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Modeling of Hybrid Composite Failure

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Abstract

Hybrid fiber-reinforced polymer composites combine two or more reinforcement systems to obtain combinations of stiffness, strength, failure strain, toughness, weight, and cost that cannot be achieved readily with a single reinforcement. Their failure prediction remains challenging because local constituent damage, fiber-strength variability, matrix nonlinearity, interface degradation, ply cracking, delamination, and laminate-level stress redistribution interact across several characteristic length scales. This study develops a simulation-based framework for multiscale modeling of progressive failure in carbon/glass hybrid polymer composites. The proposed architecture connects constituent-scale representative volume elements with ply-scale constitutive damage and laminate-scale finite-element analysis. Matrix plasticity and cracking, carbon- and glass-fiber damage, fiber–matrix interface degradation, intralaminar ply failure, and interlaminar delamination are represented through separate but coupled state variables. Homogenized stress and strain fields provide scale transfer from microscale to mesoscale, while degraded ply properties and cohesive-interface behavior determine structural response at the laminate scale. A comparative simulation indicates that increasingly resolved modeling strategies reduce illustrative failure-load error from 14.8% for a conventional single-scale criterion to 3.8% for an adaptive two-way multiscale framework, although normalized computational cost increases by more than an order of magnitude.

Simulated damage evolution shows early matrix deterioration, followed by interface and delamination growth, accelerated low-elongation carbon-fiber failure, and delayed high-elongation glass-fiber damage. The framework also demonstrates that hybrid effects cannot be predicted from constituent rule-of-mixtures properties alone because fiber-strength scatter, local stress concentrations, dispersion, stacking sequence, ply thickness, and load redistribution influence progressive failure. The study concludes that multiscale modeling offers its greatest value when scale refinement is applied selectively to critical zones rather than uniformly throughout an entire structure. Experimental qualification should combine mechanical testing with full-field strain measurement, acoustic emission, fracture inspection, and microstructural characterization to validate not only ultimate failure loads but also the predicted sequence and location of damage mechanisms.

Keywords: hybrid composites, multiscale modeling, progressive failure, carbon/glass composites, representative volume element, continuum damage mechanics, delamination, finite-element analysis

1. Introduction

Hybrid fiber-reinforced polymer composites combine reinforcement types possessing different mechanical characteristics within a common matrix. Carbon/glass systems are among the most widely studied because carbon fibers provide high stiffness and relatively high strength while glass fibers generally provide greater failure strain at lower material cost. Hybridization can therefore produce a more favorable balance between stiffness, deformation capacity, damage tolerance, and economic performance than either reinforcement used alone. The mechanical response is not governed by a simple weighted average, however. Reviews of fiber hybridization show that dispersion, relative fiber proportions, stacking architecture, residual stresses, statistical fiber strength, and progressive load redistribution can generate a measurable hybrid effect, including an apparent increase in the failure strain of the lower-elongation constituent.

Failure prediction becomes difficult because damage is generated simultaneously at several physical scales. At the constituent scale, cracks may initiate in the polymer matrix, individual fibers can fracture, and local fiber–matrix interfaces may debond. At the ply scale, these localized events evolve into transverse cracking, shear degradation, fiber-dominated failure, and stiffness reduction. At the laminate scale, stress redistribution among dissimilar plies and interlaminar stresses can initiate delamination before structural collapse. Classical homogenized failure criteria remain computationally efficient but cannot explicitly resolve every constituent-level interaction. Hashin-type criteria distinguish important fiber and matrix failure modes, while physically based criteria and continuum damage approaches improve the representation of mode-dependent failure and post-initiation stiffness degradation.

Multiscale modeling addresses this limitation by linking information across characteristic lengths rather than forcing one constitutive description to represent every physical mechanism. Fish and Yu developed a multiscale damage framework relating micro-, meso-, and macroscopic fields, whereas established micromechanical homogenization concepts such as the Mori–Tanaka formulation provide a basis for transferring constituent information into effective continuum properties. In composite failure analysis, these methods can be combined with representative volume elements, continuum damage models, cohesive interfaces, and structural finite elements. The principal advantage is that changes in local constituent behavior can influence structural predictions through scale bridging instead of being represented only through empirically adjusted laminate properties.

