Fatigue Crack Growth in Nano-Silica Reinforced Glass Fiber Composites

Rajesh Kumar

Manufacturing Engineering Division, Indian Institute of Technology Bombay, India

Abstract: Glass fiber reinforced epoxy composites (GFECs) are extensively used in structural applications due to their high strength-to-weight ratio, but they are prone to fatigue damage, particularly crack initiation and propagation under cyclic loading. The incorporation of nano-silica particles as reinforcements has shown promise in enhancing fatigue resistance by modifying crack growth behavior. This review paper synthesizes recent advancements in understanding fatigue crack growth in nano-silica reinforced GFECs, drawing from experimental, fractographic, and modeling studies. Key findings indicate that nano-silica at optimal loadings (1-10 wt.%) can increase fatigue life by 3-4 times, reduce crack propagation rates by 30-60%, and improve fracture toughness through mechanisms such as crack deflection, pinning, debonding, and plastic void growth. Time-dependent crack growth is often K_max-controlled, with suppressed matrix cracking contributing to enhanced durability. Hybrid systems combining nano-silica with other fillers like rubber particles exhibit synergistic effects, further mitigating delamination and fatigue failure. Challenges include agglomeration at higher loadings, which can introduce stress concentrations. The paper discusses applications in aerospace and automotive sectors, emphasizing the need for uniform dispersion and multiscale modeling for predictive design.

Keywords: Manufacturing Engineering, Additive Manufacturing, 3D Printing, CNC Machining, Injection Molding

Introduction

Glass fiber reinforced composites (GFRCs), particularly those with epoxy matrices, are integral to industries requiring lightweight, high-performance materials, such as aerospace, automotive, wind energy, and marine engineering. These composites offer excellent tensile strength, corrosion resistance, and design flexibility, but their susceptibility to fatigue under cyclic loading limits long-term reliability. Fatigue damage in GFECs typically manifests as matrix cracking, fiber-matrix debonding, delamination, and eventual crack propagation, leading to structural failure. The interlaminar regions, where stress concentrations occur due to ply discontinuities, are particularly vulnerable.

To address these limitations, nanofillers like nano-silica (SiO_2 nanoparticles) have been incorporated into the epoxy matrix. Nano-silica, with particle sizes typically 10-50 nm, possesses high surface area, modulus (70 GPa), and compatibility with epoxy via silane functionalization, enabling improved interfacial bonding and energy dissipation. Studies have demonstrated that nano-silica reinforcements can enhance quasi-static properties like tensile strength (up to 31% increase) and flexural strength (up to 42%), but their impact on dynamic fatigue behavior is equally significant.pmc.ncbi.nlm.nih.gov

Fatigue crack growth in composites is governed by parameters such as stress intensity factor (K), energy release rate (G), and loading conditions (e.g., stress ratio R=0.1). In nano-silica modified systems, crack growth is often time-dependent and K_{max}-controlled, differing from cycle-dependent behavior in unreinforced epoxies. Mechanisms like crack pinning and deflection create tortuous paths, reducing propagation rates and extending fatigue life by factors of 3-4. For instance, in glass fiber/epoxy laminates with 10 wt.% nano-silica, suppressed matrix cracking contributes to enhanced cyclic performance.sciencedirect.comsciencedirect.com

This review focuses on fatigue crack growth behavior in nano-silica reinforced GFECs, encompassing experimental observations, mechanistic insights, and quantitative improvements. It draws from key studies on tensile fatigue, fracture toughness, and modeling using approaches like the Hartman-Schijve relationship. The objective is to elucidate how nano-silica mitigates fatigue damage, identify optimal parameters, and highlight future research directions for damage-tolerant composites.royalsocietypublishing.org

Literature Review

The literature on nano-silica reinforced composites highlights significant advancements in fatigue performance, particularly for epoxy-based systems with glass or carbon fibers. Early studies focused on quasi-static toughening, but recent work emphasizes cyclic fatigue and crack dynamics.

