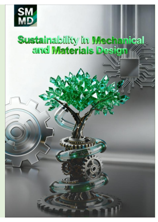
Sustainability in Mechanical and Materials Design

smmd.pol-aca.com



Article

Review and Prospects of Experimental Research and Phase-Field Modeling on Fracture Behavior of Composite Materials under Hygrothermal Environments

Lin Wang [1], Tingting Xie [2] , jianxing Li [3,*]

[1]Chongqing Polytechnic University of Electronic Technology,School of Mechanical Engineering, Chongqing,China.
[2]ChengDu University of Traditional Chinese Medicine,School of Mechanical Engineering,chengdu,Sichuan,China.
[3]Si Chuan Film and Television University,School of Mechanical Engineering,chengdu,Sichuan,China.

Keywords:
Composite materials
Hygrothermal environments
Fracture behavior
Phase-field modeling

ARTICLE INFO **ABSTRACT**

This review systematically examines recent advances in understanding the fracture behavior of composite materials under hygrothermal environments, with a focus on experimental studies, phase-field modeling, and the emerging role of artificial intelligence. Experimental investigations have elucidated moisture diffusion mechanisms — ranging from Fickian to non-Fickian behavior — and identified critical degradation processes at fiber-matrix interfaces. The phase-field method has emerged as a powerful numerical tool for simulating complex crack propagation, with ongoing efforts to extend its capability to multi-physics scenarios involving thermo-hydro-mechanical coupling. Meanwhile, machine learning techniques, especially physics-informed neural networks (PINNs), are increasingly integrated into constitutive modeling and failure prediction, offering solutions to challenges such as computational cost and limited experimental data. Despite these advancements, key gaps remain, particularly in fully coupled hygrothermal-mechanical phase-field frameworks and the integration of physical mechanisms into data-driven models. Future research is expected to prioritize intelligent, multi-scale simulation platforms and digital twin technologies to achieve accurate lifecycle prediction and design optimization for composites in critical engineering applications.

1. Introduction

Composite materials are widely used in major engineering fields such as aviation, aerospace, and energy, and their performance is often significantly affected by coupled hygrothermal environments. The combined action of moisture ingress and

* **Correspondence authors**

Email address:3405712964@qq.com

Citation: To be added by editorial staff during production.

temperature changes can easily lead to material performance degradation, interface failure, and even macroscopic fracture. In recent years, significant progress has been made in experimental research, fracture phase-field models, and AI-assisted modeling. This article provides a systematic review focusing on the moisture absorption behavior, multi-physics coupled fracture mechanisms, and emerging modeling methods of composite materials under hygrothermal environments, aiming to provide reference for further research in this field.

2. Advances and Trends in Experimental Research under Hygrothermal Environments

The influence of hygrothermal environments on the performance of composite materials has become an important direction for experimental research, mainly focusing on moisture diffusion behavior, moisture absorption kinetics, and their degradation mechanisms on mechanical properties. Multiple studies, through controlled temperature and humidity experiments, have systematically revealed the response laws of different material systems under coupled hygrothermal conditions.

Fan et al. (2009) early on experimentally studied the moisture intrusion behavior in various polymer materials, found that the diffusion process can be distinguished into typical Fickian and non-Fickian diffusion modes, and established governing equations for moisture-containing phase change considering temperature effects, providing a theoretical basis for subsequent hygrothermal aging modeling. Sature and Mache (2017) developed composite laminates with natural fibers, and experiments showed that hybrid composites possess better moisture resistance, with significantly lower moisture absorption rates than pure natural fiber composites. Jiang et al. (2013) used the gravimetric method to study the moisture diffusion behavior in GFRP/adhesive systems under hygrothermal conditions, finding that the interface region between the FRP section and the adhesive layer is most sensitive to moisture effects.

