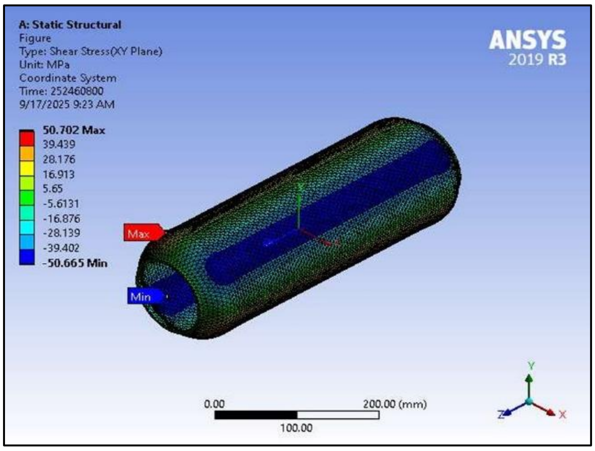

Figure 21. Illustrates the shear stress at a concentration of 0.16% nano silicon dioxide with a weight fraction of 55%.

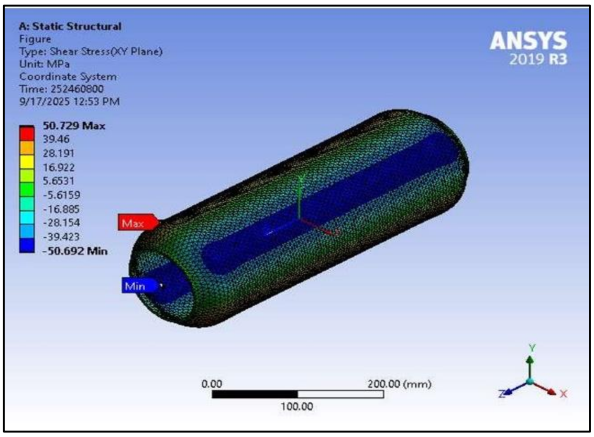

Figure 22. Illustratesthe shear stress at a concentration of 0.2% nano silicon dioxide with a weight fraction of 55%

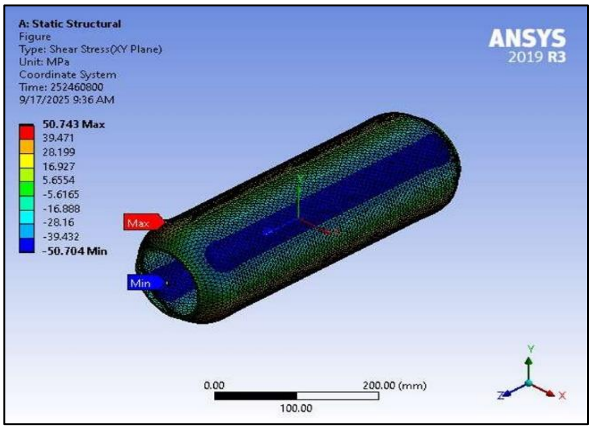

Figure 23. Illustratesthe shear stress at a concentration of 0.24% nano silicon dioxide with a weight fraction of 55%.

