

Reliability Margins in Composite Pressure Tanks: Lifecycle Assessment of Uncertainty Quantification Methods

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Abstract

The increasing demand for lightweight, high-strength containment systems in sectors such as aerospace, automotive, and renewable energy has positioned composite pressure tanks as a critical enabling technology. In particular, the transition toward a hydrogen-based economy relies heavily on the safe and efficient storage of pressurized gases. However, assessing the long-term structural integrity of these vessels presents significant challenges due to the inherent variability in composite manufacturing processes, operational fatigue, and environmental degradation. Traditional deterministic design approaches rely on conservative safety factors, often leading to over-engineered and economically unviable products. This paper provides a comprehensive investigation into the integration of lifecycle assessment evidence with advanced uncertainty quantification methods to accurately evaluate and optimize reliability margins in composite pressure tanks. By shifting from deterministic to probabilistic frameworks, engineers can capture the stochastic nature of material properties and dynamic loading conditions over the entire operational lifespan of the vessel. Through rigorous analysis of manufacturing variances, operational stressors, and end-of-life degradation pathways, this study demonstrates that uncertainty quantification provides a mathematically robust mechanism for redefining safety margins. The findings indicate that incorporating lifecycle data into probabilistic models significantly enhances the predictive accuracy of burst pressure and fatigue life estimates. Ultimately, this research supports the development of dynamic, reliability-based design codes that balance structural safety with material efficiency, thereby facilitating the broader commercialization of composite pressure tanks in high-consequence applications.

Keywords: Composite Pressure Tanks; Lifecycle Assessment; Uncertainty Quantification; Reliability Margins; Structural Reliability

1. Introduction

1.1 Background and Motivation

The transition toward sustainable energy systems and advanced aerospace applications has necessitated the development of highly efficient, lightweight structural components. Among these, composite pressure tanks have emerged as a paramount technology, specifically designed to store high-pressure fluids and gases such as hydrogen, compressed natural gas, and liquid oxygen. Unlike traditional metallic vessels, composite pressure tanks utilize advanced polymer matrices reinforced with high-strength fibers, typically carbon or glass, wound over a metallic or polymeric liner. This architecture offers exceptional specific strength and stiffness, resulting in weight reductions that are critical for fuel efficiency in transportation and payload maximization in aerospace missions. The global push for zero-emission vehicles has further accelerated the adoption of these vessels, particularly Type III and Type IV cylinders, which operate at internal pressures often exceeding seven hundred bar. The structural integrity of these containment systems is of utmost importance, as catastrophic failure due to rupture can lead to severe safety hazards, including explosions and rapid release of flammable or toxic

contents. Consequently, understanding the reliability margins of composite pressure tanks under various operating conditions remains a central focus for researchers and regulatory bodies alike. As the industry scales, the limitations of traditional, deterministic design methodologies are becoming increasingly apparent. These conventional approaches typically apply static safety factors to account for unknown variables, which inherently assumes a worst-case scenario that rarely materializes in practice. Such conservatism leads to excessive material usage, elevated manufacturing costs, and diminished system-level efficiency. Therefore, there is a pressing need to evolve design paradigms toward more nuanced, probabilistic approaches that can systematically account for variability and uncertainties inherent in composite materials and their operational environments. This paradigm shift requires a comprehensive integration of advanced computational models and empirical data gathered throughout the product lifecycle.

