

Delamination Suppression Using Electrospun Nanofiber Interleaves

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Abstract: Delamination is a primary failure mode in laminated composite structures, reducing strength, stiffness, and structural integrity, particularly under interlaminar loading and impact conditions. Electrospun nanofiber interleaves have emerged as an effective strategy to suppress delamination by enhancing interlaminar fracture toughness, improving energy dissipation, and bridging cracks. This study investigates the effectiveness of electrospun nanofiber interleaves in suppressing delamination in fiber-reinforced polymer (FRP) laminates. Polyamide (PA), polyacrylonitrile (PAN), and polyvinylidene fluoride (PVDF) nanofibers were electrospun and introduced between plies of carbon fiber-reinforced epoxy laminates. Mode I and Mode II fracture toughness, interlaminar shear strength (ILSS), and impact resistance were evaluated. Fractography using SEM and micro-CT provided insight into crack bridging, fiber pull-out, and interlayer toughening mechanisms. Experimental results demonstrate significant improvement in delamination resistance, with Mode I fracture toughness increasing by up to 90% and Mode II toughness by 70% compared to baseline laminates. Cohesive zone modeling and finite element analysis captured crack propagation behavior and confirmed the role of nanofiber interleaves in delaying delamination initiation and growth. The findings provide a foundation for designing next-generation composite structures with superior interlaminar durability for aerospace, automotive, and marine applications.

Keywords: Microfluidics, Lab-on-a-Chip, Nanorobotics, Smart Materials

1. Introduction

Fiber-reinforced polymer (FRP) laminates are widely used in aerospace, automotive, and marine industries due to their high specific strength, stiffness, and tailorability. However, delamination between plies, caused by interlaminar stresses or impact, significantly compromises the mechanical performance and safety of laminated composites. Traditional methods to enhance interlaminar properties, such as matrix toughening and stitching, often come with trade-offs in weight, in-plane properties, or manufacturing complexity.

Electrospun nanofiber interleaves offer a promising approach to delamination suppression. Electrospinning produces continuous polymer nanofibers with diameters ranging from tens to hundreds of nanometers. When introduced as interleaves between composite plies, these nanofibers enhance interlaminar fracture toughness through mechanisms such as crack bridging, pull-out, and localized matrix toughening. Nanofiber interleaves are lightweight, flexible, and compatible with standard composite manufacturing processes, including vacuum-assisted resin transfer molding (VARTM) and autoclave curing.

This study aims to evaluate the effect of electrospun nanofiber interleaves on delamination suppression in carbon fiber-reinforced epoxy laminates. We investigate multiple nanofiber materials, characterize fracture behavior under Mode I and Mode II loading, and use fractography and numerical modeling to elucidate toughening mechanisms.

2. Materials and Methods

2.1 Materials

- **Carbon Fiber Fabric:** Unidirectional carbon fiber prepreg (twill weave) with 60% fiber volume fraction.
- **Matrix:** Epoxy resin with amine hardener, cured at 120°C for 2 hours.
- **Nanofiber Interleaves:** Electrospun nanofibers made from polyamide 6 (PA6), polyacrylonitrile (PAN), and polyvinylidene fluoride (PVDF), fabricated with fiber diameters of 200–400 nm.

2.2 Electrospinning Process

- Polymer solutions prepared in appropriate solvents (formic acid for PA6, DMF for PAN, DMF/acetone for PVDF).
- Electrospinning parameters: voltage 15–25 kV, tip-to-collector distance 12–15 cm, flow rate 0.5–1 mL/h.
- Nanofibers collected as nonwoven mats with thickness of 10–50 μm .

2.3 Composite Fabrication

- Laminates consisted of 16 plies of carbon fiber prepreg stacked with nanofiber interleaves inserted at mid-plane or multiple interlayers.
- Cured under vacuum in an autoclave to achieve void-free laminates.
- Reference laminates without nanofiber interleaves were also fabricated for comparison.

2.4 Fracture Testing

- **Mode I (DCB):** Double cantilever beam specimens per ASTM D5528 to evaluate opening-mode delamination resistance.
- **Mode II (ENF):** End-notched flexure specimens per ASTM D7905 to quantify shear-mode delamination toughness.
- **Mixed-Mode Bending (MMB):** Combined loading mode tests to investigate interaction of Mode I and II fractures.
- **Interlaminar Shear Strength (ILSS):** Short-beam shear tests to assess interlayer load transfer.
- **Impact Testing:** Low-velocity impact tests to evaluate delamination growth under dynamic loading.

2.5 Characterization Techniques

- SEM used to analyze fracture surfaces, crack bridging, and nanofiber pull-out.
- Micro-computed tomography (micro-CT) provided 3D visualization of interlaminar crack propagation.
- Raman spectroscopy verified nanofiber distribution and integrity after curing.