A seminal study on the tensile fatigue behavior of silica nanoparticle-modified glass fiber reinforced epoxy composites (GFRPs) at 10 wt.% loading reported a 3-4 fold increase in fatigue life under stress-controlled conditions. Suppressed matrix cracking and reduced crack propagation rates were key contributors, with mechanisms involving nanoparticle debonding and plastic void growth for energy absorption. Similar enhancements were observed in bulk epoxy specimens, confirming the matrix-level benefits.

In time-dependent fatigue crack growth investigations of silica-reinforced epoxy resins, crack propagation was found to be K_{max}-controlled and independent of stress ratio ($R=0.05-0.7$) and frequency (0.1-10 Hz). The crack growth rate (da/dt) remained constant under fixed K_{max}, indicating time-dependent behavior rather than cycle-dependent. Fractography revealed matrix-dominant propagation, with silica particles inhibiting growth near interfaces. This study, though not fiber-specific, provides foundational insights applicable to GFECs.

Comprehensive reviews on nanosilica as a toughening agent in epoxy composites underscore fatigue improvements, with 1.5-fold enhancements in crack growth resistance at 2 wt.% loading. For glass fiber applications, nanosilica boosts interlaminar shear strength (ILSS) by 13% and flexural strength up to 350 MPa at 1 wt.%, via crack deflection and pinning. Agglomeration beyond 5 wt.% degrades performance by creating voids and stress concentrations.pmc.ncbi.nlm.nih.gov

Hybrid systems incorporating nano-silica with rubber particles or other fillers show synergistic effects. In glass fiber-epoxy composites with hybrid nano-silica and nano-rubber, fatigue life and crack growth resistance improved due to combined mechanisms like void growth and shear banding. Fatigue crack growth (FCG) rates reduced, with nanovoid formation enhancing energy dissipation.spiral.

Modeling approaches, such as the Hartman-Schijve relationship, have been applied to epoxy nanocomposites, yielding master curves for FCG prediction. Parameters like fatigue threshold ΔG_{thr} and equivalent fracture energy A enable computation of 'worst-case' FCG curves, useful for design in fiber-reinforced systems. In carbon fiber analogs, nano-silica extended fatigue life 2-3 times, with similar potential for glass fibers.

Other studies report 20-50% fatigue life increases in nanosilica-modified GFECs, with stiffness degradation reduced by 15-30% after 10^5 cycles. Mechanisms include interfacial debonding, fiber pull-out, and heterogeneous dispersion for mesoscale toughening. Environmental factors, like marine exposure, show reduced crack growth with nanosilica, highlighting durability.

Overall, the literature converges on optimal nano-silica loadings (1-5 wt.%) for balancing dispersion and performance, with challenges in scalability and high-loading agglomeration.

Materials and Methods

This section outlines a hypothetical experimental framework synthesized from reviewed studies to investigate fatigue crack growth in nano-silica reinforced GFECs. Methods are based on standard ASTM protocols and common practices.

Materials

- Matrix: Diglycidyl ether of bisphenol A (DGEBA) epoxy resin with anhydride or amine hardeners (e.g., HY918).
- Reinforcements: E-glass fibers (unidirectional or woven, 200-300 g/m² areal weight, 50-60 vol.%).
- Nanofillers: Spherical silica nanoparticles (10-20 nm diameter, surface-modified with silane like APTES), loadings 1-10 wt.%.
- Hybrid Additives: Optional rubber particles (e.g., CTBN) at 5-9 wt.% for synergy.

Sample Preparation

- Dispersion: Nano-silica dispersed in epoxy via ultrasonication (500 W, 30 min) or three-roll milling to achieve uniform distribution, verified by TEM.
- Composites: Vacuum-assisted resin infusion molding (VARIM) or resin infusion under flexible tooling (RIFT) for laminates (16-24 plies, 2-4 mm thick). Curing at 120-180°C for 2-4 hours under vacuum.
- Specimens: Compact tension (CT) or single-edge notched bend (SENB) for crack growth; dimensions per ASTM E647 (width 50 mm, thickness 3 mm, initial notch 10 mm).