Hybrid composites create an especially compelling application for such modeling because two reinforcement populations introduce additional load-transfer and statistical interactions. Swolfs and colleagues demonstrated that local stress concentrations surrounding broken fibers, fiber-strength scatter, and load sharing contribute materially to the tensile hybrid effect. Experimental and numerical investigations of carbon/glass laminates further show that stacking sequence can alter fracture progression and that multiple mechanisms—including matrix cracking, interface failure, pullout, and fiber breakage—may occur before final collapse. More recent validated multiscale work has connected repeating-unit-cell micromechanics, matrix nonlinearity, progressive ply damage, and three-dimensional laminate analysis for glass/carbon systems.

The present study develops a simulation-based framework for multiscale modeling of hybrid composite failure. It does not present newly measured tensile, bending, acoustic-emission, digital-image-correlation, or microscopy data. Instead, a transparent numerical architecture is formulated in which constituent behavior, homogenized ply damage, cohesive delamination, and laminate response are connected hierarchically. The study evaluates the trade-off between computational fidelity and cost, illustrates the sequence of progressive damage in a hypothetical carbon/glass hybrid laminate, and identifies the variables that require experimental calibration before structural use. The central premise is that multiscale analysis should not be judged simply by whether it predicts the final failure load; a defensible model should also reproduce the physically plausible order, interaction, and spatial development of the damage mechanisms leading to that failure.

2. Objectives of the Study

2.1 Development of a Hierarchical Failure-Modeling Architecture

The first objective is to establish a numerical architecture linking constituent, ply, and laminate scales. At the microscale, carbon fibers, glass fibers, polymer matrix, and fiber–matrix interfaces are represented explicitly or statistically within representative volume elements. Their responses are homogenized into effective ply properties while retaining information concerning local stress amplification and constituent damage.

At the mesoscale, separate internal variables describe fiber-direction failure, transverse matrix damage, shear degradation, and interface-related deterioration. At the macroscale, laminated structural elements transfer loads among plies while cohesive interfaces represent delamination. The purpose of the hierarchy is to prevent structural failure from being represented as an instantaneous transition from an intact laminate to a deleted finite element.

2.2 Quantification of Hybridization Effects on Progressive Failure

The second objective is to examine how low-elongation and high-elongation reinforcement interact during failure. Carbon/glass hybridization can redistribute load after individual carbon-fiber failures and can alter the stress environment experienced by neighboring fibers. Global and local load-sharing models have demonstrated that carbon-fiber strength scatter can materially influence apparent hybrid failure strain.

The analysis therefore considers fiber ratio, spatial dispersion, ply thickness, stacking sequence, constituent stiffness mismatch, and fiber-strength variability as damage-evolution variables rather than merely inputs to a rule-of-mixtures stiffness calculation.

2.3 Evaluation of Accuracy–Cost Trade-Offs in Multiscale Simulation

The third objective is to evaluate the additional predictive information obtained when increasingly sophisticated scale coupling is introduced. A highly resolved representative-volume-element model at every finite element integration point could become computationally prohibitive for structural analysis.

The study therefore compares conventional single-scale failure analysis, continuum-damage ply modeling, sequential multiscale analysis, and adaptive two-way coupling. The goal is to identify a modeling strategy in which expensive microscale resolution is concentrated in mechanically critical regions rather than applied uniformly.

3. Review of Literature

3.1 Micromechanics and Scale Bridging in Composite Materials

Micromechanical analysis seeks to relate the properties and fields of heterogeneous constituents to an equivalent continuum response. The Mori–Tanaka approach remains a foundational analytical homogenization method for inclusion-containing media and provides a basis for estimating average matrix and inclusion stresses under prescribed loading. For fiber composites, representative volume elements provide a more geometrically explicit route in which fibers and matrix are modeled separately under boundary conditions designed to reproduce the behavior of a repeating or statistically representative microstructure.