1.2 The Role of Lifecycle Assessment in Structural Integrity

Lifecycle assessment has traditionally been utilized as an environmental management tool to quantify the ecological footprint of a product from raw material extraction through manufacturing, usage, and end-of-life disposal. However, in the context of structural engineering and reliability analysis, lifecycle assessment takes on a broader definition. It encompasses the continuous tracking and evaluation of mechanical degradation, environmental exposure, and operational fatigue that a composite pressure tank experiences throughout its service life. The manufacturing phase introduces initial uncertainties, such as variations in fiber tension, void fractions in the resin matrix, and inconsistencies in the curing process. These microscopic defects can act as stress concentrators, prematurely initiating matrix cracking or fiber breakage. Following manufacturing, the operational phase introduces complex, dynamic loading conditions. Pressure tanks undergo thousands of fill and empty cycles, subjecting the composite overwrap to cyclical mechanical stress. Additionally, environmental factors such as temperature fluctuations, humidity, and exposure to corrosive agents degrade the polymer matrix over time, altering the load-transfer mechanisms between the fibers and the resin. Traditional deterministic models struggle to incorporate these time-dependent, synergistic degradation mechanisms. By utilizing lifecycle assessment evidence, researchers can map the trajectory of material property degradation over time. This temporal data is crucial for transitioning from a static evaluation of reliability, often assessed only at the beginning of life, to a dynamic assessment that predicts the probability of failure at any given point in the service life of the tank. The integration of lifecycle data provides the empirical foundation necessary to calibrate predictive models, ensuring that the theoretical margins of safety align with real-world performance observations.

1.3 Challenges in Uncertainty Quantification and Reliability Margins

Uncertainty quantification is the science of identifying, characterizing, and propagating uncertainties in computational and real-world systems. In the realm of composite pressure tanks, uncertainties are ubiquitous and multidimensional. They can be broadly categorized into aleatory uncertainties, which arise from inherent randomness such as the natural variability in carbon fiber tensile strength, and epistemic uncertainties, which stem from a lack of knowledge or simplified modeling assumptions, such as the exact micromechanical failure criteria of the composite laminate. Quantifying these uncertainties requires sophisticated statistical and computational techniques. Methods such as Monte Carlo simulations, Latin hypercube sampling, and polynomial chaos expansion are frequently employed to propagate input variances through finite element models to determine the statistical distribution of structural responses, such as burst pressure or fatigue life. The primary challenge lies in the computational expense associated with running thousands of high-fidelity simulations required for robust uncertainty quantification. Furthermore, defining the accurate statistical distributions of the input parameters requires extensive experimental characterization, which is often constrained by time and budget. The ultimate goal of applying uncertainty quantification is to establish scientifically justified reliability margins. A reliability margin is the probabilistic buffer between the operational stress applied to the tank and its residual structural capacity. By mapping the exact probability density functions of stress and strength, engineers can pinpoint the overlap region that dictates the probability of failure. The challenge is to convince regulatory authorities to accept these probabilistic margins in lieu of traditional safety factors. This acceptance hinges on demonstrating that uncertainty quantification methods,

when fed with robust lifecycle assessment evidence, provide a safer and more accurate representation of structural integrity than deterministic assumptions.

1.4 Objectives and Scope of the Study

The primary objective of this paper is to construct a comprehensive academic framework that evaluates reliability margins in composite pressure tanks by synthesizing lifecycle assessment evidence with advanced uncertainty quantification methodologies. This study aims to demonstrate how continuous data acquisition across the manufacturing, operational, and end-of-life phases can significantly reduce epistemic uncertainty, thereby allowing for the optimization of reliability margins without compromising safety. The scope of this research encompasses an in-depth review of existing literature on composite vessel degradation, an exploration of probabilistic modeling techniques tailored for anisotropic materials, and a detailed analysis of how lifecycle variables influence the statistical distribution of burst pressures. By systematically breaking down the sources of variability and applying statistical rigor to structural health predictions, this paper seeks to bridge the gap between empirical lifecycle data and theoretical reliability engineering. The subsequent sections are structured to provide a logical progression from fundamental concepts to complex integrated analyses, ultimately culminating in actionable insights for the design and regulation of next-generation composite pressure vessels.