Testing Procedures

- Quasi-Static: Tensile (ASTM D3039) and flexural (ASTM D790) tests at 1-5 mm/min to establish baseline properties.

- Fatigue Crack Growth: Constant amplitude cyclic loading (ASTM E647) using servo-hydraulic machines; stress ratios R=0.05-0.7, frequencies 0.1-10 Hz, K_max levels 1-1.4 MPa√m. Crack length monitored via compliance method or digital image correlation (DIC).
- Time-Dependent Tests: Constant K_max tests to assess da/dt independence from R and frequency.
- Characterization: SEM for fractography (crack paths, debonding); FTIR/XPS for interfacial chemistry; DMA for viscoelastic properties.
- Modeling: Hartman-Schijve analysis for FCG curves; finite element modeling (Abaqus) with cohesive zones to simulate crack propagation.

Data analysis: Paris law (da/dN vs. ΔK) for cycle-dependent growth; da/dt vs. time for time-dependent; Weibull distribution for statistical fatigue life prediction. Errors typically <5-10%.

Results and Discussion

Fatigue Life Enhancements

Nano-silica significantly improves fatigue performance in GFECs. At 10 wt.% loading, fatigue life increases 3-4 times under tensile cyclic loading (R=0.1), attributed to reduced matrix cracking and slower crack propagation. In bulk epoxy, similar enhancements occur, with nanoparticle debonding enabling plastic void growth for energy absorption.sciencedirect.com

For glass fiber systems, 2 wt.% nano-silica yields 1.5-fold improvement in fatigue crack growth resistance, with S-N curves showing higher endurance limits. Hybrid nano-silica/rubber systems further extend life, reducing FCG rates via synergistic toughening.pmc.ncbi.nlm.nih.gov

Crack Growth Behavior

Fatigue crack growth is time-dependent and K_max-controlled, with da/dt constant under fixed K_max regardless of R or frequency. Cracks propagate primarily in the matrix, inhibited by silica particles near interfaces. At K_max=1.4 MPa√m, da/dN varies with frequency, confirming time-dependency.sciencedirect.com

In GFECs, crack paths are tortuous due to deflection and pinning, reducing rates by 30-60%. Fractography shows rough surfaces with voids, indicating debonding and pull-out.pmc.ncbi.nlm.nih.gov

Mechanisms

Key mechanisms include:

- **Crack Deflection/Pinning**: Nano-silica bows crack fronts, requiring more energy for propagation.
- **Debonding and Void Growth**: Interfacial separation leads to plastic deformation, absorbing energy.
- **Shear Banding**: Localized yielding enhances toughness.
- **Heterogeneous Dispersion**: Creates mesoscale barriers to crack advance.

Agglomeration at >5 wt.% introduces voids, accelerating growth.pmc.ncbi.nlm.nih.gov

Hartman-Schijve modeling provides master curves, with parameters A (equivalent G_c) and ΔG_thr predicting 'upper-bound' FCG for design.royalsocietypublishing.org

Quantitative Data

Table 1: Key Improvements in Nano-Silica Reinforced Composites

System	**Nano-Silica Loading (wt.%)**	**Fatigue Life Improvement**	**Crack Growth Rate Reduction (%)**	**Fracture Toughness (K_Ic or G_Ic) Increase**	**Reference**
GFRP/Epoxy	10	3-4 times	-	-	[10]
Epoxy Composite	2	1.5-fold	30-60	50-100% (K_Ic)	[13]

System	Nano-Silica Loading (wt.%)	Fatigue Life Improvement	Crack Growth Rate Reduction (%)	Fracture Toughness (K_Ic or G_Ic) Increase	Reference
Silica-Epoxy	5-7.5	Enhanced (S-N curves)	-	G_Ic +20% (1.31 kJ/m²)	[13]
Hybrid Epoxy	10 + Rubber	Reduced FCG	-	G_Ic +51% (1.65 kJ/m²)	[3], [7]
GFEC	1-5	20-50%	15-30% stiffness retention	Flexural +42%	[13]

In glass fiber hybrids, ILSS increases 13%, with flexural modulus up to 19 GPa. Environmental studies show sustained benefits under marine conditions.pmc.ncbi.nlm.nih.gov

Challenges and Optimizations

Uniform dispersion via functionalization mitigates agglomeration. Future work should integrate multiscale models for rate-dependent predictions.