Jansen et al. (2020) proposed a new multi-step characterization method to investigate the dependency between temperature, humidity, and material parameters. The study found that when the temperature reaches 85°C, moisture diffusion basically follows Fick's law, and moisture absorption can be simulated using a single temperature-dependent diffusion coefficient. These experiments not only reveal the physical nature of the hygrothermal coupling effect but also lay the foundation for building more accurate multi-field coupled constitutive models.

3. Development and Application of Fracture Phase-Field Models

The Phase Field Method (PFM) for fracture has become an important numerical tool for simulating material fracture due to its ability to naturally describe complex behaviors such as crack initiation, propagation, merging, and branching. Francfort and Marigo (1998) proposed PFM based on Griffith's theory, introducing a continuous damage variable to describe material degradation, avoiding preset crack paths and criteria in traditional fracture mechanics. Subsequently, the method was extended to multi-physics coupling scenarios. Wang et al. (2020) developed a thermo-elastic-plastic phase-field model based on the Borden model to simulate the damage behavior of adiabatic shear bands . Liu et al. (2025) proposed a thermo-hydro-mechanical cohesive phase-field model for hydraulic fracturing in deep coal seams, considering the thermal exchange between cold fluid and hot rock .

The multiphase structure and complex failure behavior of composite materials place higher demands on modeling. Zhang et al. (2020) combined the phase-field method with the cohesive element (CE) model to construct a numerical framework capable of simulating delamination, debonding, and matrix cracking, and validated it through simulations of cross-ply composite laminations . Yin et al. (2023) further embedded the cohesive zone model into the phase-field framework, achieving accurate capture of the progressive failure and damage behavior of multi-fiber systems, and systematically explored the effects of fiber distribution, fiber volume fraction, and boundary conditions.

However, the difficulty in accurately obtaining composite interface parameters hinders the practical application of models. Zhou et al. (2024) proposed a Modified Crack Surface Displacement Extrapolation (MCSDE) method to identify the actual interfacial fracture toughness and studied the crack propagation behavior in bimaterial structures and sandwich specimens with different initial notch positions. Regarding hygrothermal coupling, Au-Yeung et al. (2023) established a coupled phase-field framework considering moisture diffusion, hygroscopic expansion, and fracture behavior, studying composite performance degradation across micro, meso, and macro scales, but this study did not consider temperature effects. Furthermore, some scholars have studied the effects of hygrothermal conditions on the nonlinear viscoelastic fracture behavior of epoxy resin and nanocomposites under finite deformation only involving the thermal environment, without introducing humidity conditions, such as Arash et al. (2023) who coupled PFM with a nonlinear viscoelastic constitutive model in a thermodynamically consistent manner and explored the effects of temperature, deformation rate, and moisture content on the force-displacement response of nano-boehmite/epoxy samples, but did not further investigate the influence of moisture concentration and temperature distribution on the fracture behavior of polymer nanocomposites, indicating a research gap in this area.

4. The Rise of Artificial Intelligence in Material Constitutive and Fracture Modeling

In recent years, artificial intelligence (AI) technology has deeply integrated with traditional mechanical modeling, significantly enhancing the ability to establish constitutive relationships and predict fracture behavior in composite materials. Raissi et al. (2019) proposed Physics-Informed Neural Networks (PINNs), providing a new paradigm for solving forward and inverse problems involving nonlinear partial differential equations. Chen and Gu (2021) developed an elasticity identification method (ElastNet) based on measured strain distributions, overcoming the ill-posed nature of traditional elastographic inverse problems.

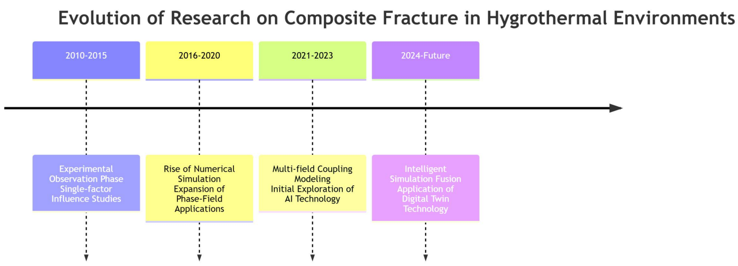
In constitutive modeling, Li and Chen (2022) used neural networks to directly represent the multiaxial stress-strain relationship of hyperelastic materials, avoiding the limitations of traditional model equations . Abdolazizi et al. (2024) introduced Viscoelastic Constitutive Artificial Neural Networks (vCAAN), whose constitutive behavior relies on the concept of a generalized Maxwell model enhanced by nonlinear strain (rate)-dependent properties represented by a neural network, and demonstrated that vCAAN can accurately and efficiently capture these material behaviors without human guidance .

