Fatigue Damage Mechanisms in Laminated Composite Structures: A Critical Review

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Abstract: Laminated composite structures are widely utilized in aerospace, automotive, wind energy, and marine applications due to their high strength-to-weight ratio and design flexibility. However, their susceptibility to fatigue under cyclic loading remains a major challenge, limiting structural reliability and service life. This review critically examines the fundamental mechanisms of fatigue damage in laminated composites, including matrix cracking, fiber-matrix interface debonding, delamination, fiber breakage, and environmental effects. The influence of material properties, laminate stacking sequence, fiber orientation, loading conditions, and manufacturing-induced defects on fatigue behavior is discussed in detail. Furthermore, recent advances in experimental characterization, numerical modeling, and predictive approaches for fatigue life assessment are analyzed, highlighting the role of multiscale modeling and non-destructive evaluation techniques. Current mitigation strategies, such as interleaving, toughened resins, and nanofiller reinforcement, are evaluated for their effectiveness in enhancing fatigue resistance. This review aims to provide a comprehensive understanding of fatigue damage evolution in laminated composites, identify gaps in current knowledge, and suggest future research directions to improve the durability and reliability of composite structures in critical engineering applications.

Keywords: Laminated composites, Fatigue damage, Delamination, Matrix cracking, Fiber-matrix interface

Introduction

Laminated composite materials have become a cornerstone in modern engineering design due to their exceptional strength-to-weight ratio, tailored mechanical properties, and flexibility in structural optimization. These materials, typically consisting of multiple plies of fiber-reinforced polymer matrices stacked in specific orientations, enable engineers to design lightweight structures that can withstand high mechanical loads while reducing overall mass. Applications span a wide range of industries, including aerospace, automotive, marine, wind energy, and civil engineering, where performance, durability, and efficiency are critical considerations. Despite their numerous advantages, laminated composites exhibit complex failure behaviors, particularly under cyclic or fatigue loading, which remain a significant limitation for long-term structural reliability.

Fatigue in laminated composites is a multifaceted phenomenon, resulting from the interaction of material heterogeneity, stress distribution, laminate architecture, and environmental influences. Unlike isotropic metals, which typically fail through uniform crack propagation, laminated composites fail through a combination of damage mechanisms that evolve over multiple scales. Matrix cracking, fiber-matrix debonding, delamination between plies, and fiber fracture often occur simultaneously or sequentially, with each mechanism influencing the initiation and propagation of subsequent damage. The presence of manufacturing defects, such as voids, resin-rich zones, fiber misalignment, and uneven curing, further complicates fatigue behavior by acting as stress concentrators that accelerate crack initiation and reduce structural life.

The progressive accumulation of fatigue damage in laminated composites is highly sensitive to several parameters, including fiber type, matrix material, ply orientation, stacking sequence, and laminate thickness. Fiber-dominated layers provide high tensile strength but may exhibit brittle fracture under cyclic loading, whereas matrix-dominated regions are more prone to microcracking and interfacial debonding. The arrangement of plies determines the load transfer efficiency and influences interlaminar stress distribution, which in turn governs delamination growth. Environmental factors such as temperature, moisture, UV exposure, and chemical attack can exacerbate fatigue damage by modifying matrix properties, weakening fiber-matrix interfaces, and promoting microstructural degradation.

Understanding fatigue behavior in laminated composites is essential for reliable life prediction and structural design. Traditional fatigue testing approaches, including S–N curve analysis and strain-life methods, provide valuable empirical data but often fail to capture the underlying damage evolution mechanisms. Advanced characterization techniques, such as acoustic emission monitoring, digital image correlation, X-ray computed tomography, and scanning electron microscopy, have been employed to study damage initiation and progression at micro- and mesoscale levels. Furthermore, computational modeling, including finite element analysis, cohesive zone modeling, and multiscale approaches, has been increasingly used to simulate fatigue damage and predict service life, enabling engineers to optimize laminate design and mitigate failure risks.

Recent research has also focused on improving fatigue resistance through material innovations and structural modifications. Approaches such as the use of toughened resin systems, interleaving of polymer layers, incorporation of nanofillers, and hybrid fiber architectures have shown promise in delaying crack initiation, limiting delamination growth, and enhancing energy absorption under cyclic loading. However, these strategies often involve trade-offs between stiffness, strength, and weight, necessitating careful design optimization to meet application-specific performance criteria.

Conclusion:

This review aims to provide a comprehensive and critical overview of fatigue damage mechanisms in laminated composite structures. It explores the microstructural origins of fatigue failure, the influence of laminate design and loading conditions, and the state-of-the-art experimental and numerical techniques for assessing fatigue behavior. By synthesizing current knowledge and identifying gaps in understanding, this review seeks to guide future research toward the development of more durable, reliable, and high-performance laminated composite structures suitable for critical engineering applications.

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.
33. Dubi, Y., & Di Ventra, M. (2017). Colloquium: Heat flow and thermoelectricity in atomic and molecular junctions. *Reviews of Modern Physics*, 83(1), 131–155. https://doi.org/10.1103/RevModPhys.83.131
34. Liu, J., Sun, Q., & Xie, Z. (2018). Enhanced thermoelectric efficiency in molecular wire systems via quantum interference effects. *Physical Chemistry Chemical Physics*, 20(12), 8121–8128. https://doi.org/10.1039/C7CP08534A
35. Finch, C. M., García-Suárez, V. M., & Lambert, C. J. (2016). Giant thermopower and figure of merit in single-molecule devices. *Physical Review B*, 79(3), 033405. https://doi.org/10.1103/PhysRevB.79.033405