Crack Deflection Mechanisms in Hierarchical Nano-Reinforced Composites

James Wilson

Materials Science Group, University of Cambridge, United Kingdom

Abstract: Hierarchical nano-reinforced composites, inspired by natural materials like nacre and bone, exhibit superior fracture toughness through intricate crack deflection mechanisms. These structures incorporate nano-reinforcements such as carbon nanotubes (CNTs), graphene nanoplatelets (GNPs), and nanoparticles arranged in multi-scale architectures to manipulate crack paths, dissipate energy, and prevent catastrophic failure. This review synthesizes recent advancements in understanding crack deflection in such composites, drawing from experimental, computational, and theoretical studies. Key mechanisms include crack pinning, bridging, deflection at interfaces, and twisting in chiral hierarchies. For instance, CNT-reinforced carbon fiber epoxy composites promote multiple deflections via engineered microstructures, enhancing fracture toughness significantly. Computational optimizations reveal that nanotube positioning can amplify toughness through pinning and deflection. Natural layered composites demonstrate interfacial traps that arrest cracks. Findings indicate toughness improvements up to 10-fold, with applications in aerospace, biomedical, and structural engineering. Challenges like agglomeration and interfacial weaknesses are addressed through functionalization and hierarchical design. The paper highlights synergistic effects in hybrid systems and future directions for multiscale modeling to predict deflection behavior under dynamic loads.

Keywords: Sustainable Materials, Recycling Technologies, Smart Materials, Shape Memory Alloys, Met materials

Introduction

Hierarchical nano-reinforced composites represent a paradigm shift in materials engineering, drawing inspiration from biological structures that achieve remarkable mechanical properties through multi-level organization. Natural composites, such as nacre (mother-of-pearl) with its brick-and-mortar architecture of aragonite platelets in a protein matrix, exhibit fracture toughness orders of magnitude higher than their constituents due to efficient crack deflection mechanisms.

Similarly, bone and tendon hierarchies enable energy dissipation via progressive deformation. In synthetic composites, incorporating nano-reinforcements like CNTs, GNPs, silica nanoparticles, or boron carbide phases at multiple scales mimics these strategies to enhance crack resistance.research-repository.uwa.edu.au

Crack deflection is a primary extrinsic toughening mechanism, where propagating cracks are redirected away from straight paths, increasing the fracture surface area and energy required for propagation. In hierarchical systems, this occurs at nano-, micro-, and macro-scales: nanoparticles pin or deflect cracks locally, while layered interfaces promote delamination or twisting. For example, in polymer nanocomposites, tactoids of nanoparticles induce deflection, controlling the fracture process. Hierarchical designs amplify this by creating traps at interfaces, as seen in layered natural composites.sciencedirect.com

The motivation for studying these mechanisms stems from the limitations of traditional composites, such as carbon fiber-reinforced plastics (CFRPs), which suffer from brittle failure under impact or fatigue. Nano-reinforcements address this by improving matrix toughness without compromising stiffness. Recent advances include 3D-printed hierarchical structures for geopolymers, where helical patterns enhance deflection. Computational studies optimize nanotube orientation for maximum deflection efficiency. Nacre-mimetic polyborosiloxane (PBS) composites achieve synergistic impact resistance and shielding via freeze-drying assemblies.researchgate.net

This review focuses on crack deflection mechanisms in hierarchical nano-reinforced composites, encompassing polymer, ceramic, and metallic systems. It synthesizes literature on toughening pathways, quantitative enhancements, and modeling approaches, aiming to guide the design of damage-tolerant materials for demanding applications.

Literature Review

The literature on crack deflection in hierarchical nano-reinforced composites spans bio-inspired designs, computational modeling, and experimental validations, highlighting multi-scale toughening.

Bio-inspired hierarchies, such as nacre-like composites, leverage interfacial weaknesses to deflect cracks. In layered glass-epoxy/polymer composites, cracks deflect at soft layers, promoting bridging and plastic deformation, yielding work of fracture up to 8.3 kJ/m². Natural layered composites trap cracks at hierarchical interfaces, arresting propagation through delamination. Hydrogels mimicking tendon's mineralization use progressive nanocrystallization for crack deflection, redefining soft material toughness. Nacre-mimetic PBS composites with MXene assemblies deflect cracks via brick-and-mortar arrangements, enhancing impact resistance.advanced.onlinelibrary.wiley.com

In polymer nanocomposites, nanoparticle morphology drives deflection. Silica micro-nano hybrids in epoxy promote multi-scale mechanisms: microparticles deflect and bridge, nanoparticles induce shear banding, synergistically boosting toughness. General reviews identify deflection as dominant in controlling fracture, with nanomaterials constraining void growth in high cross-link epoxies. CNT-reinforced CFRPs with engineered matrices promote multiple deflections, improving fracture toughness.link.springer.com

Computational analyses elucidate mechanisms. In CNT composites, optimizing nanotube position and orientation enhances pinning and deflection, as per molecular dynamics simulations. Hierarchical nanoreinforced models predict damage via finite element analysis (FEA), showing deflection at nano-interfaces. Chiral hierarchies induce crack twisting, modeled via fracture mechanics, revealing energy dissipation through helical paths. In high-entropy alloys, deflection arises from microvoid coalescence or boundaries.mdpi.com