In micro-mechanical and composite modeling, AI also shows great potential. Qu et al. (2021) developed a machine learning-based constitutive modeling approach for granular materials informed by micromechanics . Li et al. (2023) proposed a mechanics-informed machine learning approach that uses a small training database to predict the elastoplastic behavior of unidirectional fiber-reinforced composites by incorporating mechanics-based strain and stress decomposition into an Artificial Neural Network (ANN) . Sepasdar et al. (2024) proposed an image-based deep learning framework for predicting nonlinear stress distribution and failure patterns in the characterization of composite microstructures, which includes two stacked fully convolutional networks; their research showed an accuracy of up to 90% in predicting nonlinear stresses and failure patterns . To address complex loading conditions, Chen et al. (2021) proposed a method for failure prediction of IM7/8552 unidirectional composite laminates under triaxial loading based on ANN combined with micromechanics, and the trained model showed high accuracy in biaxial compression .

Research on the fracture behavior of composite materials under hygrothermal environments is undergoing a critical transition from phenomenological observation to mechanistic understanding, from single physics to multi-field coupling, and from traditional methods to intelligent enhancement. Although current research has clarified the existence of both Fickian and non-Fickian diffusion modes for moisture, and identified the interface region as a sensitive weak point for hygrothermal aging, the underlying physical mechanism of how temperature and humidity synergistically act to precisely trigger the complete failure chain from moisture absorption and swelling to interface debonding and even matrix cracking remains incompletely understood. As a powerful tool for fracture analysis, the phase-field model, while demonstrating unique advantages in describing complex crack propagation, is still in the early stages of exploration for applications in fully coupled thermo-hygro-mechanical scenarios, facing challenges such as complex constitutive relationships and difficulties in accurately obtaining key interface parameters. Meanwhile, artificial intelligence technologies, represented by Physics-Informed Neural Networks, are bringing new hope for solving the challenges of nonlinear constitutive modeling and cross-scale failure prediction in composites through the new paradigm of "data-driven + physics-constrained"; however, ensuring the physical consistency and extrapolation reliability of models under small-sample conditions remains an obstacle that must be overcome for their engineering application. In summary, the breakthrough point for future research lies in the deep integration of physical mechanisms and data intelligence, constructing a thermo-hygro-mechanically fully coupled phase-field theoretical framework strictly validated by multi-scale experiments, thereby achieving accurate prediction and proactive design of the service life and failure behavior of composite materials in harsh hygrothermal environments.

Based on the analysis and organization of relevant literature, we have constructed a timeline diagram, as shown in Figure 1.

Figure 1. Evolution of Research on Composite Fracture in Hygrothermal Enviromments



Through a focused analysis of the timeline diagram for research on composite material fracture in hygrothermal environments, a clear four-stage evolutionary path of research paradigms in this field can be observed: The starting point focused on fundamental experimental observations and single-factor analyses (2010-2015), followed by a stage of vigorous development in numerical simulation techniques, where advanced numerical tools like the phase-field method began to be widely applied (2016-2020). In the third stage (2021-2023), the research focus shifted towards multi-physics coupling modeling and began exploring the application potential of artificial intelligence technologies. The current and future stage (2024-) is characterized by the deep integration of intelligent simulation, with digital twin technology emerging as the dominant research direction. This evolutionary process fully reflects the paradigm shift in this field from phenomenological description to mechanistic exploration, from single-field analysis to multi-field coupling, and from traditional methods to intelligent algorithms. It also indicates that future research will place greater emphasis on interdisciplinary integration and the precision and intelligence of engineering applications.