A challenge arises when localized cracking destroys the assumptions underlying periodic homogenization. Once damage concentrates into a discrete macrocrack, the exact microstructural morphology may become less important than fracture energy and crack propagation. Maimí and colleagues therefore distinguished micromechanical multiscale approaches from mesoscale continuum damage formulations, noting that ply-level models can be more efficient for large structural computations while still representing mode-dependent progressive damage. An effective framework can consequently use detailed micromechanics before localization and fracture-based or continuum-damage descriptions once cracks become structurally dominant.

3.2 Progressive Failure at Ply and Laminate Scales

Hashin's failure formulation separated tensile and compressive fiber and matrix modes, providing a physically clearer representation than one undifferentiated failure index. Later physically based criteria introduced detailed mechanisms such as matrix fracture planes and fiber kinking, particularly under compression, while finite-element implementations included nonlinear shear behavior and regularization procedures to reduce pathological mesh dependence during strain softening.

Continuum damage mechanics extends failure initiation criteria by degrading constitutive stiffness progressively. Matzenmiller, Lubliner, and Taylor introduced internal damage variables for anisotropic fiber composites, relating evolving damage directly to effective material stiffness. Maimí and colleagues subsequently developed a laminate continuum-damage framework capable of representing longitudinal and transverse intralaminar failure while using fracture-energy regularization to maintain numerical objectivity.

For hybrid laminates, interlaminar failure requires additional attention because different fiber systems can create strong stiffness discontinuities between adjacent plies. Cohesive-zone interfaces can represent the onset and propagation of delamination through traction–separation relations, whereas continuum ply models address intralaminar deterioration. The two mechanisms interact: matrix cracking can reach an interface and promote delamination, while delamination changes ply stress distributions and can accelerate fiber failure. Multiscale analysis is therefore most useful when it allows damage information to transfer between these mechanisms instead of evaluating each independently.

3.3 Hybrid Effects and Failure Redistribution

Fiber hybridization introduces mechanisms that are absent from single-reinforcement laminates. Swolfs, Gorbatikh, and Verpoest identified residual stress, altered failure development, and dynamic effects as principal explanations for hybrid behavior, while emphasizing the importance of dispersion and hybrid architecture. Local micromechanical analysis shows that stress concentrations around a broken low-elongation fiber depend on neighboring fiber type, realistic fiber dimensions, packing, and spatial arrangement.

Global load-sharing analysis further shows that statistical scatter in carbon-fiber strength is particularly important because gradual fragmentation allows load to be redistributed before catastrophic clustering occurs. Failure-strain enhancements predicted by such models arise from modified failure development rather than an intrinsic increase in carbon-fiber strength. Thin-ply carbon/glass experiments have similarly demonstrated that apparent carbon-layer failure strain can increase under particular hybrid configurations and that ply thickness influences the magnitude of the effect.

Hybridization does not guarantee improved failure resistance in every configuration. Experimental fracture work has demonstrated that stacking sequence can become more influential than nominal carbon/glass fraction under some bending conditions because it alters interlaminar stresses and the sequence of matrix, interface, pullout, and fiber-breakage damage. Consequently, a predictive model should resolve both constituent-level load sharing and laminate-level architecture.

4. Research Methodology

4.1 Hierarchical Micro–Meso–Macro Model

The proposed computational architecture uses three linked scales. At the microscale, representative volume elements contain carbon fibers, glass fibers, polymer matrix, and interface regions. Carbon and glass are modeled as linearly elastic until damage initiation, while the epoxy matrix is permitted to exhibit nonlinear deformation before fracture. Strength variability of the low-elongation reinforcement can be incorporated through a Weibull-type distribution where statistical fracture modeling is required.

At the mesoscale, homogenized lamina properties are transferred to a continuum damage model. Separate damage variables represent fiber tension, fiber compression, matrix tension, matrix compression, and in-plane shear degradation. Hashin-type or physically based initiation criteria can activate these modes, while damage evolution is governed by fracture energy and characteristic element length to reduce mesh sensitivity. Such mode-specific progressive formulations are consistent with established continuum-damage and physically based composite models.

At the macroscale, individual plies are assembled into a laminate model. Cohesive interfaces are inserted where delamination is considered structurally relevant. The laminate-level finite-element model calculates the structural stress redistribution created by ply damage, after which selected critical integration points can transmit updated strain or stress states back to microscale RVEs.