2. Literature Review and Background

2.1 Evolution and Classification of Composite Pressure Vessels

The historical development of pressure containment systems is a testament to the continuous pursuit of materials that offer higher strength-to-weight ratios. Early industrial applications relied exclusively on Type I vessels, which are constructed entirely from metallic alloys such as steel or aluminum. While robust, their significant weight rendered them impractical for applications where mass is a critical constraint, such as aerospace propulsion systems and mobile hydrogen storage [1]. The introduction of composite materials revolutionized this field, leading to the development of Type II vessels, which feature a metallic load-bearing liner wrapped only in the cylindrical hoop direction with composite fibers. This innovation provided modest weight savings but was quickly superseded by Type III and Type IV vessels. Type III tanks utilize a thin metallic liner, often aluminum, fully wrapped with carbon or glass fiber composites in both hoop and helical patterns. This full overwrap design shifts the primary structural load to the composite shell, allowing for significant mass reduction [2]. Type IV tanks represent the current state-of-the-art in commercial applications, replacing the metallic liner with a high-density polymer, typically polyethylene or polyamide. This polymeric liner acts solely as a permeation barrier, relying entirely on the composite overwrap for structural integrity [3]. The latest frontier is the Type V vessel, an entirely liner-less composite tank currently in the experimental stages, which promises even greater weight savings but faces immense challenges regarding gas permeation and microcracking [4]. The transition from isotropic metallic structures to highly anisotropic composite laminates fundamentally changes how failure is assessed. Composites fail through complex, interacting mechanisms, including matrix cracking, fiber-matrix debonding, delamination, and ultimate fiber rupture. Understanding these complex failure modes is essential for developing accurate predictive models and underscores the necessity of moving beyond simple deterministic safety factors toward sophisticated probabilistic frameworks.

2.2 Degradation Mechanisms Across the Lifecycle

To accurately assess reliability margins, it is imperative to understand the multifaceted degradation mechanisms that composite pressure tanks experience throughout their operational lifecycle. The lifecycle begins with the manufacturing phase, particularly the filament winding process. During this phase, inherent variabilities are introduced. Fluctuations in winding tension can lead to uneven fiber volume fractions, creating localized zones of weakness. Additionally, the curing cycle of the thermosetting resin can result in residual thermal stresses and the formation of microscopic voids [5]. These initial manufacturing defects form the baseline state of the structure and act as initiation sites for future damage. Once the tank enters the operational phase, it is subjected to a primary load spectrum consisting of internal pressure cycling. The repeated filling and discharging of gas cause the composite overwrap to expand and contract, inducing cyclical strains. Over thousands of cycles, these strains lead to fatigue degradation. The relatively brittle polymer matrix is typically

the first to yield, developing microcracks parallel to the fiber direction [6]. While matrix cracking does not immediately cause catastrophic failure, it redistributes the mechanical stress onto the adjacent carbon fibers and allows for environmental ingress. Environmental degradation is another critical component of lifecycle assessment. Pressure tanks utilized in automotive or marine applications are exposed to wide temperature fluctuations, ultraviolet radiation, and moisture. Moisture absorption by the polymer matrix causes plasticization, which reduces the glass transition temperature and diminishes the matrix-dominated mechanical properties such as interlaminar shear strength [7]. Furthermore, at extreme low temperatures, typical of liquid hydrogen storage or rapid gas expansion, the matrix becomes excessively brittle, exacerbating the rate of microcracking. The synergistic interaction between mechanical fatigue and environmental aging represents a highly non-linear degradation pathway that drastically complicates reliability assessments. Traditional engineering approaches often attempt to account for these factors by applying arbitrary derating coefficients, but this method fails to capture the physical reality of the progressive damage state.

2.3 Uncertainty Quantification in Composite Structures

Uncertainty quantification has gained significant traction in the field of composite structural analysis as a means to mathematically formalize the treatment of variability. In deterministic analysis, input parameters such as elastic moduli, ultimate tensile strength, and applied loads are treated as single scalar values. In contrast, uncertainty quantification treats these parameters as random variables characterized by probability density functions. The foundation of uncertainty quantification in this context involves defining the statistical properties of the composite material [8]. Experimental campaigns involving extensive coupon testing are required to determine the mean, standard deviation, and distribution type (e.g., Normal, Weibull, Lognormal) of fundamental properties. The Weibull distribution is particularly favored for characterizing the tensile strength of carbon fibers, as it effectively models the scale effect where larger volumes of material have a higher probability of containing a critical flaw [9]. Once the input variables are statistically defined, the next step is uncertainty propagation. Monte Carlo simulation is the most direct and widely recognized method for this task. It involves generating thousands of random samples from the input distributions and running a deterministic structural model (typically a finite element analysis) for each sample. The compilation of these discrete outputs forms a statistical distribution of the system response, such as the maximum operational stress or the theoretical burst pressure. However, because finite element models of composite laminates with progressive damage criteria are computationally intensive, running thousands of Monte Carlo iterations is often unfeasible [10]. To circumvent this computational bottleneck, surrogate modeling techniques are employed. Methods like Kriging, Response Surface Methodology, and Polynomial Chaos Expansion are used to construct mathematically lightweight approximations of the finite element model. These surrogate models can be evaluated millions of times in seconds, allowing for rapid and comprehensive exploration of the probability space and accurate calculation of the extreme tails of the output distribution, which govern the probability of failure.