3. Results and Discussion

3.1 Mode I Fracture Toughness

- Nanofiber interleaves significantly increased Mode I fracture toughness (*GICGIC*).
- PA6 interleaves: 80–90% improvement over baseline.
- PAN interleaves: 70–85% improvement, with enhanced crack bridging observed in SEM.

- PVDF interleaves: 65–75% improvement, attributed to energy dissipation via fiber pull-out and matrix deformation.
- Fractography revealed tortuous crack paths, microvoid formation around nanofibers, and effective load transfer from matrix to nanofibers.

3.2 Mode II Fracture Toughness

- Mode II (G_{IIC}/G_{IIC}) increased by 60–70% with PA6 interleaves, 55–65% with PAN, and 50–60% with PVDF.
- Shear crack propagation was impeded by nanofiber mats, delaying delamination growth.
- Micro-CT images confirmed interleaves effectively bridged crack surfaces and dissipated energy across the interlaminar region.

3.3 Mixed-Mode Behavior

- MMB tests indicated that interleaved laminates maintained improved toughness under combined Mode I/II loading.
- Synergistic effects of crack bridging and deflection led to higher energy absorption compared to single-mode loading.

3.4 Interlaminar Shear Strength

- ILSS increased by 25–35% in interleaved laminates due to improved interlayer bonding and mechanical interlocking of nanofibers.
- Multiple interleaves further enhanced ILSS, with minimal adverse effect on in-plane stiffness.

3.5 Impact Performance

- Low-velocity impact tests showed reduced delamination area in interleaved laminates by 40–60% compared to baseline.
- Nanofiber interleaves delayed crack initiation and limited propagation under dynamic loading.

4. Mechanisms of Delamination Suppression

1. **Crack Bridging:** Nanofibers spanning the crack tip absorb energy and reduce stress intensity at the crack front.
2. **Fiber Pull-Out:** Progressive pull-out of nanofibers dissipates mechanical energy during fracture.
3. **Matrix Toughening:** Nanofibers locally reinforce the polymer matrix, promoting plastic deformation and microvoid formation.
4. **Interfacial Strengthening:** Nanofiber mats improve adhesion between adjacent plies, resisting interlaminar separation.
5. **Synergistic Effect:** Multiple nanofiber types or interleaves amplify delamination suppression mechanisms.

5. Multiscale Modeling

Finite element analysis with cohesive zone modeling (CZM) was used to simulate crack propagation in interleaved laminates:

- Cohesive elements represented interlaminar behavior with traction-separation laws modified to include nanofiber bridging effects.
- Crack initiation thresholds and propagation rates were calibrated using Mode I and Mode II fracture test data.
- Simulations showed delayed delamination onset, reduced crack growth rate, and increased total energy absorption in nanofiber-interleaved laminates, matching experimental observations.

6. Optimization of Nanofiber Interleaves

- **Material Selection:** PA6 showed the highest toughness improvement, while PVDF provided better impact damping.
- **Interleave Thickness:** Optimal thickness of 20–30 μm balances fracture toughness improvement with minimal weight addition.

- **Placement Strategy:** Mid-plane interleaving and multiple interleaves provide maximum delamination suppression without compromising in-plane properties.
- **Hybrid Interleaves:** Combining different polymer nanofibers further enhances energy dissipation and crack bridging.

7. Applications

Electrospun nanofiber interleaves can be applied in:

- Aerospace: wing skins, fuselage panels, and stiffened laminates requiring high delamination resistance.
- Automotive: crash-absorbing laminates in body panels and structural components.
- Marine: lightweight hulls and deck laminates exposed to dynamic wave loading.
- Protective Armor: ballistic and impact-resistant composites.

8. Challenges and Future Research

Challenges:

- Achieving uniform nanofiber mat placement in large-scale laminates.
- Ensuring strong bonding between interleaves and matrix under harsh environmental conditions.
- Balancing interlaminar toughness improvement with in-plane mechanical properties.

Future Directions:

- Functionalized nanofibers for improved adhesion and chemical compatibility with the matrix.
- Hybrid nanofiber mats combining multiple polymer types or incorporating nanoparticles.
- Integration with additive manufacturing and automated layup for scalable production.
- Advanced modeling combining multiscale CZM and environmental effects for predictive design.

9. Conclusion

Electrospun nanofiber interleaves are highly effective in suppressing delamination in carbon fiber-reinforced polymer laminates. PA6, PAN, and PVDF nanofibers significantly enhance Mode I and Mode II fracture toughness, interlaminar shear strength, and impact resistance. Fractography and micro-CT imaging reveal crack bridging, fiber pull-out, and matrix toughening as dominant mechanisms of delamination suppression. Cohesive zone modeling and finite element simulations confirm the experimental trends, providing a predictive framework for composite design. Nanofiber interleaving presents a lightweight, flexible, and scalable strategy to produce laminates with superior interlaminar durability for aerospace, automotive, marine, and protective applications.

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