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FRP-Confined Concrete Stress-Strain Calibration with Bayesian Uncertainty Quantification

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ABSTRACT

The application of fiber-reinforced polymer composites for the confinement of concrete structures has become a widespread technique in structural engineering rehabilitation and construction. Despite the proliferation of theoretical and empirical stress-strain models, the inherent material variabilities and measurement uncertainties present substantial challenges for reliable performance prediction. This paper presents a comprehensive framework for the calibration of fiber-reinforced polymer-confined concrete stress-strain models utilizing Bayesian uncertainty quantification. By transitioning from traditional deterministic approaches to a probabilistic paradigm, this research systematically integrates prior knowledge with experimental database observations to yield posterior predictive distributions. The methodology employs Markov chain Monte Carlo sampling techniques to evaluate the statistical distributions of key model parameters, notably the dilation properties and ultimate strain capacities. The analysis demonstrates that Bayesian calibration not only refines the accuracy of the ultimate stress and strain predictions but also provides robust confidence intervals that quantify both aleatory and epistemic uncertainties. The resulting probabilistic models offer a rigorous foundation for reliability-based design codes, ensuring structural safety while optimizing material utilization. The findings advocate for the paradigm shift towards stochastic modeling in structural materials engineering, laying the groundwork for more resilient infrastructure systems that can safely accommodate natural material variations and construction tolerances.

KEYWORDS

Fiber-reinforced polymer, concrete confinement, Bayesian inference, uncertainty quantification..

1. Introduction

The deterioration of civil infrastructure systems globally has necessitated the development and implementation of advanced materials and innovative retrofitting techniques. Among these, the external bonding of fiber-reinforced polymer composites has emerged as a premier solution for enhancing the structural capacity and ductility of existing concrete columns. The fundamental mechanism involves wrapping concrete elements with continuous fiber sheets, typically composed of carbon, glass, or aramid fibers embedded in an epoxy resin matrix. When the concrete core is subjected to axial compression, it expands laterally due to the Poisson effect and internal microcracking. The fiber-reinforced polymer jacket resists this lateral expansion, thereby imposing a continuously increasing confining pressure on the concrete core. This state of triaxial compression significantly elevates both the ultimate compressive strength and the ultimate axial strain of the concrete element, preventing premature catastrophic failure and ensuring substantial energy dissipation capabilities under seismic loading conditions [1]. The success of this technique has led to its extensive adoption in bridge pier rehabilitation, building column upgrades, and the construction of new high-performance composite members [2]. Despite the clear mechanical advantages and widespread field applications, the precise prediction of the structural response of fiber-reinforced polymer-confined concrete remains a formidable challenge. Over the past three decades, structural researchers have developed numerous stress-strain models aimed at describing the constitutive behavior of confined concrete. These models generally range from purely empirical formulations derived through regression analysis of experimental datasets to complex analysis-oriented models based on incremental mechanics and lateral dilation properties [3]. The traditional paradigm in structural engineering relies almost exclusively on deterministic modeling, where a specific set of input parameters produces a single, exact prediction of structural response. However, this deterministic approach fundamentally ignores the vast spectrum of uncertainties inherent in composite construction [4]. Variability in concrete compressive strength, inconsistencies in the wet lay-up application process of the fiber composites, fluctuations in material geometry, and inherent measurement errors during laboratory testing all contribute to significant discrepancies between deterministic model predictions and actual structural behavior [5]. The presence of these uncertainties compromises the reliability of design provisions and safety factors, which are often derived from the lower bound of experimental scatter [6]. Recognizing these limitations, the structural engineering community is gradually shifting towards probabilistic assessment methodologies. Uncertainty quantification has thus become a critical frontier in modern engineering mechanics. By formally characterizing and propagating uncertainties through computational models, engineers can establish confidence intervals for their predictions, thereby facilitating performance-based and reliability-based design philosophies [7]. Within the realm of uncertainty quantification, Bayesian inference offers an exceptionally rigorous and elegant mathematical framework. Unlike traditional frequentist statistics, Bayesian methodologies treat model parameters as random variables characterized by probability distributions rather than fixed constants [8]. Bayesian uncertainty quantification involves updating the prior understanding of material parameters with new experimental evidence to obtain a posterior probability distribution. This approach is particularly advantageous for fiber-reinforced polymer-confined concrete, as it seamlessly integrates historical expert knowledge, theoretical constraints, and empirical observations from diverse laboratory campaigns [9]. Furthermore, Bayesian methods naturally decompose total uncertainty into aleatory uncertainty, which represents inherent material randomness, and epistemic uncertainty, which stems from a lack of knowledge or model simplifications. The quantification of these distinct uncertainty sources allows researchers to identify whether predictive shortcomings are due to natural scatter or structural deficiencies in the mathematical models themselves [10]. The primary objective of this comprehensive study is to implement a Bayesian uncertainty quantification framework to calibrate a