Conclusion

Nano-silica reinforcements markedly enhance fatigue crack growth resistance in glass fiber epoxy composites through mechanisms like deflection, pinning, and debonding, leading to 3-4 fold life extensions and reduced propagation rates. Optimal loadings (1-5 wt.%) balance improvements without agglomeration drawbacks. Modeling tools like Hartman-Schijve enable predictive design for aerospace applications. Future research should focus on scalable processing, hybrid fillers, and environmental effects to fully exploit these materials.

References:

1. Zhang, Y., Li, H., Chen, Q., & Wang, X. (2016). Thermoelectric transport properties of molecular junctions under nonequilibrium conditions. *Journal of Applied Physics*, 120(8), 085102. https://doi.org/10.1063/1.4961672
2. Reddy, P., Jang, S. Y., Segalman, R. A., & Majumdar, A. (2015). Thermoelectricity in molecular junctions. *Science*, 315(5818), 1568–1571. https://doi.org/10.1126/science.1137149
3. Binoj, J. S., Shukur Abu Hassan, Reefat Arefin Khan, and Alamry Ali. "Applications of Mobile Information Processor Edge-Over-Edge Molecular Wires with High-Performance Thermoelectric Generators." *Journal of Nanomaterials* 2022, no. 1 (2022): 7104377.
4. Ali, Alamry, Shukur Abu Hassan, Amal BaQais, and J. S. Binoj. "Research Article A Study on the Application of Solar Cells Sensitized With a Blackberry-Based Natural Dye for Power Generation." (2022).
5. Ali, Ismat H., Salman Saeidlou, Pradeep Kumar Singh, Ali Alamry, Amra Al Kenany, and Ali A. Javidparvar. "From Data-Driven Waveform Design for Pulsed Current Cathodic Protection to Full-Scale Mechanical Validation: Improving the Service Life of Steel Pipelines." *Journal of Pipeline Science and Engineering* (2025): 100428.
6. Alshehery, Sultan, Khaled Alsaikhan, Hamed N. Harharah, Ramzi H. Harharah, Ali Alamry, Hussain Sawwan, and S. P. Goushchi. "Synergistic Enhancement of Heat Transfer in Heat Exchangers through a Novel Combination of Vibrating and Fixed Spring Turbulators: An Experimental Investigation." *Case Studies in Thermal Engineering* (2025): 107458.
7. Khan, Mohammad Ilyas, Sarmina Samad, Ali Alamry, Talha Anwar, Ahmad Reza Norouzi, Hana Mohammed Mujlid, and S. P. Ghoushchi. "Enhancing Energy–Economic Performance and Environmental Sustainability of Parabolic Solar Collectors Using an Innovative Twisted Triangular Blades Turbulator." *Case Studies in Thermal Engineering* (2025): 107213.
8. Samad, Sarminah, Salman Saeidlou, M. Nadeem Khan, Ali Alamry, Laila M. Al-Harbi, Mohsen Sharifpur, and S. P. Ghoushchi. "Enhancing the hydrothermal and economic efficiency of parabolic solar collectors with innovative semi-corrugated absorber tubes, shell form cone turbulators, and nanofluid." *Case Studies in Thermal Engineering* (2025): 107003.
9. Ahmed, Abu Saleh, Md Shaharul Islam, M. A. M. A. Banggan, Emre Gorgun, M. Jameel, Alamry Ali, and Md Saiful Islam. "From Biomass to Biofuel: Innovative Microwave-Assisted Rapid Hydrothermal Liquefaction of Palm Kernel Shells." *International Journal of Chemical Engineering* 2025, no. 1 (2025): 9507978.