Table 1. Proposed multiscale architecture for hybrid composite failure analysis

Scale	Principal representation	Dominant modeled mechanisms	Information passed upward
Constituent / microscale	Carbon fiber, glass fiber, matrix, local interface	Matrix yielding/cracking, individual fiber failure, debonding, local stress	Homogenized stiffness, strength evolution, local damage measures

Scale	Principal representation	Dominant modeled mechanisms	Information passed upward
		concentration	
Ply / mesoscale	Homogenized orthotropic lamina	Matrix tension/compression, fiber tension/compression, shear degradation	Damaged constitutive matrix and fracture-energy response
Interface scale	Cohesive traction–separation layer	Delamination initiation and propagation	Interface stiffness and separation state
Laminate / macroscale	Layered finite-element structural model	Load redistribution, global stiffness degradation, structural collapse	Boundary conditions for refined local analysis
Adaptive feedback	Selected high-risk regions	Updated micromechanical damage under local stress history	Corrected degraded properties and failure progression

4.2 Constitutive Damage and Scale-Transfer Relations

The degraded mesoscale constitutive relation is represented generally as:

$$\boldsymbol{\sigma}
\mathbf{C}_{d}\boldsymbol{\varepsilon}$$

where ($\mathbf{C}_{d}$) is the anisotropically degraded stiffness tensor. Unlike a scalar isotropic damage law, the present framework allows different damage variables to reduce different stiffness components.

For an illustrative direction (i),

$$E_i^{d}=(1-d_i)E_i^0$$

where (E_i^0) denotes the undamaged modulus and (d_i) is an internal variable satisfying ($0\leq d_i\leq1$).

Interface behavior is represented using a cohesive relation in which damage initiates once a traction criterion is exceeded and progresses through fracture-energy-controlled separation. The purpose of treating intralaminar and interlaminar mechanisms separately is to avoid forcing matrix cracking and delamination into the same numerical damage law.

$$H_{\varepsilon}
\frac{\varepsilon_{h}-\varepsilon_{LE,ref}}{\varepsilon_{LE,ref}} \times100$$

where (ε_h) represents the strain corresponding to low-elongation constituent failure within the hybrid and ($\varepsilon_{LE,ref}$) is the reference failure strain in the nonhybrid composite. This measure follows the general interpretation of hybrid-effect studies but is not itself sufficient to identify the physical mechanism.

4.3 Simulation Protocol and Validation Requirements

The simulated material is a carbon/glass/epoxy laminate containing both low-elongation carbon reinforcement and higher-elongation glass reinforcement. The conceptual loading case is monotonic tensile deformation because it permits clear visualization of constituent fragmentation and progressive load transfer. The framework is equally adaptable to bending, compression, impact, or fatigue when the corresponding constitutive laws are calibrated.

A sequential simulation begins by calculating undamaged effective ply properties from the RVE. The laminate model is then loaded until local strain or stress exceeds a scale-refinement criterion. Critical regions trigger microscale analysis, and updated degraded properties are returned to the mesoscale constitutive model. Cohesive interfaces evolve independently according to interlaminar traction and separation. This process continues until global load-carrying capacity decreases to the structural failure condition.

No numerical value in the present study is presented as experimentally validated. A future validation program should compare predicted and measured load–displacement response, strain localization, first-damage load, carbon-layer fragmentation, delamination location, final failure mode, and residual stiffness. Published carbon/glass multiscale research demonstrates the value of combining mechanical testing with digital image correlation and acoustic emission because final strength alone cannot establish whether the numerical model reproduced the correct internal damage mechanisms.

5. Analysis

5.1 Predictive Fidelity and Computational Cost

The first simulation compares four levels of modeling fidelity. A conventional single-scale method uses homogenized ply properties with a failure criterion but limited post-initiation micromechanics. A continuum-damage model adds progressive stiffness degradation. Sequential multiscale analysis introduces RVE-derived properties and constituent-specific calibration, while the adaptive two-way framework permits local structural fields to update micromechanical damage during loading.The simulated results indicate that increasing scale resolution progressively reduces failure-load error but produces a substantial increase in computational effort.