state-of-the-art analysis-oriented stress-strain model for fiber-reinforced polymer-confined concrete. By compiling a vast database of experimental test results from the global literature, this research systematically identifies the probabilistic distributions of crucial model parameters that govern confinement effectiveness and lateral dilation [11]. The methodology heavily relies on advanced computational techniques, specifically Markov chain Monte Carlo sampling algorithms, to navigate the high-dimensional parameter spaces and extract the posterior distributions. Ultimately, this paper aims to transition the evaluation of confined concrete structures from a deterministic mindset to a probabilistic paradigm, providing structural engineers with robust statistical tools to assess safety, optimize material usage, and develop next-generation design guidelines [12].

2. Literature Review and Theoretical Background

2.1 Mechanics of Fiber-Reinforced Polymer Confinement

The mechanical interaction between a concrete core and an external composite jacket is a dynamic and evolving process dictated by the respective stiffness and deformation capacities of the constituent materials. In unconfined concrete, axial compression leads to the initiation and propagation of longitudinal microcracks. As these cracks coalesce, the concrete exhibits significant lateral volumetric expansion, eventually resulting in macroscopic spalling and failure [13]. Passive confinement provided by fiber-reinforced polymer jackets fundamentally alters this failure mechanism. During the initial stages of axial loading, the lateral expansion of the concrete is minimal, and the confining pressure exerted by the composite jacket remains negligible. Consequently, the initial ascending branch of the stress-strain curve for confined concrete closely mirrors that of unconfined concrete [14]. As the axial stress approaches the unconfined compressive strength of the concrete, the rate of lateral dilation increases dramatically due to extensive internal crack propagation. The composite jacket, being highly stiff in the hoop direction, increasingly resists this expansion. Because fiber-reinforced polymer materials typically exhibit linear elastic behavior up to brittle rupture, the confining pressure they apply is not constant but increases continuously and proportionally to the lateral strain of the concrete [15]. This continuously increasing confinement represents a distinct departure from the constant confining pressure typically applied by traditional steel yielding jackets or active fluid pressure in triaxial testing chambers. The continuous restraint delays the unstable propagation of internal shear bands, transforming the inherently brittle failure of the concrete into a pseudo-ductile response characterized by a bilinear or strain-hardening stress-strain curve [16]. The ultimate failure of the composite system is overwhelmingly dictated by the tensile rupture of the fiber-reinforced polymer jacket in the hoop direction. Extensive experimental investigations have consistently demonstrated that the actual hoop rupture strain achieved in the composite jacket is significantly lower than the ultimate tensile strain determined from flat coupon tests of the fiber materials. This premature rupture phenomenon is attributed to several complex factors, including multiaxial stress states in the jacket, localized strain concentrations near concrete cracking sites, misalignment of fibers during the wrapping process, and the geometric curvature of the column cross-section [17]. Understanding and quantifying the exact distribution of this strain efficiency factor is crucial for accurate capacity prediction, yet it remains one of the most significant sources of uncertainty in confinement mechanics.

2.2 Evolution of Deterministic Stress-Strain Models

The profound need to quantify the enhancements in compressive strength and ultimate axial strain has driven the development of numerous stress-strain models for composite-confined concrete. These models are broadly categorized into two distinct philosophical approaches: design-oriented models and analysis-oriented models [18]. Design-oriented models are predominantly empirical, formulating direct closed-form expressions for the ultimate compressive strength and ultimate axial strain as functions of the unconfined concrete properties, jacket stiffness, and jacket ultimate strain. These expressions are typically derived through multiple linear or non-linear regression analyses over extensive databases of cylindrical test specimens [19]. While design-oriented models are highly