Looking ahead to the next five years, research on the fracture behavior of composite materials under hygrothermal environments will exhibit distinct characteristics of deep intelligence and multi-scale precision. The research focus will concentrate on developing fully coupled thermo-hygro-mechanical phase-field models embedded with physical mechanisms, aiming to break through the bottlenecks of computational efficiency and physical consistency in traditional numerical simulations by deeply integrating Physics-Informed Neural Networks (PINNs) with multi-field coupled phase-field theory. Simultaneously, the "experiment-model-data" driven paradigm based on digital twins will gradually mature, achieving a closed-loop research process from microstructural image recognition to macroscopic performance prediction, and further to inverse design. This progress will greatly rely on interdisciplinary collaboration, promoting the formation of a new system for predicting the full-lifecycle performance and design optimization of composite materials under the guidance of the materials genome initiative concept, ultimately providing highly reliable material solutions for major engineering fields such as aerospace and new energy.

References

Arash, B., Exner, W., & Rolfes, R. (2023). Effect of moisture on the nonlinear viscoelastic fracture behavior of polymer nanocomposites: A finite deformation phase-field model. Engineering with Computers, 39, 773–790. https://doi.org/10.1007/s00366-022-01763-x

Au-Yeung, K., Quintanas-Corominas, A., Martínez-Pañeda, E., et al. (2023). Hygroscopic phase field fracture modelling of composite materials. Engineering with Computers, 39, 3847–3864. https://doi.org/10.1007/s00366-022-01772-w

Chen, C.-T., & Gu, G. X. (2021). Learning hidden elasticity with deep neural networks. Proceedings of the National Academy of Sciences, 118(31), e2102721118. https://doi.org/10.1073/pnas.2102721118

Chen, J. Y., Wan, L., Ismail, Y., et al. (2021). A micromechanics and machine learning coupled approach for failure prediction of unidirectional CFRP composites under triaxial loading: A preliminary study. Composite Structures, 267, 113876. https://doi.org/10.1016/j.compstruct.2021.113876

Du, Y., & Ma, Y. E. (2022). Study on tensile properties of carbon fiber epoxy resin composites under hygrothermal environment. Journal of Northwestern Polytechnical University, 40(1), 33–39.

Fan, X. J., Lee, S. W. R., & Han, Q. (2009). Experimental investigations and model study of moisture behaviors in polymeric materials. Microelectronics Reliability, 49, 861–871. https://doi.org/10.1016/j.microrel.2009.03.002

Francfort, G. A., & Marigo, J.-J. (1998). Revisiting brittle fracture as an energy minimization problem. Journal of the Mechanics and Physics of Solids, 46(8), 1319–1342. https://doi.org/10.1016/S0022-5096(98)00034-9

Gao, Y., Wang, Z., Lu, C., et al. (2023). Research status on dynamic mechanical behavior of high-performance resin matrix composites under typical aerospace environments. Journal of Materials Engineering, 43(3), 106–112.

Jansen, K. M. B., Zhang, M. F., Ernst, L. J., et al. (2020). Effect of temperature and humidity on moisture diffusion in an epoxy moulding compound material. Microelectronics Reliability, 107, 113596. https://doi.org/10.1016/j.microrel.2020.113596

Jiang, X., Kolstein, H., & Bijlaard, F. S. K. (2013). Moisture diffusion in glass–fiber-reinforced polymer composite bridge under hot/wet environment. Composites Part B: Engineering, 45(1), 407–416. https://doi.org/10.1016/j.compositesb.2012.04.074

Li, L. F., & Chen, C. Q. (2022). Equilibrium-based convolution neural networks for constitutive modeling of hyperelastic materials. Journal of the Mechanics and Physics of Solids, 164, 104931. https://doi.org/10.1016/j.jmps.2022.104931