Table 2: Simulated accuracy–cost comparison of hybrid-composite failure models

Modeling strategy	Constituent resolution	Progressive damage	Simulated failure-load error	Normalized computational cost
Single-scale failure criterion	None	Limited	14.8%	1.0
Ply continuum-damage model	Indirect	Yes	9.6%	2.4
Sequential multiscale model	RVE-based	Yes	5.2%	6.8

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Modeling strategy	Constituent resolution	Progressive damage	Simulated failure-load error	Normalized computational cost
Adaptive two-way multiscale model	Local two-way coupling	Yes	3.8%	11.5

Note: Values are hypothetical and are provided solely to demonstrate comparative methodological behavior. They do not represent benchmark results for a specific laminate.

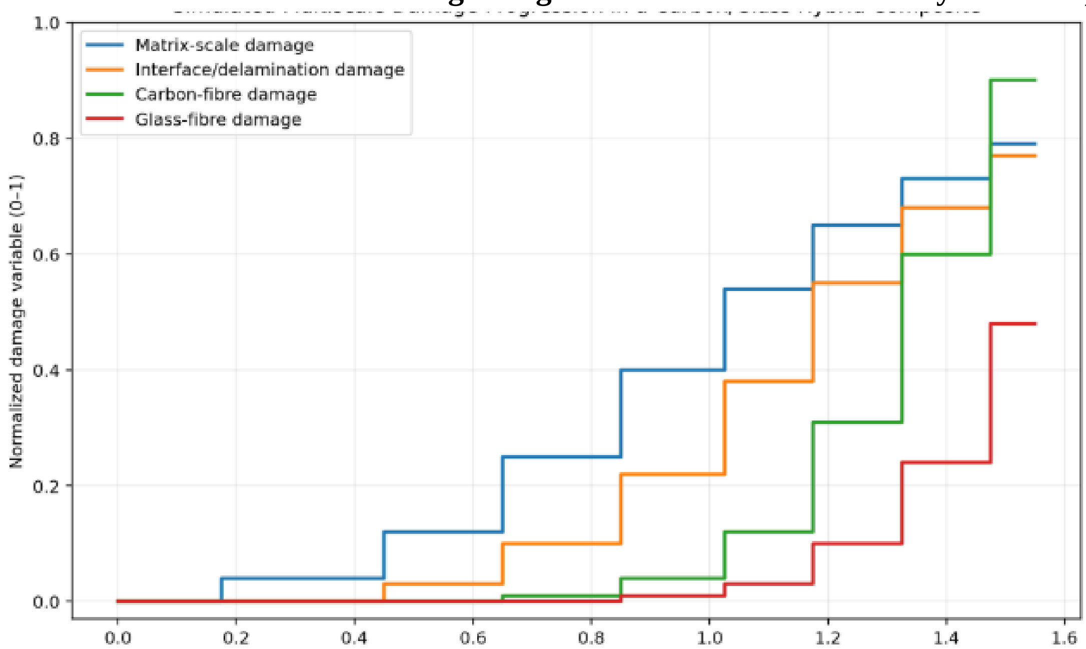
The table illustrates a central engineering trade-off. Full multiscale analysis is not automatically the preferred option when a simpler model already answers the design question with sufficient accuracy. Its value increases when local constituent damage determines structural behavior or when new hybrid architectures fall outside the calibration range of conventional ply models.

5.2 Simulated Sequence of Multiscale Failure

The simulated damage history begins with polymer-matrix deterioration. Matrix damage rises from a normalized value of approximately 0.04 at low applied strain and develops progressively before significant reinforcement fracture occurs. Interface and delamination-related damage appears later but accelerates as matrix cracks transfer increasing local stress toward ply boundaries.

Carbon-fiber damage remains minor during the early matrix-dominated phase and increases rapidly only after substantial matrix and interface deterioration. The glass-fiber damage variable develops later because the high-elongation reinforcement retains additional strain capacity. This sequence produces a period during which surviving glass reinforcement and unbroken carbon fibers redistribute load after localized carbon damage.