favored in engineering practice due to their mathematical simplicity and ease of implementation in standard design codes, they suffer from significant limitations. Because they are curve-fitted to specific datasets, their predictive accuracy diminishes rapidly when extrapolated outside the parameter range of the calibration data [20]. In contrast, analysis-oriented models attempt to capture the fundamental physical mechanisms governing the composite interaction. These models compute the complete stress-strain response using an incremental iterative procedure based on two foundational components: an active confinement model that describes the behavior of concrete subjected to a constant lateral pressure, and a lateral dilation model that dictates the relationship between the axial strain and the lateral strain of the concrete under varying continuous confinement [21]. The dilation model is the most critical and complex element of the analysis-oriented approach, as it must accurately reflect the transition of concrete volumetric behavior from compaction to rapid expansion [22]. Despite their superior theoretical rigor, analysis-oriented models are incredibly sensitive to the selection of their internal calibration parameters. In conventional deterministic practice, these parameters are fixed based on best-fit optimizations. However, this single-point estimation completely fails to address the inherent variability in the material dilation response, leading to deterministic outputs that exude a false sense of precision [23].

2.3 Principles of Bayesian Inference in Structural Engineering

To circumvent the inherent limitations of deterministic parameter calibration, structural engineers are increasingly adopting Bayesian statistical frameworks. At its core, Bayesian inference is a mathematically rigorous mechanism for updating the state of knowledge regarding unknown model parameters in light of new observed data [24]. In the context of stress-strain modeling, the unknown parameters represent the fundamental physical constants within the lateral dilation equations and the strain efficiency factors. Prior to analyzing any experimental data, engineers formulate prior probability distributions for these parameters based on existing theoretical bounds, engineering judgment, or historical studies [25]. The introduction of experimental datasets, typically comprising measured ultimate strengths, ultimate strains, and full stress-strain curve trajectories, allows for the computation of the likelihood function. The likelihood function quantifies the probability of observing the specific experimental data given a proposed set of model parameters. Through the application of Bayes theorem, the prior distributions and the likelihood function are multiplied and normalized to produce the posterior probability distributions [26]. These posterior distributions encapsulate the updated, comprehensive understanding of the model parameters, reflecting both the initial assumptions and the empirical evidence. A critical advantage of the Bayesian framework is its capacity to explicitly model different sources of uncertainty through the inclusion of variance parameters in the likelihood function. Structural models are inherent simplifications of complex reality, leading to epistemic model errors. Furthermore, material heterogeneity introduces aleatory physical scatter [27]. By estimating the variance of the discrepancy between model predictions and physical observations, Bayesian methodologies directly quantify the total predictive uncertainty. This allows for the generation of credible intervals around the median stress-strain prediction, providing a probabilistic envelope that contains a specified percentage of true potential outcomes. Such probabilistic outputs are invaluable for reliability analysis, as they allow designers to rationally determine load and resistance factors that correspond to target safety indices [28].

3. Methodology and Analytical Framework

3.1 Database Compilation and Material Characterization

The foundation of any robust statistical calibration is the quality, diversity, and volume of the underlying observational data. For this research, a comprehensive database of experimental test results on fiber-reinforced polymer-confined concrete cylinders subjected to monotonic axial compression was compiled through an exhaustive review of published literature over the past twenty years. The compilation process prioritized cylindrical specimens because they exhibit a uniform distribution of confining pressure, thereby isolating the fundamental material constitutive behavior

from the geometric stress concentrations associated with square or rectangular columns [29].

Strict filtering criteria were applied to ensure the integrity of the Bayesian calibration process. Specimens were excluded if they exhibited premature failure modes unrelated to jacket rupture, such as load application eccentricities or localized boundary crushing. Furthermore, tests lacking complete documentation of fundamental material properties, such as the unconfined concrete cylinder strength, the elastic modulus of the composite jacket, and the ultimate tensile strain of flat coupons, were discarded. The finalized database comprises hundreds of distinct test specimens encompassing a vast parametric space. The unconfined concrete strengths range from normal strength variants to high-strength concrete mixtures. The composite jackets encompass various fiber types, primarily unidirectional carbon and glass fibers, with varying volumetric ratios and jacket thicknesses [30].