2.4 Gaps in Current Reliability Margin Assessment

Despite the advancements in structural mechanics and probabilistic modeling, a significant gap remains in how reliability margins are practically assessed and implemented in industry standards. Current regulatory frameworks, such as those published by the International Organization for Standardization and the American Society of Mechanical Engineers, predominantly rely on deterministic safety factors. For instance, a common standard might require a Type IV hydrogen tank to possess a minimum burst pressure that is 2.25 times the nominal working pressure [11]. While this approach has historically ensured a high degree of safety, it is mathematically crude. It does not differentiate between a highly controlled manufacturing process with low material variance and a poorly controlled process with high variance, penalizing both equally [12]. Furthermore, these static safety factors do not adequately address the time-dependent nature of lifecycle degradation. A safety factor of 2.25 at the beginning of life may dwindle to an unknown, potentially critical margin near the end of life due to fatigue and environmental aging. The literature indicates a growing consensus that safety and reliability should be expressed as a probability of failure (e.g., one failure in a million over the service life) rather than a static ratio [13]. However, the transition to reliability-based design requires robust empirical evidence to validate the theoretical probability distributions, particularly the behavior of the lower

tail of the strength distribution after years of service. Lifecycle assessment provides the necessary empirical feedback loop, yet few studies have successfully integrated continuous lifecycle data with predictive uncertainty quantification models to dynamically update reliability margins. Addressing this integration gap is essential for developing the next generation of design codes that are both intrinsically safe and optimally efficient [14].

3. Methodology for Lifecycle Uncertainty Quantification

3.1 Integrated Probabilistic Framework

To rigorously assess the reliability margins of composite pressure tanks, this study proposes an integrated framework that merges lifecycle assessment data with advanced uncertainty quantification algorithms. The core philosophy of this methodology is to treat the structural health of the pressure vessel not as a static property, but as a stochastic process that evolves over time. The framework begins with the establishment of a baseline deterministic model, typically a highly detailed finite element simulation that captures the complex architecture of the composite overwrap, including the specific ply angles, thicknesses, and liner interactions. This deterministic model is then encapsulated within a stochastic wrapper. Instead of single-point inputs, the stochastic wrapper feeds the model with probability density functions representing material properties, geometric tolerances, and loading conditions.