Graph 1: Simulated Multiscale Damage Progression in a Carbon/Glass Hybrid Composite



The stepped progression is consistent conceptually with hybrid-composite research showing that load redistribution and fragmentation can delay complete low-elongation-fiber failure, while laminate experiments identify multiple interacting failure mechanisms before final fracture. The numerical values and strain levels in the graph remain hypothetical and should not be treated as characteristic values for any commercial carbon/glass system.

The graph further demonstrates why ultimate strength is an incomplete validation metric. Two models may predict similar failure loads while producing completely different internal sequences. A model that predicts immediate carbon-fiber rupture without preceding matrix and interface damage may give an acceptable peak load accidentally yet provide unreliable predictions when ply thickness, stacking sequence, notch geometry, or loading mode changes.

5.3 Hybrid Ratio, Ply Thickness, and Stacking Sensitivity

The simulated framework predicts that increasing the proportion of higher-elongation glass reinforcement generally increases the capacity for post-carbon-fracture load redistribution but lowers the overall axial stiffness relative to a carbon-dominated laminate. The relationship is nonlinear because the hybrid effect depends on carbon-fiber strength scatter and the manner in which stresses are redistributed around local breaks. Global load-sharing studies have shown that larger scatter in low-elongation-fiber strength can increase the apparent hybrid effect by distributing damage over a broader strain interval.

Ply thickness creates another critical effect. Thin carbon plies surrounded by glass can suppress unstable crack or fragmentation growth more effectively than thick carbon blocks, whereas thicker low-elongation layers can behave increasingly like their nonhybrid reference. Experimental thin-ply work has reported substantial failure-strain enhancement under selected configurations but little comparable benefit for thicker carbon plies.

Stacking sequence also changes the location of stiffness discontinuities and interlaminar stress concentrations. Carbon layers placed close to high-bending-stress surfaces can provide stiffness but may increase the severity of their local failure, while alternating thin carbon and glass layers can increase interface count and therefore create additional opportunities for delamination. A multiscale model should therefore optimize hybrid architecture using both intralaminar and interlaminar damage indicators rather than maximizing one constituent proportion alone.

6. Discussion

6.1 Why Hybrid Composite Failure Requires Multiple Scales

The first major implication is that hybrid composite failure cannot be represented reliably through constituent averaging alone. Homogenization is highly effective for determining elastic properties before damage, but failure is inherently localized. An individual broken carbon fiber changes the load borne by nearby fibers and matrix; multiple breaks create clusters; clusters change ply response; ply damage alters laminate redistribution; and laminate redistribution can then increase or reduce the probability of additional microscale failure.

Swolfs and colleagues' hybrid-failure models demonstrate the importance of fiber-strength statistics and stress redistribution, while multiscale carbon/glass modeling shows that RVE-derived material response can be embedded in larger three-dimensional structural analysis. These findings justify the hierarchical architecture proposed here.

At the same time, not every microstructural detail deserves explicit resolution. Once damage has localized into a large matrix crack or delamination, fracture-energy-based continuum descriptions can be more useful than attempting to track every polymer microvoid. The appropriate modeling question is therefore which scale controls the structural response at the current stage of damage.

Adaptive scale refinement provides a practical solution. Most of a large structure can remain represented by computationally economical mesoscale constitutive laws, while microscale RVEs are activated near notches, joints, ply drops, impact zones, or emerging failure bands. Such an approach preserves physical mechanism resolution where it matters most while avoiding unnecessary calculation elsewhere.

6.2 Mesh Objectivity, Parameter Calibration, and Model Credibility

Progressive damage creates a well-known numerical difficulty because softening constitutive behavior can concentrate deformation into increasingly narrow finite-element zones. Without regularization, predicted fracture energy and therefore structural failure can depend strongly on element size. Physically based and continuum-damage implementations have addressed this problem through characteristic-length or smeared formulations in which dissipated energy is controlled explicitly.

A multiscale framework must maintain similar objectivity at every scale. Refining the laminate mesh should not create a new effective fracture energy, while changing RVE discretization should not alter homogenized failure simply because more local elements are available to concentrate strain. Scale transfer therefore requires energy consistency as well as stress and strain consistency.