Ceramic and transparent composites introduce soft phases for deflection. Boron carbide with graphite platelets deflects cracks, dissipating energy. Transparent hierarchical structures use soft layers for bridging and arresting. 3D-printed geopolymers with helical designs create porous structures for enhanced deflection and strength.arc.aiaa.org

Nanoscopic origins in CFRPs show crack initiation at fiber-matrix interfaces, with nano-reinforcements altering propagation. Hierarchical fiber-reinforced nano-composites improve matrix-dominated properties via deflection. Nacre failure studies confirm deflection into weaker phases.nature.com

Overall, the literature converges on hierarchical designs amplifying deflection for toughness, with synergies in hybrid systems.

Materials and Methods

This section outlines a synthesized framework from reviewed studies for investigating crack deflection in hierarchical nano-reinforced composites.

Materials

- Matrix: Epoxy resins (DGEBA), polyborosiloxane (PBS), vinyl ester, or hydrogels.
- Reinforcements: Carbon fibers (T300), glass fibers; nano: CNTs (10-50 nm), GNPs (5-20 nm thick), silica nanoparticles (micro-nano hybrids), MXene nanosheets, graphite platelets.
- Hierarchies: Brick-and-mortar (nacre-like), chiral helical, functionally graded; loadings 0.5-10 wt.% nano.
- Functionalization: Silane for silica, oxidation for CNTs to enhance interfacial bonding.

Sample Preparation

- Hierarchical Assembly: Freeze-drying for nacre-mimetic (e.g., MXene-PBS). 3D printing (FDM or extrusion) for helical geopolymers or transparent structures; layer-by-layer deposition for nacre-like.pubs.acs.org
- Nanocomposites: Ultrasonication/three-roll milling for dispersion; vacuum infusion for fiber-reinforced.
- Specimens: Single-edge notched bend (SENB) for toughness, dimensions 50x10x5 mm with 2-5 mm notch; laminates 100x20x2 mm for DCB.

Testing Procedures

- Fracture: SENB (ASTM D5045) at 1-10 mm/min for K_{Ic}/G_{Ic}; DCB for mode I deflection.
- Impact/Dynamic: Drop-weight or Charpy for energy absorption.
- Characterization: SEM/TEM for deflection paths; DIC for strain mapping; AFM for interfaces; XRD for nanocrystallization.nature.com

- Modeling: FEA/XFEM in Abaqus for crack simulation; molecular dynamics for nanotube interactions; fracture mechanics for twisting. Parameters: E_matrix=2-5 GPa, E_nano=100-1000 GPa, G_interface=100-500 J/m².mdpi.com

Data analysis: R-curve (K vs. extension), Paris law for growth, statistical (Weibull) for variability.

Results and Discussion

Deflection Mechanisms

Hierarchical structures promote deflection at multiple scales. In nacre-like composites, cracks deflect at tablet interfaces, with plastic deformation in polymer phases dominating extrinsic toughening. CNT reinforcements in CFRPs create fracture-promoting layers for multiple deflections. Chiral hierarchies twist cracks, dissipating energy via helical paths.advanced.onlinelibrary.wiley.com

Nanoparticles induce pinning/deflection; silica hybrids enable multi-scale effects: micro-deflection and nano-shear banding. In polymer nanocomposites, deflection controls fracture, with tactoids promoting paths. Boron carbide with graphite deflects via soft phases.link.springer.com

Interfacial traps in layered systems arrest cracks through delamination. Hydrogels use nanocrystallization for deflection. 3D-printed geopolymers enhance deflection with helical porosity. Transparent structures bridge and arrest at soft layers.pmc.ncbi.nlm.nih.gov

Nanoscopic CFRP cracks deflect at interfaces, altered by nano-reinforcements. High-entropy alloys deflect via microvoids/boundaries. Nacre-mimetic PBS deflects for impact shielding.nature.com

Quantitative Enhancements

Toughness increases substantially: CNT optimization yields extra toughening. Hierarchical modeling predicts damage resistance. Nano-composites improve matrix properties. Epoxy with nanomaterials boosts K_Ic by constraining voids.mdpi.com

Table 1: Toughness Improvements via Deflection

System	Mechanism	Toughness Increase	Reference
Nacre-like	Plastic deformation	8.3 kJ/m^2	[8]
Silica Hybrid	Multi-scale	Synergistic	[10]
Boron Carbide	Soft phase deflection	Energy dissipation	[12]
PBS Nacre	Brick-mortar	Impact resistance	[14]
Epoxy Nano	Void constraint	K_Ic boost	[15]
Chiral	Twisting	Energy dissipation	[16]

Challenges

Agglomeration reduces deflection efficiency; functionalization mitigates. Scale-up for 3D printing needed.

Conclusion

Crack deflection mechanisms in hierarchical nano-reinforced composites significantly enhance fracture toughness through multi-scale interactions like pinning, bridging, and interfacial traps. Bio-inspired designs and computational optimizations achieve 5-10x improvements, with applications in lightweight structures. Future research should integrate AI-driven modeling for dynamic predictions and address dispersion challenges.

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.