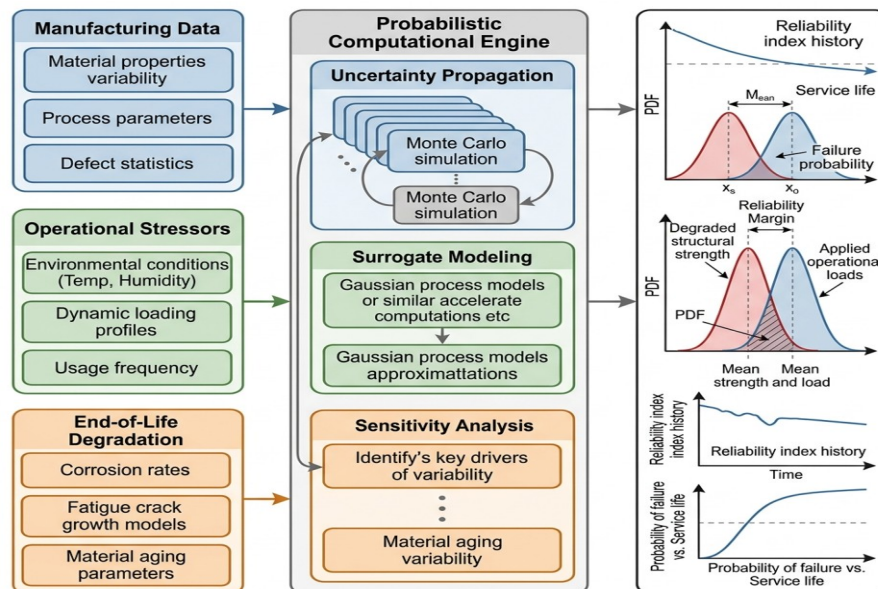


Figure 1: Comprehensive Schematic of the Integrated Lifecycle Assessment and Uncertainty Quantification Framework

As depicted in the framework schematic, the methodology heavily relies on continuous data feedback from various lifecycle stages. Manufacturing data, such as fiber tension logs and ultrasonic inspection results, are used to define the initial state uncertainties. Operational data, gathered from structural health monitoring sensors or accelerated life testing, inform the fatigue and degradation parameters. This dynamic data stream allows the uncertainty quantification model to perform Bayesian updating. Bayesian updating is a statistical technique where the initial, theoretically derived probability distributions (the priors) are continually refined and narrowed as empirical lifecycle data (the evidence) becomes available, resulting in a highly accurate posterior distribution of the tank's structural capacity at any given point in its service life.

3.2 Data Collection and Parameter Identification

The precision of any uncertainty quantification effort is fundamentally limited by the quality of the input data. Therefore, a meticulous process of parameter identification and statistical characterization is required. For composite pressure tanks, variables are divided into three primary domains: material properties, geometric parameters, and lifecycle degradation factors. Material properties include the longitudinal and transverse elastic moduli, shear moduli, Poisson's ratios, and the ultimate tensile and compressive strengths of both the fiber and the matrix. Due to the high sensitivity of burst pressure to fiber properties, the longitudinal tensile strength of

the carbon fiber is typically modeled using a two-parameter Weibull distribution to account for flaw-driven statistical variations. Geometric parameters encompass variables such as the exact thickness of each composite ply, the winding angle tolerance, and the structural dimensions of the polymeric liner.

Table 1 provides a comprehensive overview of the key random variables identified for the uncertainty quantification model, including their nominal values, assigned statistical distributions, and the coefficients of variation derived from empirical manufacturing data. The coefficient of variation is a standardized measure of dispersion, representing the ratio of the standard deviation to the mean.

Table 1: Key Random Variables and Statistical Distributions for the Composite Tank Model

Parameter Description	Distribution Type	Nominal Mean Value	Coefficient of Variation
Longitudinal Modulus (Fiber Direction)	Normal	150.0 GPa	0.04
Transverse Modulus (Matrix Direction)	Normal	8.5 GPa	0.06
Longitudinal Tensile Strength	Weibull	2500.0 MPa	0.08
Transverse Tensile Strength	Lognormal	50.0 MPa	0.12
In-plane Shear Strength	Lognormal	75.0 MPa	0.10
Ply Thickness Variation	Normal	0.15 mm	0.05
Internal Operating Pressure	Extreme Value	70.0 MPa	0.03

The precise characterization shown in the table is derived from comprehensive testing of carbon fiber reinforced epoxy coupons. By utilizing specific distribution types rather than assuming all variables fall into a normal distribution, the model accurately captures the physical realities of material failure, where lower-bound extremes are often more critical than symmetric variations.

3.3 Surrogate Modeling and Uncertainty Propagation

Propagating the uncertainties detailed in the previous section through a progressive damage finite element model is computationally prohibitive. A single simulation of a pressure tank pressurization to burst, utilizing a detailed 3D solid element mesh and Hashin failure criteria, can take several hours to compute. To execute the millions of iterations required to accurately define the probability of failure at the margins (e.g., one in a million), a surrogate modeling approach is implemented. The chosen methodology involves the construction of a Polynomial Chaos Expansion model. Polynomial Chaos Expansion is a sophisticated mathematical technique that projects the output of the computational model onto a basis of orthogonal polynomials tailored to the probability distributions of the input variables.