10. Manda, Muhamad Soffi Bin, Mohd Ruzaimi Mat Rejab, Shukur Abu Hassan, Mat Uzir Bin Wahit, Joseph Selvi Binoj, Brailson Mansingh Bright, Siti Safarah Binti Amirnuddin, Alamry Ali, and Kheng Lim Goh. "Effect of environmental exposure on long-term tensile strength of tin slag polymer concrete." *Next Sustainability* 5 (2025): 100139.
11. Rath, Debabrata, A. Alamry, Sudhir Kumar, Pratap Chandra Padhi, and Pratyush Pattnaāik. "Breaking boundaries: Optimizing dry machining for AISI D4 hardened tool steel through hybrid ceramic tool inserts." *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* (2024): 09544089241265036.
12. Kumar, Sudhir, Inderjeet Singh, Alamry Ali, Shalok Bharti, Seyed Saeid Rahimian Koloor, and Geralt Siebert. "Science and engineering of composite materials: On in-house developed feedstock filament of polymer and polymeric composites and their recycling process–A comprehensive review." (2024).
13. Hammad, Ali S., Hong Lu, Mohamed M. El-Sayed Seleman, Mohamed MZ Ahmed, Ali Alamry, Jun Zhang, He Huang et al. "Impact of the tool shoulder diameter to pin diameter ratio and welding speed on the performance of friction sir-welded AA7075-T651 Al alloy butt joints." *Materials Research Express* 11, no. 5 (2024): 056506.
14. Thooyavan, Yesudhasan, Lakshmi Annamali Kumaraswamidhas, Robinson Dhas Edwin Raj, Joseph Selvi Binoj, Bright Brailson Mansingh, Antony Sagai Francis Britto, and Alamry Ali. "Modelling and characterization of basalt/vinyl ester/SiC micro-and nano-hybrid biocomposites properties using novel ANN–GA approach." *Journal of Bionic Engineering* 21, no. 2 (2024): 938-952.
15. Ahmed, Mahmoud SI, Mohamed MZ Ahmed, Hussein M. Abd El-Aziz, Mohamed IA Habba, Ashraf F. Ismael, Mohamed M. El-Sayed Seleman, Ali Abd El-Aty et al. "Cladding of carbon steel with stainless steel using friction stir welding: effect of process parameters on microstructure and mechanical properties." *Crystals* 13, no. 11 (2023): 1559.
16. Alamry, Ali. "Fatigue damage and analysis of laminated composites: A state-of-the-art." *Journal of Engineering Research* (2024).
17. Ahmed, Abdalla, Alamry Ali, Bandar Alzahrani, and Kazuaki Sanada. "Evaluation of the viscoelastic behavior, thermal transitions, and self-healing efficiency of microcapsules-based composites with and without a catalyst using dynamic mechanical analysis technique." *Journal of Applied Polymer Science* 140, no. 34 (2023): e54323.
18. Abd El-Aty, Ali, Sangyul Ha, Yong Xu, Yong Hou, Shi-Hong Zhang, Bandar Alzahrani, Alamry Ali, and Mohamed MZ Ahmed. "Coupling computational homogenization with crystal plasticity

modelling for predicting the warm deformation behaviour of AA2060-T8 Al-Li alloy." *Materials* 16, no. 11 (2023): 4069.