Table 1: Summary Statistics of the Compiled Experimental Database for Model Calibration

Parameter Description	Minimum Value	Maximum Value	Mean Value	Coefficient of Variation
Unconfined Concrete Strength	18.5	112.4	45.2	0.35
Specimen Diameter	100.0	400.0	152.4	0.28
Fiber Elastic Modulus	22.5	390.0	185.6	0.42
Unconfined Peak Strain	0.0018	0.0035	0.0024	0.15
Ultimate Confined Strength	25.4	215.8	88.3	0.39

The data was systematically preprocessed to unify the units of measurement and to standardize the extraction of the ultimate conditions. Given the variability in testing equipment and strain measurement techniques across different laboratories, particular attention was paid to the ultimate axial strain values, which inherently possess a higher degree of observational noise compared to load-cell derived stress values. This curated dataset serves as the empirical foundation against which the theoretical predictions of the stress-strain model will be evaluated and updated.

3.2 Formulation of the Probabilistic Model

The deterministic baseline utilized in this study is a prominent analysis-oriented model that relies on an iterative strain-increment procedure. The core of this model is a lateral dilation relationship that computes the lateral strain as a function of the axial strain, the unconfined concrete strength, and the instantaneous confining pressure provided by the composite jacket. The fundamental equation governing the dilation involves several empirical coefficients that dictate the rate of initial compaction and the subsequent rate of lateral expansion [31]. In the deterministic framework, these coefficients are assigned constant, singular values. To transition to a probabilistic framework, we define a statistical model that explicitly links the observed experimental values to the theoretical model predictions. The observed ultimate compressive strength and ultimate axial strain for the i-th specimen in the database are formulated as the sum of the deterministic model prediction and a corresponding error term. The model predictions are dependent on the input geometry, material properties, and the vector of unknown calibration parameters. The error terms are assumed to follow

zero-mean Gaussian distributions, which capture the combined effects of measurement noise, material randomness, and structural model inadequacies. The covariance structure of these error terms is a critical component of the methodology. Because the ultimate stress and ultimate strain for a single specimen are physically correlated outcomes of the same loading process, the errors cannot be treated as independent. Therefore, a multivariate normal likelihood function is constructed, incorporating a covariance matrix that captures both the individual variances of the stress and strain predictions and the correlation coefficient between them [32]. The calibration parameter vector consists of the primary physical coefficients governing the concrete dilation equation, the universal strain efficiency factor describing the premature rupture of the jacket, and the statistical parameters of the covariance matrix. Prior probability distributions must be assigned to each element within the calibration parameter vector. For the physical parameters of the dilation model, lognormal distributions are specified to ensure strictly positive values, maintaining the physical meaning of the coefficients. The prior means are centered around the originally published deterministic values, with relatively wide standard deviations reflecting substantial initial uncertainty. The strain efficiency factor is modeled with a bounded beta distribution, reflecting the physical constraint that the in-situ rupture strain must be a fraction between zero and the coupon failure strain. The standard deviations of the error terms are assigned non-informative uniform priors over a broad positive range, allowing the data to entirely dictate the magnitude of the model uncertainty.

3.3 Markov Chain Monte Carlo Sampling Strategy

The complex, non-linear nature of the analysis-oriented stress-strain model, coupled with the high dimensionality of the calibration parameter space, renders analytical computation of the posterior distributions mathematically intractable. To overcome this computational hurdle, advanced Markov chain Monte Carlo simulation techniques are employed. Markov chain Monte Carlo is a class of algorithms designed to draw representative samples from complex probability distributions by constructing a Markov chain that has the desired posterior distribution as its equilibrium distribution. Specifically, this study utilizes an adaptive Metropolis-Hastings algorithm. The sampling procedure initiates at a starting point within the parameter space, typically chosen as the prior mean. In each iteration, a candidate parameter vector is generated by adding a random perturbation, drawn from a proposal distribution, to the current parameter vector. The proposed vector is then evaluated by computing the likelihood of the entire experimental database given these new parameters, utilizing the analysis-oriented model to generate the theoretical predictions. The product of the new likelihood and the prior probability is compared to the corresponding product for the current parameter vector.

If the proposed vector yields a higher posterior probability, it is systematically accepted as the next step in the Markov chain. If it yields a lower probability, it is accepted with a probability proportional to the ratio of the posterior probabilities. This stochastic acceptance criterion allows the algorithm to thoroughly explore the parameter space, escaping local maxima and accurately mapping the regions of highest probability density.