Li, Z. Q., Li, X., Chen, Y., et al. (2023). A mechanics-informed machine learning approach for modeling the elastoplastic behavior of fiber-reinforced composites. Composite Structures, 323, 117473. https://doi.org/10.1016/j.compstruct.2023.117473

Liu, J. P., Yang, Z. Z., Yi, L. P., et al. (2025). Coupled thermo-hydro-mechanical cohesive phase-field model for hydraulic fracturing in deep coal seams. Applied Mathematics and Mechanics, 46, 663–682. https://doi.org/10.1007/s10483-025-3117-8

Liu, S. F., Cheng, X. Q., & Bao, J. W. (2014). Analysis of the effect of hygrothermal environment on the properties of resin matrix composites. Polymer Materials Science and Engineering, 30(9), 183–190.

Liu, S. J., Feng, Y., Zhang, T., et al. (2023). Moisture absorption properties of aeronautical composite stiffened panels in hygrothermal environment. Journal of Aerospace Power, 38(9), 2231–2240.

Qu, T. M., Di, S. C., Feng, Y. T., et al. (2021). Towards data-driven constitutive modelling for granular materials via micromechanics-informed deep learning. International Journal of Plasticity, 144, 103046. https://doi.org/10.1016/j.ijplas.2021.103046

Raissi, M., Perdikaris, P., & Karniadakis, G. E. (2019). Physics-informed neural networks: A deep learning framework for solving forward and inverse problems involving nonlinear partial differential equations. Journal of Computational Physics, 378, 686–707. https://doi.org/10.1016/j.jcp.2018.10.045

Sature, P., & Mache, A. (2017). Experimental and numerical study on moisture diffusion phenomenon of natural fiber based composites. Materials Today: Proceedings, 4(9), 10293–10297. https://doi.org/10.1016/j.matpr.2017.06.349

Sepasdar, R., Karpatne, A., & Shakiba, M. (2022). A data-driven approach to full-field nonlinear stress distribution and failure pattern prediction in composites using deep learning. Computer Methods in Applied Mechanics and Engineering, 397, 115126. https://doi.org/10.1016/j.cma.2022.115126

Su, H. B., Chen, B. H., Wu, X., et al. (2024). A phase field model for multi-mode cohesive fracture of fiber reinforced composites. Chinese Journal of Engineering Design, 31(3), 301–308.

Wang, T., Liu, Z. L., Cui, Y. N., et al. (2020). A thermo-elastic-plastic phase-field model for simulating the evolution and transition of adiabatic shear band. Part I. Theory and model calibration. Engineering Fracture Mechanics, 232, 107028. https://doi.org/10.1016/j.engfracmech.2020.107028

Yin, B. B., Akbar, A., Zhang, Y., et al. (2023). Modeling progressive failure and crack evolution in a randomly distributed fiber system via a coupled phase-field cohesive model. Composite Structures, 313, 116959. https://doi.org/10.1016/j.compstruct.2023.116959

Zhang, B., Shi, D. Q., Xia, Z. Y., et al. (2025). Application of artificial intelligence in performance prediction and optimization of oxide/oxide ceramic matrix composites. Acta Materiae Compositae Sinica. Advance online publication. https://doi.org/10.13801/j.cnki.fhclxb.20250821.001

Zhang, P., Feng, Y. Q., Bui, T. Q., et al. (2020). Modelling distinct failure mechanisms in composite materials by a combined phase field method. Composite Structures, 232, 111551. https://doi.org/10.1016/j.compstruct.2019.111551

Zhang, Z. C., Dong, H. C., & Wang, F. X. (2024). A phase field fracture model for orthotropic materials based on spherical-deviatoric stress decomposition. Acta Materiae Compositae Sinica, 41(8), 4408–4417.

Zhou, C., He, J., Berggreen, C., et al. (2024). A combined interface phase field (CIPF) model for interfacial crack propagation. Engineering Fracture Mechanics, 295, 109779. https://doi.org/10.1016/j.engfracmech.2023.109779