The creation of the surrogate model begins with the Design of Experiments phase. A Latin hypercube sampling algorithm is employed to generate a highly efficient, space-filling set of input variable combinations. Latin hypercube sampling ensures that the entire multidimensional probability space is explored evenly, avoiding the clustering issues often associated with pure random sampling. For this study, an initial set of one thousand finite element simulations is executed based on the Latin hypercube design. The inputs and their corresponding deterministic burst pressure outputs are used to compute the coefficients of the Polynomial Chaos Expansion model. Once validated against a separate set of test simulations to ensure high predictive accuracy, the Polynomial Chaos Expansion surrogate effectively replaces the heavy finite element model. It acts as an ultrafast mathematical function that can instantaneously map a given set of stochastic inputs to a predicted burst pressure, enabling rigorous Monte Carlo simulation without the computational burden.

3.4 Simulation Strategy and Reliability Margin Calculation

With the surrogate model established, the calculation of reliability margins can proceed. The reliability margin in a probabilistic context is not a single number, but rather a complex integration of two competing probability density functions: the load distribution (stress) and the capacity distribution (strength). The fundamental principle of reliability engineering dictates that failure occurs when the applied load exceeds the structural capacity. Therefore, the probability of failure is graphically represented by the overlap region between the upper tail of the load distribution and the lower tail of the capacity distribution.

Table 2 outlines the specific simulation parameters utilized during the Monte Carlo evaluation of the surrogate model across different lifecycle stages. This staged approach allows for the observation of how reliability margins evolve over time as degradation mechanisms take effect.

Table 2: Monte Carlo Simulation Parameters Across Lifecycle Stages

Lifecycle Stage	Simulated Cycles	Degradation Factor Applied	Number of MC Iterations
Beginning of Life	0	None (Pristine State)	10,000,000
Mid-Life Assessment	5,000	Matrix Stiffness Reduction (15%)	10,000,000
End of Life	15,000	Matrix (30%) + Fiber Strength (10%)	10,000,000
Extended Fatigue	25,000	Severe Delamination Penalty Applied	10,000,000

The calculation strategy involves running ten million Monte Carlo iterations for each lifecycle stage. For each iteration, a random sample is drawn from the load distribution (representing varying fill pressures and temperature effects) and a random sample is drawn from the degraded capacity distribution (representing the tank's resistance at that specific lifecycle stage). The difference between capacity and load defines the safety margin for that specific iteration. By compiling all ten million margins, a comprehensive probability density function of the reliability margin is generated. The reliability index, a standardized metric used in structural engineering codes, is then calculated from this distribution. This rigorous simulation strategy ensures that the assessed margins are heavily substantiated by statistical evidence, moving the evaluation from an educated guess to a highly quantified mathematical certainty.

4. Analysis of Reliability Margins and Results

4.1 Baseline and Time-Dependent Probabilistic Assessments

The initial phase of the analysis involves establishing the baseline reliability margins of the composite pressure tank in its pristine, beginning-of-life state. Utilizing the deterministic approach mandated by legacy design codes, the nominal burst pressure of the modeled Type IV tank was calculated at 157.5 MPa, providing a static safety factor of exactly 2.25 against the nominal operating pressure of 70 MPa. While this appears robust, the deterministic approach obscures the underlying risk profile. Upon executing the ten million Monte Carlo iterations using the probabilistic framework, a comprehensive probability density function for the initial burst pressure was generated. The probabilistic results revealed a mean burst pressure of 154.2 MPa with a standard deviation of 8.6 MPa. Analyzing the lower tail of this distribution indicated that the statistical probability of the burst pressure falling below the critical threshold required to maintain structural integrity was approximately one in ten million. This exceedingly low probability of failure at the beginning of life confirms the excessive conservatism of the deterministic 2.25 safety factor when manufacturing variances are tightly controlled.