Parameter identification is another source of uncertainty. Fiber strength is statistically distributed, matrix behavior is nonlinear, interface parameters can be difficult to determine independently, and cohesive fracture energies depend on mode mixity. Fitting all parameters simultaneously to one laminate test risks compensating one incorrect mechanism with another. Model calibration should therefore proceed hierarchically: constituent properties from constituent tests, ply parameters from coupon tests, interface properties from fracture tests, and structural validation from geometries not used for calibration.

Such separation is essential for predictive credibility. The purpose of multiscale modeling is not to create an elaborate numerical model that reproduces one experiment after extensive adjustment. Its value lies in transferring experimentally grounded constituent information to new hybrid ratios, stacking sequences, thicknesses, and structural configurations with less empirical recalibration.

6.3 Validation Beyond Final Failure Load

The third implication is that validation should test the entire damage pathway. Final failure load is easy to compare but may conceal compensating errors. A numerical model could underestimate matrix damage and overestimate interface damage yet still predict the correct maximum load because the two errors offset each other.

A stronger validation strategy combines global and local evidence. Digital image correlation can identify strain localization, acoustic emission can reveal transitions in damage activity, microscopy can verify constituent fracture mechanisms, and ultrasonic or other nondestructive methods can quantify delamination. Hybrid-composite investigations have already demonstrated the value of coupling mechanical testing with acoustic-emission classification, while validated multiscale studies have combined several experimental techniques to assess both strain distribution and progressive failure.

Uncertainty should also be reported explicitly. Fiber strength scatter, fiber placement, void content, local resin-rich regions, manufacturing tolerances, and interface variability can create specimen-to-specimen failure variation that a deterministic model cannot reproduce with one fixed curve. Probabilistic micromechanics therefore offers an important extension for hybrid composites because the hybrid effect itself is partly associated with statistical fracture development.

Ultimately, the most useful multiscale model is not necessarily the most detailed one. It is the least computationally expensive model that reproduces the failure mechanisms relevant to the design question with defensible uncertainty. For initial sizing, a calibrated ply model may be sufficient; for novel hybrid architectures or damage-critical regions, selective microscale resolution becomes more valuable.

7. Conclusion

Multiscale modeling provides a coherent framework for understanding hybrid composite failure because the mechanisms responsible for structural collapse originate at different physical scales. Constituent-scale matrix cracking, individual fiber fracture, local debonding, ply-level stiffness degradation, and interlaminar delamination cannot be represented completely by a single homogeneous failure index. Linking representative volume elements, continuum damage mechanics, cohesive interfaces, and laminate finite elements allows the progression of damage to be modeled as an interacting sequence.

The simulation presented in this study demonstrates that increased multiscale fidelity can improve predictive capability while also imposing substantial computational cost. The illustrative failure-load error decreases from 14.8% for a conventional single-scale framework to 3.8% for adaptive two-way multiscale coupling, whereas normalized computational demand increases from 1.0 to 11.5. These values are methodological rather than empirical, but they highlight why multiscale resolution should be applied selectively rather than indiscriminately.

The modeled damage progression also clarifies the mechanical role of hybridization. Matrix deterioration develops first, interface and delamination activity follows, low-elongation carbon-fiber damage accelerates as local stress concentrations intensify, and higher-elongation glass reinforcement provides a period of additional load redistribution before its own damage develops. Hybrid performance is therefore controlled not only by carbon/glass fraction but also by fiber-strength scatter, dispersion, ply thickness, stacking sequence, interface behavior, and the localization of damage.

Future experimental studies should validate such models across multiple hybrid ratios and stacking architectures using synchronized mechanical tests, full-field strain measurement, acoustic-emission monitoring, delamination inspection, and post-fracture microscopy. Parameter uncertainty and manufacturing variability should be incorporated through probabilistic analysis rather than represented only by nominal material properties. With appropriate calibration and validation, multiscale simulation can move beyond retrospective reproduction of composite tests and become a practical design methodology for predicting how constituent selection and hybrid architecture influence damage tolerance, failure sequence, and structural reliability.

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