5.3. SEM pictures of composite creep specimens

The composite samples were prepared by coating them with a gold/palladium (Au/Pd) layer, as they are non-conductive. This coating prevents charge distortions and enhances secondary electron emission perpendicular to the electron beam. A slow scanning speed was employed to achieve low noise and high image resolution. The Working Distance (WD) was set at 7.5 mm, while the Secondary Electron and Accelerating Voltage (HV) were maintained at 30.00 kV. The magnification was adjusted to 1000x to identify the topography of the fiber and matrix surfaces clearly. Figure 24 presents scanning electron microscopy (SEM) images of composite samples containing 55% carbon fibers along with varying concentrations of nano-silicon dioxide at 0.16%, 0.2%, and 0.24%. These images highlight the internal microstructure of the composite, specifically focusing on the nanoparticle distribution within the matrix surrounding the carbon fibers. The nanoparticles, represented as small white dots, appear to be fairly well distributed throughout the matrix. However, there are some areas with slight agglomeration of the nanoparticles, which manifest as irregular white clumps. Overall, the composition displays a uniform distribution of nanoparticles, which effectively enhances the bonding between the fibers and the matrix. At a concentration of 0.2%, the nanoparticles show a more uniform dispersion, attributed to an efficient mixing process. This optimal distribution is crucial for improving the properties of the binder, as the particles provide a large surface area for interaction with the polymer, ultimately enhancing the material's toughness and crack resistance. The decrease in property improvement beyond 0.2% is attributed to the significant agglomeration of nanoparticles, as observed in scanning electron microscopy (SEM) images at 0.24%. In contrast, a homogeneous and optimal distribution is achieved at 0.2%. Agglomeration results in the formation of stress concentration points within the bonding material and reduces the effective surface area of the particles, which limits their interaction with the polymer. Additionally, it creates pathways that facilitate crack propagation, ultimately diminishing the benefits to durability. Although mechanical properties continue to improve up to a concentration of 0.24%, the rate of improvement slows due to saturation and the effects of agglomeration. Therefore, a concentration of 0.2% is considered optimal for achieving economic efficiency and balanced performance.

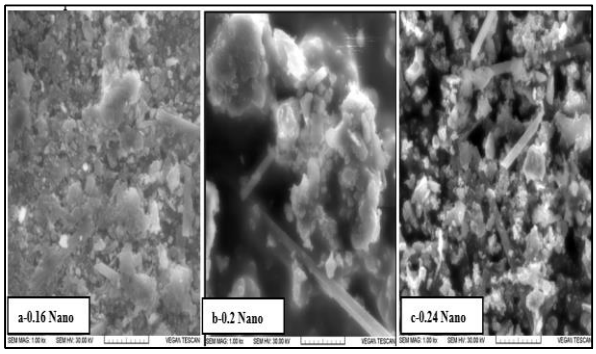

Figure 24. The SEM microstructure pictures of samples contain 55% carbon fibers with 0.16%, 0.2%, and 0.24% nano silicon dioxide.

6. Conclusions

- The results indicated significant improvements in mechanical properties, particularly with a 0.24% reinforcement ratio of nano silicon dioxide. This led to a notable reduction in creep stress and an increase in creep life under constant pressure over time. The findings demonstrated the lowest elastic stress and optimal long-term performance in simulated pipeline operating conditions, specifically over 8 years at an internal pressure of 6.8948 MPa.
- Raising the weight percentage of nanoparticles from 0.16% to 0.2% resulted in a 21% reduction in creep strain. Further raising the nanoparticle from 0.2% to 0.24% led to a 35% decrease in creep strain.
- Microstructure analysis using scanning electron microscopy revealed a uniform dispersion of nanoparticles at a 0.2% concentration, which enhanced adhesion between matrix fibers and improved mechanical properties. At 0.24%, while the dispersion remained relatively homogeneous, there was some agglomeration. However, this concentration still exhibited better creep resistance due to enhanced strengthening of the matrix.
- Numerical analysis via finite element modeling (using ANSYS) validated the experimental results, showing that an increase in nanoparticle content correlates with a reduction in creep stress. The analysis further revealed that the highest stress concentrations occur at pipe joints, highlighting critical areas that require inspection. The Norton creep model, applied under constant temperature conditions, was effective in predicting long-term creep behavior, with experimental constants established for each percentage of nano-SiO_2.
- In terms of design and application, reinforcing composite pipes with nano-SiO_2 enhances their stress tolerance for extended periods, making them more suitable for oil and gas applications compared to non-reinforced composites.

The study also emphasizes the need for regular inspection of pipe joints due to the concentration of stress in these critical areas.

- For a tube reinforced with 0.2% by weight of nano-SiO_2, the equivalent creep stress after 8 years reaches approximately 65.2% of the material's maximum stress, allowing for the adoption of a practical safety factor of ≈1.53 when designed for a long-life cycle.

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