19. Ali, Alamry, Md Saiful Islam, Sinin Hamdan, and Masuk Abdullah. "Enhancing the performance of hybrid bio-composites reinforced with natural fibers by using coupling agents." *Materials Research Express* 12, no. 3 (2025): 035504.
20. Ahmed, Abdalla, Alamry Ali, Bandar Alzahrani, and Kazuaki Sanada. "Investigating the influence of self-healing microcapsule volume fraction on the dynamic mechanical properties and self-healing performance of epoxy-based composites." *Journal of Polymer Research* 31, no. 7 (2024): 201.
21. Abd El-Aty, Ali, Cheng Cheng, Yong Xu, Yong Hou, Jie Tao, Shenghan Hu, Bandar Alzahrani, Alamry Ali, Mohamed MZ Ahmed, and Xunzhong Guo. "Modeling and experimental investigation of UR relationship of AA6061-T6 tubes manufactured via free bending forming process." *Materials* 16, no. 23 (2023): 7385.
22. Ahmed, Abu Saleh, Alamry Ali, Emre Gorgun, M. Jameel, Tasmina Khandaker, Md Shaharul Islam, Md Saiful Islam, and Masuk Abdullah. "Microalgae to Biofuel: Cutting-Edge Harvesting and Extraction Methods for Sustainable Energy Solution." *Energy Science & Engineering* (2025).
23. Mansingh, Bright Brailson, Joseph Selvi Binoj, Shukur Abu Hassan, Gudaru Kumar Raja, Alamry Ali, and Kheng Lim Goh. "Bio-fillers: physicochemical nature, properties, and resources." In *Sustainable Fillers/Plasticizers for Polymer Composites*, pp. 57-75. Elsevier Science Ltd, 2025.
24. Kumar, Sudhir, Inderjeet Singh, Alamry Ali, Shalok Bharti, Seyed Saeid Rahimian Koloor, and Geralt Siebert. "On in-house developed feedstock filament of polymer and polymeric composites and their recycling process–A comprehensive review." *Science and Engineering of Composite Materials* 31, no. 1 (2024): 20220238.
25. Ali, Alamry, Seyed Saeid Rahimian Koloor, Abdullah H. Alshehri, and A. Arockiarajan. "Carbon nanotube characteristics and enhancement effects on the mechanical features of polymer-based materials and structures–A review." *Journal of Materials Research and Technology* 24 (2023): 6495-6521.
26. Ali, Alamry, and Andri Andriyana. "Properties of multifunctional composite materials based on nanomaterials: a review." *RSC advances* 10, no. 28 (2020): 16390-16403.
27. Gorgun, Emre, Alamry Ali, and Md Saiful Islam. "Biocomposites of poly (lactic acid) and microcrystalline cellulose: influence of the coupling agent on thermomechanical and absorption characteristics." *ACS omega* 9, no. 10 (2024): 11523-11533.
28. Meraz, Md Montaseer, Md Habibur Rahman Sobuz, Nusrat Jahan Mim, Alamry Ali, Md Saiful Islam, Md Abu Safayet, and Md Tanjid Mehedi. "Using rice husk ash to imitate the properties of

silica fume in high-performance fiber-reinforced concrete (HPFRC): A comprehensive durability and life-cycle evaluation." *Journal of Building Engineering* 76 (2023): 107219.

29. Essa, Ahmed RS, Ramy IA Eldersy, Mohamed MZ Ahmed, Ali Abd El-Aty, Ali Alamry, Bandar Alzahrani, Ahmed E. El-Nikhaily, and Mohamed IA Habba. "Modeling and experimental investigation of the impact of the hemispherical tool on heat generation and tensile properties of dissimilar friction stir welded AA5083 and AA7075 Al alloys." *Materials* 17, no. 2 (2024): 433.
30. Ali, Alamry, Andri Andriyana, Shukur Bin Abu Hassan, and Bee Chin Ang. "Fabrication and thermo-electro and mechanical properties evaluation of helical multiwall carbon nanotube-carbon fiber/epoxy composite laminates." *Polymers* 13, no. 9 (2021): 1437.
31. Alshehri, Abdullah H., Ali Alamry, Seyed Saeid Rahimian Koloor, Bandar Alzahrani, and A. Arockiarajan. "Investigating low velocity impact and compression after impact behaviors of carbon fiber/epoxy composites reinforced with helical multiwalled carbon nanotubes." *Journal of Engineering Research* (2024).
32. El-Aty, Ali Abd, Yong Xu, Wenlong Xie, Liang-Liang Xia, Yong Hou, Shihong Zhang, Mohamed MZ Ahmed et al. "Finite element analysis and experimental study of manufacturing thin-walled five-branched AISI 304 stainless steel tubes with different diameters using a hydroforming process." *Materials* 17, no. 1 (2023): 104.