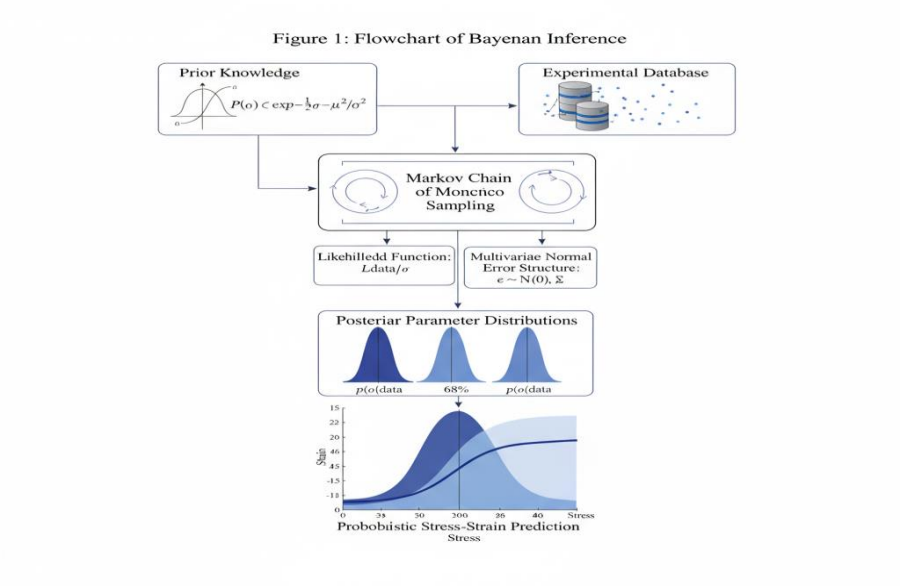


Figure 1: Flowchart of Bayesian Inference

To ensure the statistical validity of the drawn samples, several parallel Markov chains are executed starting from overdispersed initial locations. The initial phase of the sampling, known as the burn-in period, is discarded to eliminate the influence of the starting positions. The convergence of the chains to the stationary posterior distribution is rigorously monitored using established statistical diagnostics, such as the potential scale reduction factor, which compares the variance within individual chains to the variance between different chains. Once convergence is confirmed, the remaining tens of thousands of accepted samples form an accurate discrete representation of the multidimensional posterior probability density function, enabling deep statistical insights into the model parameters.

4. Results and Discussion

4.1 Analysis of Posterior Parameter Distributions

The execution of the Markov chain Monte Carlo sampling algorithm successfully yielded stable and robust posterior probability distributions for all target parameters. A comprehensive analysis of these posterior distributions reveals critical insights into the physical mechanisms of fiber-reinforced polymer confinement and the inherent limitations of previous deterministic approaches. The marginal posterior distributions for the dilation model coefficients demonstrate a significant narrowing of variance compared to their respective prior distributions. This reduction in uncertainty confirms that the experimental database contains substantial information capable of refining our understanding of concrete lateral expansion behavior.

Notably, the central tendencies of the posterior distributions for several key parameters shifted distinctly away from the originally proposed deterministic values. The parameter governing the initial compaction rate of the concrete under axial load exhibited a higher mean value, suggesting that the existing analysis-oriented model systematically underestimated the stiffness of the concrete matrix prior to substantial microcracking. Conversely, the coefficient dictating the rapid volumetric expansion phase shifted lower, indicating that concrete dilation under high confinement pressures is slightly more constrained than historically modeled.

Table 2: Statistical Summary of the Posterior Parameter Distributions from MCMC Sampling

Model Parameter	Prior Mean	Posterior Mean	Posterior Standard Deviation	95% Credible Interval
Dilation	0.050	0.062	0.004	[0.054,

Coefficient A				0.070]
Dilation Coefficient B	1.500	1.315	0.082	[1.155, 1.475]
Strain Efficiency Factor	0.650	0.584	0.035	[0.515, 0.653]
Stress Error Variance	N/A	145.2	12.6	[120.5, 169.8]
Strain Error Variance	N/A	0.0004	0.00005	[0.0003, 0.0005]

The statistical evaluation of the strain efficiency factor is of paramount importance for practical design. The posterior mean for this factor converged to approximately 0.58, which is lower than the commonly adopted deterministic values ranging from 0.6 to 0.7 found in many current design guidelines. This finding strongly suggests that relying on higher efficiency factors may result in unconservative predictions of ultimate axial strain and displacement capacity. Furthermore, the posterior standard deviation for the efficiency factor highlights substantial remaining uncertainty. This spread represents the genuine aleatory variability associated with the complex mechanics of jacket rupture, influenced by local aggregate interlocking, resin distribution variations, and subtle application defects that cannot be entirely eliminated even in controlled laboratory environments.