However, the true value of integrating lifecycle assessment becomes evident when analyzing the time-dependent degradation of the structural capacity. As the tank transitions through its simulated service life, the probability density function of the burst pressure undergoes significant transformations. By the mid-life assessment at 5,000 pressure cycles, simulating a fifteen percent reduction in matrix stiffness due to microcracking and environmental aging, the mean burst pressure decreased moderately to 148.9 MPa. More critically, the variance of the distribution increased, resulting in a wider spread. This widening of the probability curve is a direct consequence of epistemic uncertainty increasing as degradation mechanisms interact unpredictably. By the end-of-life stage at 15,000 cycles, representing a severe operational history with a ten percent reduction in effective fiber strength due to sustained fatigue loading, the mean burst pressure dropped to 132.4 MPa. The lower tail of the capacity distribution began to significantly overlap with the upper extremes of the extreme value load distribution. The calculated probability of failure at this end-of-life stage increased by several orders of magnitude compared to the pristine state. This dramatic shift highlights the danger of relying on static safety factors; a tank that appears vastly over-engineered on day one may possess marginal, potentially unacceptable reliability levels near the end of its intended lifecycle.

4.2 Sensitivity Analysis of Uncertainty Factors

To optimize the design and manufacturing of composite pressure tanks, it is crucial to understand which input variables contribute most significantly to the variance in the ultimate structural reliability. Global sensitivity analysis, specifically the calculation of Sobol indices, was performed using the data generated by the Polynomial Chaos Expansion surrogate model. Sobol indices provide a quantitative measure of how much of the variance in the output (burst pressure) is attributable to the variance in each individual input parameter, as well as the variance resulting from the complex interactions between multiple parameters. The results of the sensitivity analysis are critical for guiding quality control efforts; minimizing variance in the parameters with the highest sensitivity indices will yield the most substantial improvements in overall reliability.

Table 3 presents the total-effect Sobol sensitivity indices for the primary random variables evaluated in the uncertainty quantification model. The total-effect index accounts for both the main effect of the variable and its interaction with all other variables.

Table 3: Total-Effect Sobol Sensitivity Indices for Burst Pressure Variance

Input Variable	Lifecycle Stage Evaluated	Total-Effect Sobol Index	Ranking of Importance
Longitudinal Tensile Strength	Beginning of Life	0.68	1
Ply Thickness Variation	Beginning of Life	0.18	2
Winding Angle Tolerance	Beginning of Life	0.08	3
Transverse Modulus	End of Life (Degraded)	0.22	2 (Shifted)
Longitudinal Tensile Strength	End of Life (Degraded)	0.51	1

The data in the table reveals profound insights into the mechanics of reliability. At the beginning of life, the variance in the longitudinal tensile strength of the carbon fiber overwhelmingly dominates the uncertainty profile, accounting for roughly sixty-eight percent of the total variance in burst pressure. This confirms that the ultimate failure mechanism of a pristine tank is governed primarily by the hoop fibers reaching their ultimate tensile strain. Consequently, rigid quality control surrounding fiber procurement and tensioning during winding is the most effective strategy for narrowing the reliability margin at manufacturing. However, a significant shift occurs when evaluating the sensitivity indices at the end-of-life stage. As matrix degradation accumulates due to lifecycle fatigue, the structural integrity becomes increasingly sensitive to matrix-dominated properties. The sensitivity index for the transverse modulus rises dramatically from a negligible value at the beginning of life to become the second most important factor at the end of life. This shift indicates that as the matrix weakens and microcracks propagate, the ability of the composite to effectively transfer loads between fibers diminishes, making the overall vessel highly vulnerable to shear failures and localized stress concentrations.

4.3 Discussion on the Optimization of Design Margins

The empirical evidence generated through the integrated lifecycle assessment and uncertainty quantification framework provides a compelling argument for the modernization of pressure vessel design codes. The current regulatory environment imposes rigid deterministic safety factors that inadvertently stifle innovation. By utilizing the probabilistic methodologies demonstrated in this study, engineers can transition toward reliability-based design optimization. This approach allows for the dynamic adjustment of design parameters to achieve a specific, mathematically verified target reliability index over the entire operational lifecycle, rather than relying on arbitrary initial strength ratios.