The analysis of the covariance structure of the error terms provided another critical finding. The posterior correlation coefficient between the ultimate stress error and the ultimate strain error was found to be strongly positive. This mathematical correlation physically implies that if a specific composite-confined cylinder exhibits an ultimate strength higher than the model prediction, it is highly likely to also exhibit an ultimate strain higher than the corresponding strain prediction. Capturing this correlation is essential for accurate reliability analysis, as treating these capacities as independent variables would lead to erroneous evaluations of structural safety factors.

4.2 Predictive Performance and Reliability Implications

The true value of the calibrated Bayesian framework lies in its predictive performance and its ability to quantify predictive uncertainty. To evaluate this, the posterior parameter samples were fed back into the analysis-oriented model to simulate the stress-strain response of the specimens in the experimental database. Instead of generating a single deterministic curve for each specimen, the probabilistic model generates a dense family of curves, from which the median response and the bounds of the 95 percent credible intervals can be extracted. When comparing the deterministic baseline predictions to the median posterior predictions, a marked improvement in overall accuracy is observed. The systematic bias, quantified by the mean absolute percentage error across the entire database, was significantly reduced for both ultimate compressive strength and ultimate axial strain. The probabilistic calibration effectively centered the theoretical model within the empirical data cloud, eliminating the conservative or unconservative skews that plagued earlier formulations.

More importantly, the quantification of uncertainty provides profound implications for structural reliability. The generated 95 percent credible intervals successfully enveloped the vast majority of the experimental data points. In practical engineering applications, these credible bounds act as rigorous, statistically derived safety envelopes. An engineer designing a critical infrastructure component, such as a bridge pier situated in a highly active seismic zone, can now select material strength and ductility values from the lower percentiles of the predictive distribution, ensuring a mathematically defined margin of safety against premature collapse.

Conversely, for assessing the existing state of heavily degraded structures, upper bound predictions can prevent the costly over-estimation of required retrofit materials. The decomposition of the error variances further informs the engineering community that while the fundamental structure of the analysis-oriented model is sound, pure material randomness accounts for a substantial portion of the predictive scatter. Therefore, further refinements of deterministic equations will yield diminishing returns unless they are accompanied by stochastic mechanics approaches that natively address inherent variability.

5. Conclusion

This comprehensive academic investigation has successfully demonstrated the implementation and the profound advantages of applying Bayesian uncertainty quantification to the stress-strain modeling of fiber-reinforced polymer-confined concrete. By departing from conventional deterministic calibration paradigms, this research established a rigorous probabilistic framework capable of mathematically updating material behavioral models through the systematic integration of large-scale experimental databases. The execution of advanced Markov chain Monte Carlo simulations facilitated the precise extraction of posterior probability distributions for fundamental dilation coefficients and strain efficiency factors, revealing physical insights that are completely obscured in single-point optimization procedures. The results unequivocally indicate that the calibrated probabilistic model provides superior predictive accuracy for ultimate compressive strength and axial strain while simultaneously generating robust statistical confidence intervals. The determination of a lower-than-anticipated posterior mean for the hoop strain efficiency factor underscores the necessity for conservative evaluations of composite jacket ductility in actual structural applications. Furthermore, the explicit quantification of correlated predictive error structures provides structural engineers with the exact statistical tools required to perform sophisticated reliability-based designs and to establish rational, probability-driven safety factors. Ultimately, the findings of this research advocate for a paradigm shift in structural materials engineering. The inherent variability in composite materials, the unpredictability of field application processes, and the simplified nature of mathematical constitutive models dictate that deterministic predictions are insufficient for modern resilience requirements. The Bayesian framework detailed herein not only enhances the understanding of confined concrete mechanics but also lays the vital groundwork for the development of next-generation, probabilistically informed structural design codes. Future research endeavors must expand this stochastic approach to encompass more complex loading scenarios, including cyclic seismic actions and eccentric compression, to fully secure the reliability of our critical civil infrastructure systems.

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