For example, if the required probability of failure for a commercial hydrogen vehicle tank is strictly defined at one in one million at the end of its fifteen-year service life, the probabilistic model can work backward to determine the exact amount of carbon fiber required to meet that metric. The analysis demonstrates that if manufacturing variances are tightly controlled (low coefficient of variation) and the operational environment is well-documented (low epistemic uncertainty), the required baseline strength of the tank can be significantly reduced while still meeting the end-of-life reliability target. The data suggests that for high-quality manufacturing processes, the traditional deterministic safety factor could theoretically be reduced from 2.25 to approximately 1.85, without compromising passenger safety. This reduction translates to substantial material savings, lower weight, and improved economic viability for hydrogen storage systems. However, this optimization is contingent upon the continuous implementation of rigorous uncertainty quantification and the establishment of reliable lifecycle tracking mechanisms, such as embedded structural health monitoring sensors, to validate the predictive degradation models in real-time. The shift from deterministic safety factors

to probabilistic reliability margins represents a fundamental maturation of composite engineering, aligning structural assessment with the complex, stochastic realities of material behavior and operational usage.

5. Conclusion

5.1 Summary of the Integrated Approach

This comprehensive investigation has established that the integration of lifecycle assessment evidence with advanced uncertainty quantification methods is essential for accurately defining and optimizing reliability margins in composite pressure tanks. The transition from legacy deterministic safety factors to dynamic, probabilistic frameworks represents a necessary evolution in structural engineering, particularly for critical applications such as hydrogen storage and aerospace containment systems. By systematically parameterizing manufacturing variabilities, operational fatigue spectra, and environmental degradation mechanisms, this study demonstrated that the structural capacity of a composite vessel is a highly stochastic, time-dependent property. The utilization of Polynomial Chaos Expansion surrogate modeling combined with millions of Monte Carlo iterations provided a computationally viable mechanism for rigorously evaluating the extreme tails of probability distributions, which govern catastrophic failure. The temporal analysis revealed that while deterministic margins may appear robust at the beginning of life, progressive degradation significantly alters the probability density functions, drastically increasing the risk of failure near the end of the service life.

5.2 Implications for Industry Standards

The findings presented in this paper have profound implications for regulatory bodies and industry design standards. The evidence strongly supports a paradigm shift toward reliability-based design optimization, where static safety ratios are replaced by target reliability indices verified through continuous lifecycle data integration. The sensitivity analyses conducted highlight that quality control efforts must be dynamic; while controlling fiber tensile strength variance is paramount during manufacturing, mitigating matrix degradation becomes the dominant factor for ensuring long-term reliability. By accepting probabilistically verified margins, regulatory frameworks can allow manufacturers to safely reduce the amount of composite material utilized, thereby decreasing the weight and cost of pressure tanks. This optimization is critical for accelerating the economic viability of the global hydrogen economy and advancing lightweight aerospace infrastructure.

5.3 Limitations and Future Research Directions

Despite the robust framework established, several limitations warrant further investigation. The accuracy of the probabilistic models relies heavily on the quality of empirical data used for initial statistical distributions; acquiring large-scale destructive testing data for massive composite tanks remains economically challenging. Furthermore, the complex synergistic effects between multi-axial fatigue and harsh environmental exposures, such as cryogenic cycling combined with extreme humidity, require more sophisticated, physics-informed degradation models. Future research should focus on seamlessly integrating real-time structural health monitoring data—such as acoustic emission or embedded fiber optic sensor readings—directly into the Bayesian updating algorithms of the uncertainty quantification model. This would enable the creation of true digital twins for composite pressure vessels, allowing for the dynamic, real-time assessment of individual reliability margins tailored to the unique operational history of every single tank in service. Advancing these techniques will ensure that the next generation of lightweight pressure containment systems operates at the absolute optimal intersection of material efficiency and structural safety.

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